Faculty of Science and Engineering

Predictive Indicators of Success in Science & Engineering Projects - Application to the SKA Initiative

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Abstract

Projects that have scientific goals and are characterised by new engineering technologies, significant infrastructure, and big budgets are typically found to undergo much scrutiny prior to approval. What is less clear is whether concept reviews, approval, funding, or early stage planning takes proper advantage of potential indicators of success based on learnings from relevant past experience. In other words, is the likelihood of success in meeting all project goals considered at the outset, and can early stage project development/planning be made more effective?

Through examination of published literature, interviews with past and present project managers, scientists and engineers, and investigation of selected case studies in Australia, Chile, South Africa and Europe, this thesis attempts to (i) identify critical success factors relevant to large, complex high-technology projects, (ii) investigate the use of experience as success indicators within contemporary case studies, and (iii) distil the results into a set of predictive test indicators of likely project success.

While there is considerable literature concerning general management of large projects, and covering execution of complex undertakings, there is little specific material dealing with success drivers for large and complex high-technology projects. This thesis aims to fill this important gap in the current understanding.

The present study distils an epistemic view of high-technology 'mega-projects', and through case examination and inductive and deductive reasoning, shows that serious attention paid to specific aspects of project-shaping can lift the probability of success. An additional output is a practical checklist tool for 'high-tech' mega-project practitioners.

The findings from this research have direct applicability to current and future approvers and managers of large scale high-technology projects, and in particular the Square Kilometre Array (SKA) radio telescope project to be built in either Australasia or Southern Africa, and planned to commence preconstruction in 2012.

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I acknowledge the generous support of past and current Directors of CSIRO Astronomy and Space Science, and Curtin University for its financial support. I thank my academic supervisors Professors Peter Hall and Dora Marinova for their guidance and encouragement, and Professor Schilizzi, Director, SKA Program Development Office, UK. I also thank the Dutch ASTRON organisation for their co-operation with the LOFAR telescope project review, and the many other interviewees who gave their time and wisdom during the fieldwork in Chile, Europe, South Africa, and Australia. Thanks to Dr. Tony Beasley whose gift of Flyvbjerg's book on mega-projects seeded so much further reading. On a personal note, I thank my parents - Stan, the 'armchair professor', for kindling my curiosity in science and radio, and Pam for tolerating my teenage electrical experiments. Finally, this research effort would have been impossible without the unstinting support of my wife Jenni, who weathered two very cold years in the UK without complaint.

Table of Contents – Overview

Table of Contents – Chapter Detail

List of Figures

List of Tables

Abbreviations and acronyms

Term	Definition or explanation
AFE	Authority for Expenditure
ALMA	The Atacama Large Millimetre/submillimeter Array
ASPERA	AStroParticle ERAnet - a network of national government agencies responsible for coordinating and funding national research efforts in Astro-particle Physics
ASKAP	The Australian SKA Pathfinder telescope
ATCA	The Australian Compact Array radio telescope
AUGER	Pierre Auger Cosmic Ray Observatory
CASS	CSIRO (Division of) Astronomy and Space Science, Australia
CERN	European Organization for Nuclear Research
CHiPS	The Checklist for High-tech Project Success
CMMI	Capability Maturity Model Integration - a process improvement methodology. CMMI is registered in the U.S. Patent and Trademark Office by Carnegie Mellon University
CoDR	Concept Design Review
COTS	Commercial off-the-shelf (readily available from industry)
CPM	Critical Path Method
CSF	Critical Success Factor
CSIRO	The Commonwealth Scientific and Industrial Research Organisation (CSIRO) - Australia's national science agency
ESO	European Organisation for Astronomical Research
GEMINI	The Gemini Observatory
GMT	The Giant Magellan Telescope
GT	Grounded Theory – an investigative technique based on narratives
HERA	The Hydrogen Epoch of Re-ionization Array
HESS	High Energy Stereoscopic System
HIPER	High Power laser Energy Research facility
HW	Computer hardware
ICCPM	International Centre for Complex Project Management
ICT	Information, Communications, and Technology
ILC	The International Linear Collider
IPT	Integrated Project Team. A multi-disciplinary group led by a project manager. Each IPT is responsible and accountable for its defined domain, and for meeting cost, schedule and performance goals
IT	Information Technology
ITER	The International Thermonuclear Experimental Reactor
JWST	James Webb Space Telescope – a Hubble telescope replacement program
LHC	The Large Hadron Collider
LIDAR	Light Detection and Ranging instrument
LOFAR	Low Frequency Array (radio telescope)
MeerKAT	The (South African) Karoo Array Telescope
MMS	Magnetospheric Multi-scale Project
NAOJ	National Astronomical Observatory of Japan
NASA	National Aeronautics and Space Administration
NEON	National Ecological Observatory Network
NIF	The (US) National Ignition Facility

OPAL	Open Pool Australian Light-water (nuclear research) reactor
PERT	Program Evaluation Review Technique
PMBOK® Guide	Project Management Book of Knowledge (published by the Project Management Institute, USA)
PrepSKA	Preparatory phase for the SKA project
R&D	Research and Development
RM	Risk Management
RoI	Return on Investment (not necessarily financial)
SALT	The Southern African Large Telescope. The largest single optical telescope in the southern hemisphere
SE	Systems Engineering
SKA	The Square Kilometre Array radio telescope
SKADS	The SKA Design Studies – a funded work package of the project
SME	Small and Medium Enterprises
SOA	Service Oriented Architecture - the practice of sequestering changing software functions from those that don't change frequently.
SPDO	The SKA Program Development Office
SSC	The Superconducting Super Collider project A giant US based particle accelerator complex cancelled in 1993
SW	Computer software
TOPSAT	Tactical Operational Satellite. A micro-satellite launched in 2005 with advanced, down-looking, imaging cameras
TL	Transformational Leadership
VISTA	The Visible and Infrared Survey Telescope
VLT	The Very Large Telescope
WBS	Work Breakdown Structure
XFEL	X-ray free-electron laser

Glossary

Term	Definition or explanation
ATLAS	A family of U.S. space launch vehicles. The original Atlas missile designed as an ICBM
Boondoggle	Colloquial term for a scheme that wastes time and money
Constellation Program (CxP)	A human spaceflight program within NASA also dubbed 'Return to the Moon'. Cancelled by President Obama in February 2010
DAPTIV©	Proprietary software application for project portfolio management founded in 1997
Iridium System	A group of orbital satellites used to provide voice and data coverage to satellite phones and other devices over Earth's entire surface
Polaris	The Polaris missile is a submarine-launched ballistic missile (SLBM) built by Lockheed Corporation and first launched in 1960
(Project) artefacts	Objects produced or employed (in hard or soft form) to support project execution. E.g. plans, reports, policies, spreadsheets, drawings, etc.
SKA Pathfinders	Generic title given to projects where prototype technologies are deployed as testing facilities for the SKA. Includes the three main precursor instruments in Australia, South Africa, and The Netherlands
Synchrotron	A particular type of 'ring' particle accelerator in which the magnetic field and the electric field are synchronised with the particle beam

Preface

'Though this be madness, yet there is method in't.'

Hamlet Act 2, Scene 2, William Shakespeare

The seed idea for researching mega-science project success indicators came from a serendipitous conversation. Having just emerged from chairing a lengthy and tense Project Review Board at my employer organisation – a national science and industrial research body – I was bemoaning to a small group the general lack of improvement in project management performance. In that group was Peter Hall, an experienced project engineer about to fill the foundation Chair in Radio Astronomy Engineering at Curtin University. Prof. Hall shared and encouraged my interest in investigating the problem, and after further deliberations, I was generously offered a doctoral studentship to pursue my research question, with Prof. Hall and Prof. Marinova as my academic supervisors. The following year, I accepted a two-year posting to join the costing and design team for the Square Kilometre Array mega-project based at the University of Manchester, UK. This placed me in an ideal situation to closely observe a large science/engineering project in the formative stages, and to readily conduct fieldwork at several European mega-science facilities. Motivated primarily by practical imperatives and distinguished through working insights, the thesis nonetheless extends theoretical boundaries around success criteria in areas such as the implications of characterising complexity, project resilience, decision-making, and the linking of project review methodologies to successful learning organisations.

Chapter 1 - Introduction

1.1 Introduction to the study

Each year, the developed and developing nations commit billions of dollars to research and development (R&D). In Australia, the 2008/09 Government investment in R&D was A$ 3.42 billion, while R&D expenditure by Australian business for the same year was A$16.86 billion. Gross Australian R&D investment (GERD) for the 2008/09 year equalled 2.2% of GDP (almost 22,000 person-years of effort) – more than triple the 1998/99 figure (ABS, 2010). The investment budget of Australia's premier science research agency, the CSIRO[1], was A$2.8 billion for the period 2006-2010. Tax payers and shareholders have every reason to expect these resources to be effectively applied in support of innovation.

[1] The Commonwealth Scientific and Industrial Research Organisation

National support of science is vital. The Australian Prime Minister's Science, Engineering and Innovation Council 1999 meeting tabled an analysis (Boskin & Lau, 1992) estimating that 49% of economic growth came from technical progress. Another international study (Coe & Helpman, 1995) found that every 1% increase in a nation's investment in research increased productivity by 0.23%. Although these figures may not be universally applicable, it is clear that investing in science provides a significant boost for a country's future.

Investments in science and engineering R&D should be underpinned by reasonable confidence levels, yet as the present study shows, success cannot be assumed. All research involves risk, and science/engineering research by its very nature is often highly risky, yet this alone cannot explain the poor track record of high-technology (high-tech) projects. Personal observations within Australia's CSIRO suggest that there are few systems in place to effectively identify and capture lessons learned from big science, much less in a format that might be of practical use at the planning and 'authority for expenditure' (AFE) stages of future projects. Certainly evidence from CSIRO's Australia Telescope National Facility (now CSIRO Astronomy and Space Science - CASS) Project Review Board tends to confirm that analogous project histories are rarely considered seriously when initiating, approving or reviewing progress of major high-tech projects. Research for this thesis confirms the view that such failure is a widespread phenomenon.

The character of large high-tech projects tends to point investigators towards programmatical problems when seeking to learn from, or explain, failure. However traditional project management approaches are inadequate against the broader complexities of large scale endeavours known as mega-projects (ICCPM, 2011). A recent NASA Space Shuttle report (Rhatigan, 2011, p. iii) describes the more chilling consequences of failing to exploit institutional knowledge by voicing NASA's view that: *"Columbia failed to preserve the lives of our...colleagues due to our own very human errors"*.

The world of large high-tech projects is a very exciting place of discovery, break-through, and leviathan scale machines that stretch the imagination. It is also complex and messy, with frequent problems that sometimes confound the stakeholders. In a sea of failures, it is no wonder that the documented successes are sometimes overlooked.

All this spawned a two-part question. First, is there a more robust process, using theoretical and/or empirical predictive indicators derived from the literature and from best-practice contemporary large projects, that can be generally applied to lift the probability of success of high-tech mega-projects? Second, how might this be useful for one of the largest science construction project to be undertaken over the next 15 years – the Square Kilometre Array?[2]

1.2 Approach to the research question

The objectives which follow from this research question are:

- To investigate published studies and specific relevant casework to reveal the extent to which past project experience and learnings have been used as indicative success indicators;
- To identify specific pre-cursors of success in large high-tech projects that are influential in shaping projects and building resilience;
- To test any causal links to early project outcomes in contemporary mega-science projects, and identify key drivers for project success;
- To develop a set of indicators applicable as predictive tests of likely project success, and present these as a practical process tool for use by project authorities, and thereby identifying;
- The applicability of key success drivers and high-tech project management characteristics to the Square Kilometre Array project.

Success and failure in projects is a frequent topic among both project theoreticians and practitioners. Mega-projects especially have received attention from academic authors and the popular press, often recounting performance failures and cost and time overruns, and sometimes leading to *fiascos* (Grün, 2004; Cooper, 2006). While many notable mega-projects are delivered 'on time, on budget', large projects - especially those underpinned by, or delivering, new technology - are very demanding of management capability, resources, and systems engineering, and too often fail in one or more performance criteria (Merrow, 1988; Morris & Hough, 1986; Hartman & Ashrafi, 2004; MoD, 2009). One informed estimate gauges just $80 million of value is delivered for each $100 million invested (Crawford & Cooke-Davies, 1999). Whatever the return on investment (ROI), too many high-tech mega-projects continue to underperform despite increased application of systemic, disciplined project management approaches and instantaneous information transfer via the internet (Archibald, 2003).

[2] The SKA is described in section 7.2

The topic of project failure has been examined most thoroughly through case investigation, and by some scholars. Practically every project flop has met with forensic scrutiny in an effort to reveal root cause and commercial impact and often to vindicate some stakeholder. In researching for this thesis, my focus was not on causes of failure, but reasons for success. This proved to be a far more difficult assignment, since success is frequently viewed as self-evident. Moreover, success is not necessarily the antithesis of failure. Added to the cost-schedule-performance trilemma are the added dimensions of success over time, technology pathfinding, and even inspirational value. It is project success, not failure, which offers data richness.

Much has been written regarding project performance, and the literature contains empirical studies of tens, and sometimes hundreds, of projects in an effort to distil factors governing their success or failure (e.g. Müller & Turner, 2007; Pinto & Slevin, 1989; Ika, 2009). Case study work, involving report analyses, interviews and questionnaires offers much insight through evidential data complemented by qualitative judgement (Grün, 2004). Other studies derive conclusions through statistical analyses (e.g. Belassi & Tukel, 1996; Dvir et al., 1998) and although meaningful, require more interpretation by the practising project manager.

This thesis, drawing heavily on case study work and research from the previous four decades, and augmented by contemporary experience, asks: what are the key strategic areas that show strong correlation to project success at the project formation, precursor activity, execution, and review stages? Seen through the lens of several contemporary projects, the research tests theoretical boundaries, and contributes to the debates about success definitions, learning organisations, decision-making, and characterising project complexity.

Data are examined to identify success factors and success criteria for large engineering and science projects, and compare these with general mega-projects. Analyses are presented that contribute new insights for life-cycle project management, especially applicable at the project planning, formation and approval stages, and to show the comparative importance of top ranking high-tech project success drivers. The relationships concerning external stakeholders are also investigated, especially procurement processes and the importance of recognising and managing the wider project environment.

Importantly, this study looks beyond the obvious in terms of project management skills and the necessary qualities of high-tech mega-project managers. I investigate the overlapping and intertwining of disciplines (e.g. strategy, engineering, procurement, personnel, finance, etc.) needed to effectively plan and execute a high-tech mega-project. I seek to reveal the more subtle characteristics, traits, and initiatives that lead to project success and identify the personal and professional attributes, skills and exemplar initiatives that are key ingredients.

As a practical outcome of this thesis, I offer a process tool that can be applied at the early stages of project planning. This is in the form of a procedural checklist that fundamentally challenges the project design and execution team in very specific areas where research has confirmed a strong correlation between success and failure. The tool was honed using experience gained during interaction with planning engineers at the SKA Program Development Office (SPDO), and during a lessons-learned workshop for the recently commissioned Dutch LOFAR radio interferometer project.

In reporting on NASA's defunct Constellation Program, Rhatigan (2011, p. vi) writes: *"learning from experience is irreplaceable. Learning from the experience of others is the next best thing. Both are an exercise in judgement. Sifting the useful kernels in a chaos of chaff requires perception and oftentimes detachment."* This thesis seeks to embody those words while recognising that learning based on inductive references from selected projects is necessarily imperfect (Cave, 2011). It is my belief that willingness to engage intelligently with the imperfect process, and to apply cross-disciplinary thinking, allows important success drivers to be distilled.

Outside the scope of this work are the project management toolsets, applications and enterprise systems necessary for practical delivery, as well as deep discussion regarding organisational and project structures (e.g. Work Breakdown Structures). While these subjects are important at the project deployment level, they are already well described in the realm of practice manuals or deserving of discrete research programs. Also beyond the scope of the present study are investigations among the funding agencies. While they may have a view of what success means, and are clearly influential at the AFE stage, no evidence emerged that the funding agencies contributed to successful outcomes for science/engineering projects in a programmatical or technical performance sense, which is the focus area of this thesis.

The results from the present research will have direct applicability to current and future approvers and managers of large scale science projects, and in particular the Square Kilometre Array radio telescope project which is likely to receive initial approval around 2012.

1.3 Research methodology

1.3.1 Literature search

Literature-based data for this thesis is drawn from peer-reviewed journal publications, published reports, technical articles and case study extracts. I purposely sought material from a broad range of studies from the Western world covering the past 35 years, containing diverse project characteristics in terms of purpose, budget, location, engineering innovativeness, and sponsor. Care was taken to ensure a representative and significant sample of high-tech projects with some systems engineering component. Literature sources were initially selected from library searches on the keywords ‘project success’, ‘mega-project’, ‘critical success factor’, ‘lessons learned’ and ‘project learning’, and later broadened to target specific areas of project theory. A description of the extant literature is given in section 2.2.

1.3.2 Case study fieldwork

1.3.2.1 Case study research

Case study research is sometimes only seen as useful as a preliminary stage of an investigation, or supplementary to it, but not of value in itself unless linked to a hypothesis (Flyvbjerg, 2006). Yin (2009) joins Flyvbjerg in rejecting this, both arguing that casework reveals ‘context-dependent’ knowledge that encourages learning maturity from ‘rule-based’ to ‘virtuoso’ levels. Flyvbjerg goes on to explain the richness of information in the personal case-narrative, and its ability to describe realities which are hard to reveal or define in scientific parlance. Ika (2009 p.15) supports in-depth interviews as allowing: *“project actors to tell their professional life stories or talk about success factors”* and adds the rhetorical question, *“Are not words, by their very nature, infinitely richer than numbers?”*

Aubry et al. (2010) show that mixed-method empirical research designs are usually robust, particularly when part of a wider, mixed-method program of research. The combined methodologies of literature research complemented and validated through case-based fieldwork, though by its nature always incomplete, enable the extraction of several recurring topics that I show to be pivotal when dealing with large, high-technology, project success.

The case study as a research method is strongly endorsed by Yin (2009), who describes the rigorous methodological approach required for conclusion validity, and usefulness when investigating complex phenomena. Yin offers sound advice about when a case study approach to research is most appropriate, suggesting that is; when the research questions are predominantly ‘how’ and ‘why’; when behavioural control is *not* required; and when the focus is on contemporary events. Further, Yin (p. 9) explains that ‘how’ questions, as derivatives of ‘who’, ‘what’, and ‘where’: “*are likely to favour survey methods...[and]...are advantageous when the research goal is to describe the incidence or prevalence of a phenomenon or when it is to be predictive about certain outcomes*”. I have adopted the foregoing advice in research for this thesis.

The effectiveness of case study research is becoming increasingly acknowledged at NASA, where the method is codified. NASA’s methodology document remarks: “*knowledge is most useable when it is contextual – when it relates to one’s own experience, and is placed in the context of an actual event...*[a case study]*...is told for the purpose of illuminating the decision-making processes and the outcomes of that particular event, so that others can learn from past or current projects.*” (NASA, 2008, p. 2).

The questions and responses that form the conversation and ultimate narrative that informs casework research require careful construction and interpretation – a process known as discourse analysis. With an emphasis on reflexivity, discourse analysis inevitably introduces the researcher as a component of the discourse, though as a constructive effect (Phillips & Hardy, 2002). A key point is that the researcher or analyst should not attempt to interpret individual statements or texts, but consider summations of remarks and bodies of texts to derive a broader reality. As Phillips and Hardy (2002 p. 9) put it: “*Content analysis, not in terms of a mechanistic counting but in a more interpretive form, can be used to connect textual content to broader discursive contexts.*”

1.3.2.2 Approach to casework for this thesis

The casework for this thesis, and a vital component of the research, is a series of field investigations conducted at 17 large scientific institutions/facilities in Europe, Chile, South Africa, Australia, and Antarctica (Table 1-1). The chosen sites each satisfy my chosen general criteria of having substantial and specialised infrastructure (i.e. a complex scientific facility), budgets of at least tens of millions of dollars, and a science goal concerned with astrophysics, particle physics, or nuclear physics. Visits of 1-3 days were pre-planned to ensure access to key project management representatives, each of whom agreed to an interview typically lasting 3-5 hours. Use of a question list (See Appendix A) enabled a systematic approach and consistency of topic coverage; however interviewees were encouraged to amplify their responses as necessary. For each case study, a nominated point of contact was sent an information and consent letter drafted by my research supervisor, and he or she then responded with a signed agreement to participate in the research.

While much casework research on project success is, by and large, quantitative (Ika, 2009), this thesis uses essentially a qualitative methodology, complemented by a Grounded Theory (GT) approach enabling the systematic generation of theory from data that contains both inductive and deductive thinking (Georgieva & Allen, 2008). GT practice does not attempt to test an existing hypothesis, merely offer a method for evolving theory from collected data (Schalken et al., 2006). As such, the approach is highly appropriate as a framework for extracting empirical data from a broad variety of real-life science facility settings.

In this study and in accordance with Glaser and Strauss's GT methodology, a variety of data sources were considered valid for inclusion, not just theoretical research and planned observations. I made extensive field notes (and sometimes audio recordings) from both formal and informal interviews, as well as general observations from my experiences and observations in the workplace. A few of the cases restricted my interviews to two or three senior, well informed personnel (e.g. TOPSAT, OPAL), whereas most others permitted a broader survey. Several facilities (e.g. ILC, VISTA) arranged group entry and exit meetings to frame my investigations within shared knowledge and experiences. I finished all interviews with a recapitulation of the key facts and views expressed by the interviewee. Although not especially aiming for a phenomenological approach, my conversational style (derived from many years in technical auditing) elicited self reporting, accompanied by expressive gesture and sometimes strong emotion as described by Whitty (2010).

The gathered data were coded by topic/question, grouped into similar concepts in order to make them more workable and often collated non-numerically – the whole process known as *axial coding* within GT (Schalken et al., (2006). Given the relatively moderate scale of the survey, I completed the abstraction and analysis manually. From these concepts, categories were formed, which were later developed into theme headings for ease of reference, and generally support the research and conclusions of the present study. As emerging theory from this thesis, I present these concepts in the form of questions within a practical checklist ('CHiPS') tool and evidence guide. Although the CHiPS tool was shown to several practitioners for their opinion (and is now being applied in one project), validation in the real world is not required since, as Georgieva and Allen (2008 p. 45) reason: *"the emerging theory is reliable and does not require further testing because it comes directly from the real world data itself."*

Critics of GT have focused on its misunderstood status as theory, as opposed to a method of *discovering* theory; and on the claim that it develops inductive knowledge. Others suggest that it is impossible to discount preconceptions in the collection and analysis of data in the way that Glaser and Strauss (1967) say is necessary. Goulding (1999) documents these perceived shortcomings, and adds the problems of premature closure (leaving the field too early), and methodological transgression (not following the prescribed process). Finally one must add the inability to practice the approach to the required professional standard and thereby minimise erroneous generalisation, and researcher bias. To a large extent, these problems can be countered through a member-checking process to establish data fidelity and credibility.

Curtin University has issued the ethics protocol approval No. RD-25-09 for this work. Note that where case studies are referenced throughout this thesis, they are shown in full upper case, year format, for example (SKA, 2010).

Table 1-1. List of case study projects, organisations, and interviewees

Project Acronym & web link	Sponsor Organisation	Description	Interview details (principal contact(s) only identified)	Approx Budget
ALMA http://www.almaobservatory.org/en/home	ESO – NAOJ – NRAO Collaboration	Radio telescope array of ~66 dishes located in northern Chile. Under construction.	Dr. Tony Beasley, ex-Project Manager ALMA radio-telescope project. Discussions on mega-project management and risk. Personal interviews, Chile, 19-22 November, 2007, and Oxford, 28 October, 2010. Dr. Lewis Ball, ALMA Deputy Director. Discussion on project reviews. Email exchange 24 February, 2010. Total interviewees = 6	US1.4 billion
ASKAP http://www.atnf.csiro.au/projects/askap/	The Commonwealth Scientific and Industrial Organisation (CSIRO), Australia	Radio telescope array of 36 dishes located in the mid-West of Western Australia. ASKAP is a precursor for the SKA project currently under construction.	Dr. Dave DeBoer, former Project Director - ASKAP telescope. Discussion on radio-astronomy project management. Frequent Personal interviews during 2007-2011. Mr. Ant Schinckel, Project Director – ASKAP. Several discussions on ASKAP execution. 2010-2011. Total interviewees = 10	A$170 million
ATCA http://www.narrabri.atnf.csiro.au/	The Commonwealth Scientific and Industrial Organisation (CSIRO), Australia	Radio telescope array of 6 dishes located in northern NSW, Australia. Completed in 1988.	Dr. Ron Ekers, ex-Director Aust. Telescope. Discussion on major project success factors. Personal interview, Australia, 12 March, 2008. Email exchange 5 February, 2011. Ex-Director, CSIRO-ATNF, Dr. Bob Frater, 17 March, 2009. Total interviewees = 4	A$49.5 million
HIPER http://www.hiper-laser.org/index.asp	High Power laser Energy Research facility, STFC + Partners	High power laser to demonstrate the feasibility of laser-driven fusion. Currently in early stage planning. Site not yet decided.	Dr. Chris Edwards, Project Coordinator, RAL. Personal interview, Didcot, 15 November, 2010. Total interviewees = 4	€800 million for one-shot design, €5-10 billion for continuous power
ILC http://www.linea	Deutsches Elektronen-Synchrotron	Dual opposing linear colliders of super high power. Site not yet decided.	Dr. Wilhelm Bialowons, ILC Global Design Effort member. Discussions concerning science project structures. Personal interview, Germany, 13 July, 2009.	US$6.65 billion + US$1.8

Project Acronym & web link	Sponsor Organisation	Description	Interview details (principal contact(s) only identified)	Approx Budget
rcollider.org/	(DESY), Germany.		Email exchange 9 February, 2011. Dr. Reinhard Brinkmann, DESY-Directorate and Head of the Accelerator Division. Personal interview, Germany, 13 July, 2009. Total interviewees = 8	billion for site infrastructure
IRIDIUM Centre http://www.boeing.com/defense-space/support/bsc/iridium.html	Boeing – Iridium Inc	A constellation of 66 satellites providing voice and data coverage to satellite phones, pagers and integrated transceivers over Earth's entire surface.	Mr Steve Miles, Systems Engineer, Iridium Satellite Operations Center. Personal interview, Washington DC, USA, 8 September, 2008. Total interviewees = 3	~US6.0 billion.
ITER http://www.iter.org/	International Thermonuclear Experimental Reactor (ITER), France	International Thermonuclear Experimental Reactor that aims to demonstrate energy from fusion. Under construction in France.	Mr. Peter Swenson, Head of Project Office -ITER Facility. Discussion on major project management. Personal interview, France, 20-21 July, 2009. Email exchange 10 February 2011. Total interviewees = 5	Unclear – but in the region of €4.5-6.5 billion
LHC http://public.web.cern.ch/public/en/lhc/lhc-en.html	The European Organization for Nuclear Research (CERN), Switzerland.	Large Hadron Collider – a gigantic particle accelerator located under the border of France and Switzerland. Began operating in 2010.	Dr. Lyndon Evans, Project Manager - Large Hadron Collider. Discussion on characteristics of mega-projects. Personal interview, Switzerland, 23-24 July, 2009, and Manchester, 24 February, 2011. Email exchange 9 February, 2011. Total interviewees = 7	Approx €4.5-7.5 billion. (Accelerator plus experiments)
LIDAR http://www.antarctica.gov.au/about-antarctica/fact-files/studying-the-atmosphere/probing-the-atmosphere-with-lidar	Australian Antarctic Division	A light detection and ranging instrument especially configured to probe the mesosphere above Antarctica, with associated logistics. Commissioned in 2004, and since upgraded.	Dr. Andrew Klekociuk, Leader -Antarctic LIDAR project. Discussion on science program management and logistics. Personal interview, Antarctica, 1 December, 2004, and email exchanges Australia, 16 January, 2009, and August, 2011. Total interviewees = 3	A$2.0 million (including deployment to Antarctica)

Project Acronym & web link	Sponsor Organisation	Description	Interview details (principal contact(s) only identified)	Approx Budget
LOFAR http://www.lofar.org/	ASTRON, The Netherlands	Radio telescope consisting of thousands of omni-directional dipole antennas. Centred in North Holland, it commenced operations in 2010, and is continually being expanded.	Dr. Marco de Vos, Head R&D ASTRON/LOFAR mega-array. Discussion on science project characteristics. Personal interview, The Netherlands, 16 July, 2009 and 27 January, 2011. Dr. Michiel van Haarlem, LOFAR Managing Director. Personal interview, The Netherlands, 16 July, 2009 and 27 January, 2011. Total interviewees = 8	€83M cash plus €83M in-kind from partners
MeerKAT http://www.ska.ac.za/meerkat/index.php	SKA South Africa	Radio telescope array of 7 dishes (to be expanded to ~80) located in the Northern Cape of South Africa. MeerKAT is a precursor for the SKA project currently under construction.	Ms Anita Loots, Ass. Director Project Management. Personal interview, Cape Town, 26 February, 2009. Mr Willem Esterhuyse, MeerKAT Project Manager. Personal interview, Carnarvon, Northern Cape, SA, 20-22 February, 2009. Total interviewees = 4	US$140 million
OPAL http://www.ansto.gov.au/discovering_ansto/anstos_research_reactor	Australian Nuclear Science & Technology Organisation (ANSTO)	A state-of-the-art 20 mega-watt open-pool research reactor located in south Sydney, Australia. Commissioned in 2009.	Dr. Ross Miller, Project Manager OPAL nuclear reactor project. Discussion on approach to project governance. Personal interview, Australia, 7-8 Oct, 2009. Email exchanges 17 November, 2009, and 23 February, 2011. Total interviewees = 3	A$348 plus A$28 million for neutron beam.
SKA http://www.skatelescope.org/pages/page_skares.htm	The SKA Program Development Office, UK.	A giant radio telescope with 1 million square metres of collecting area using thousands of receptors, in early design phase. Location is either Southern Africa, or Australasia.	Prof. Richard Schilizzi, Project Director – SKA Program Development Office (SPDO). Discussions concerning project establishment conditions. Personal interview, UK, autumn, 2010. Meeting of Domain Specialists, Manchester, UK, 2010 Total interviewees = 10	€1.5 billion (notional)
SYNCH http://www.synchrotron.org.au/	Australian Synchrotron, Melbourne.	A particle accelerator accommodating 30 beamlines, located in Melbourne, Australia. It began operations in 2007.	Australian SYNCHROTRON, Dr. Dean Morris, Head of Operations - Aust Synchrotron. Discussion on mega-project management. Personal interview, Australia, 4 March 2009. Total interviewees = 5	A$157 million

Project Acronym & web link	Sponsor Organisation	Description	Interview details (principal contact(s) only identified)	Approx Budget
TOPSAT http://www.sstd.rl.ac.uk/Topsat/	TOPSAT Cube Satellite, RAL-QinetiQ-Surrey Satellites	A micro-satellite with advanced, down-looking, imaging cameras. Launched in 2005.	Prof. Richard Holdaway, Director - Space Science and Technology Department, RAL. Personal interview, Didcot, 20 May, 2010. Email exchange 5 February 2011. Total interviewees = 2	US$20 million
VISTA http://www.vista.ac.uk/	Visible and Infrared Survey Telescope for Astronomy, STFC-ESO	A visible and infra-red survey telescope located in northern Chile. Commissioned in 2009.	Dr. Ian Bryson, Head of Strategic Management, and Dr. Alistair McPherson VISTA Project Manager, Personal interview, Edinburgh, 27 January, 2010. Email exchange 22 February, 2011. Total interviewees = 7	£36 million
XFEL http://xfel.desy.de/	Deutsches Elektronen-Synchrotron (DESY), Germany.	X-Ray high power free electron laser	Dr. Hans Weise, Deputy Project Leader, XFEL. Personal interview, Germany, 14 July, 2009. Total interviewees = 5	€986 million.

Table 1-2. Interviewees for Task Force survey (ref section 5.1.4.2 Managing task forces)

Name	Affiliation
Mr. Charles Adler	Senior Systems Engineer, Boeing Company.
Mr. Robin Sharpe	Ex-Senior Director – Strategy and Technology, NXP Semiconductors (subsidiary of Philips Semiconductors).
Mr. Brett Biddington	Ex-Space Team leader, ASIAPAC, Cisco Systems Inc.
Dr. Allan Paull	Research Leader, Applied Hypersonics, Air Vehicles Division, DSTO.
Dr. Richard Schilizzi	Director, Square Kilometre Array Program Development Office.
Dr. Peter Hall	Prof. Of Radio Astronomy Engineering, Curtin University; Deputy Director, ICRAR
Dr. James Bradfield Moody	Executive Director, Development, CSIRO
Ms. Dawn Schaible	Manager, Systems Engineering Office, NASA Engineering & Safety Centre (comments reported in ASK Journal, NASA, Fall 2009)

1.4 Structure of the thesis

Following the introduction of the research question and description of the research methodology in chapter one, chapter two discusses the historical and contemporary context for success and failure of large science/engineering projects. The body of literature is described, and a working definition is given for high-tech mega-projects as 'multi-million dollar enterprises with a challenging science goal and substantial infrastructure component.[3] The performance expectations in terms of innovation and technology outcomes are then probed in terms of project success factors, the challenge of complexity, and some of the broader 'scene-setting' aspects and actors are discussed.

Chapter three looks at pre-cursors to project success, and examines the effectiveness of project shaping activities including structure, the establishment of contractual and procurement arrangements, and the building of project resilience.

Chapter four contains the 'meat' of the research within an in-depth review of success factor studies and a findings regarding key success drivers from casework conducted in Australia, Chile, South Africa, and Europe. Here I apply scientific method and enquiry to test the hypothesis that it is possible to detect and refine success factors, such that they become reliable success drivers and thus predictive indicators of high-tech project success.

Chapter five examines in more depth several less obvious aspects concerning project manager traits, dubious practices, and the all-important project reviews and lessons-learned practices. In the next chapter, the Checklist for High-tech Project Success (the CHiPS Tool) is introduced, informed by the preceding research and conclusions.

Chapter seven aligns and applies the study findings to the SKA project, examines how these factors might be implemented in project strategies, planning, and execution, and posits ideas for lessons learned. Finally chapter eight presents the conclusions of this thesis, and suggests further research areas. The logic and flow in sequencing the chapters and content in this thesis is shown in Fig. 1-1.

[3] Amplified definition shown in section 2.3

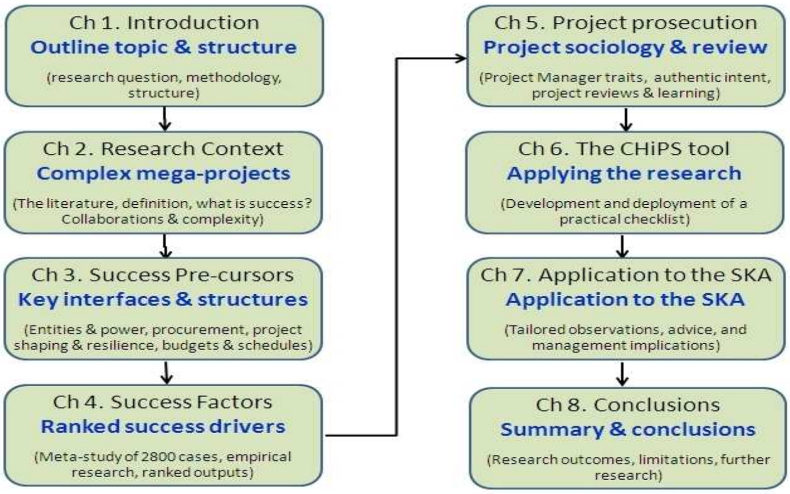

Fig. 1-1. Research flow adopted for this thesis

The quest to research, analyse and present factors in high-tech project success covers many aspects of classic project management, technical execution, and human behaviour. Inevitably I touch on several topics many times as they are approached from differing perspectives. For this reason, I include a subject index after the references section.

Finally, I note that section 3.3 (resilience), chapter 4 (success drivers), and section 5.1 (project manager characteristics) are slightly edited versions of papers accepted for publication in International Journals. Section 3.2 (procurement) is published on-line as a peer reviewed technical memo within the international SKA project website.

1.5 Statement of originality

In the preparation of this thesis I personally researched some 250 professional papers from high impact peer reviewed journals, consulted over 40 topical books and management texts, and read more than 80 related articles and miscellaneous publications. Case material from investigations at many big-science facilities provides a source of contemporary experience, as do conference papers, especially those from the intensive NASA Project Management Challenge event that I attended in 2009. I returned to the same forum in 2010 to present an invited paper based on the present research work. Much of the research material is summarised within the very thorough literature review, however it is the body of the manuscript that demonstrates how I have used this research to contribute intellectually to the subject knowledge through a theorised, and heuristically rigorous, approach to the topic.

There is a good deal of (mostly disjointed) information in the published literature about project success and lessons learned, and many authors have covered the general topic of mega-projects. There is considerably less material concerning the specific management requirements of high-tech projects. Each of these topics (sometimes in combination) also features in conferences, workshops, and reports. This thesis is believed to be the first attempt to draw together this material, add richness through primary field research, and present the reader with a practical tool for increasing the likelihood of project success. To quote Grossmann (2010, p. 4): *"It is clear that ITER-like projects are different – there is currently no Body of Knowledge that adequately addresses management issues associated with these projects."*

In the process of researching and writing this thesis, three papers have been prepared and accepted for publication in peer-reviewed international journals, and another (also peer-reviewed) added to the official SKA project memo series. I have also presented these papers at several conferences and colloquia (Refer Appendix K).

The material in this thesis has not previously been submitted for a degree in any university, and to the best of my knowledge, contains no material previously published or written by another person except where due acknowledgement is made.

Chapter 2 – Research context

2.1 The rationale for research: a short modern history of high-tech projects

As high-tech projects have grown in size, cost and risk, so has the challenge in realising success. To understand the problem and set context, I briefly review the recent history of project success, the response in terms of mega-project management, and indicate where the knowledge gaps remain.

Ika's (2009) study of articles related to project success within the leading project management journals identified three recent eras that describe a changing focus across the decades and span the core period of research sources used in this thesis. Table 2-1 shows how the basic parameters of project success have been augmented over recent historical periods.

Table 2-1. A view of general project success parameters across time (after Ika, 2009 p. 11)

Research Focus	Period 1 1960s–1980s	Period 2 1980s–2000s	Period 3 21st Century
Success criteria	"Iron triangle" (time, cost, quality)	Iron triangle Client satisfaction Benefits to organization End-user satisfaction Benefits to stakeholders Benefits to project personnel	Iron triangle Strategic objective of client organizations and business success End-user satisfaction Benefits to stakeholders Benefits to project personnel and symbolic and rhetoric evaluations of success and failure
Success factors	Anecdotic lists	Critical Success Factor (CSF) lists and frameworks	More inclusive CSF frameworks and symbolic and rhetoric success factors
Emphasis	Project management success	Project/product success	Project/product, portfolio, and program success and narratives of success and failure

The post-WW2 years have seen a notable change in the mode of mega-project funding, approval, and leadership style. The first half of the 20th century saw ambitious undertakings in science and engineering usually championed by visionaries (Miller & Lessard, 2000) recognised for their personal knowledge, discoveries, and influence. The latter half of the 1900's saw increased complexity of machines and the project structures to build them. Such projects increasingly depended on formal organisation, plans, and budgets, and began to be more often identified with the host institute (e.g. NASA, CERN) than with a single champion.

This development in management is epitomised by the case of the giant Mount Palomar optical telescope opened in 1949. Its undoubted driving force was George Hale whose style reflects the age of the ‘Great Man’ projects, as Florence (1994, p. 92) notes:

> *“a round of handshakes was enough to inaugurate the largest scientific project ever undertaken”*, and *“the committees met from time to time, but most of the decisions...emerged in notes and memoranda from Hale...[who] kept his fingers in every pie”*.

However Florence (1994) notes that even superb project champions have their limit (p. 91):

> *“Not even Hale at the peak of his abilities had the energy to manage this project alone. The two-hundred inch telescope was one of the first ventures into big science. No one had tried to research so many aspects of technology simultaneously, except perhaps [in wartime].”*

In the UK, this experience was echoed by (now Sir) Bernard Lovell in The Story of Jodrell Bank (1968). In this classic account of building a post-war iconic radio-telescope, Lovell tells of the personal burden of dealing with ever-increasing budget demands, crises management, contractor issues, government inquiries amid the need to maintain confidence and urgency. His personal exhaustion, and eventual relief when a Nuffield Foundation grant met the project’s debt, is understated when Lovell (1968 p. 244) writes: *“It was a fairy-tale ending to the years of anxiety the depths of which were probably known only to my family.”*

Systematic management of projects emerged in missile projects in the 1950s such as ATLAS and POLARIS. Around this period the US Navy launched its Program Evaluation and Review Technique (PERT), and in the civil arena, DuPont created the Critical Path Method (CPM). These methodologies continued to proliferate into defence and civil works through the 1960s and 1970s, capitalising on advances in computing platforms (Archibald, 2009). By 1990, project management was effectively professionalised and great science and engineering endeavours in the realm of physics research, computing, aerospace, and communications became established within modern organisational structures, along with their attending bureaucracies, stakeholders, and various forms of review and management committees.

My research shows that complexity factors, and the associated project budget, is a major factor that tests both the stamina and purses of funding stakeholders, and demands project leadership competence. Whereas traditional scientific endeavours on small or intermediate scales (i.e. <$100 million) have often been directed by charismatic science leaders, boldly leading highly motivated teams in a spirit of self-sufficiency and improvisation, this approach is empirically shown to falter when project budgets enter the $ billions. A modern OECD (2010, p. 32) report goes further, saying: *"if a distinguished scientist is chosen as Director* [of a major science project], *it could be wise to hire a highly experienced project manager as well, and to give this person the appropriate authority, staff and resources."* [4]

High-tech projects in the commercial sphere are not immune to poor outcomes, especially when attributed to incompetent business capability, says Ellis (2008). His statistical analysis of performance in 100 high-tech companies revealed only a 32% probability of project success by design, with 50% of firms carrying "runaway" projects in terms of time and cost.

The apparent maturing and professionalization of high-tech project management towards a holistic theory-based approach has not led to a corresponding improvement in project success, and despite practitioner effort and application of scientific activity, stakeholders remain disappointed with project performance and investment returns. (Ika, 2009; Winch, 1996; Turner, 2004; Cooper, 2006; Eveleens & Verhoef, 2010; Cerpa & Verner, 2009; Cooke-Davies, 2001; Grün, 2004; Shenhar & Dvir, 2007; Thomas & Mengel, 2008).

Is there any evidence that investment in technology research is linked to successful high-tech outcomes? Edgerton (2006) looks at invention, and with appropriate caveats, analyses the statistical information on patents. He finds the overall rate of patent lodgement has not altered in recent decades, and concludes that R&D expenditure is decoupled from patent numbers. Innovation extends invention to commercialisation (Dodgson et al., 2008). China's recent innovation efforts supported by a 10% per year increase in R&D and 28% per year growth in patent applications implies that its domestic policies are successful (Ernst, 2011). However as Ernst explains, only 26% of China's patent applications are actually inventions, as opposed to utility models and industrial designs.

Notwithstanding China's top-five ranking in high-tech industries and computing, its stock of 134,000 patents is just 2% of the world total, of which 95% are enforceable only in China

[4] This topic is further explored in section 3.1.4.

(Ernst, 2011). Further, there is nothing to link this data to project success. Fig. 2-1 shows that both China and India have some way to go to reach the R&D investment levels of Japan and the USA that, in terms of applied resources of scientists and engineers and monetary investment, are the basis for a successful modern technical economy.

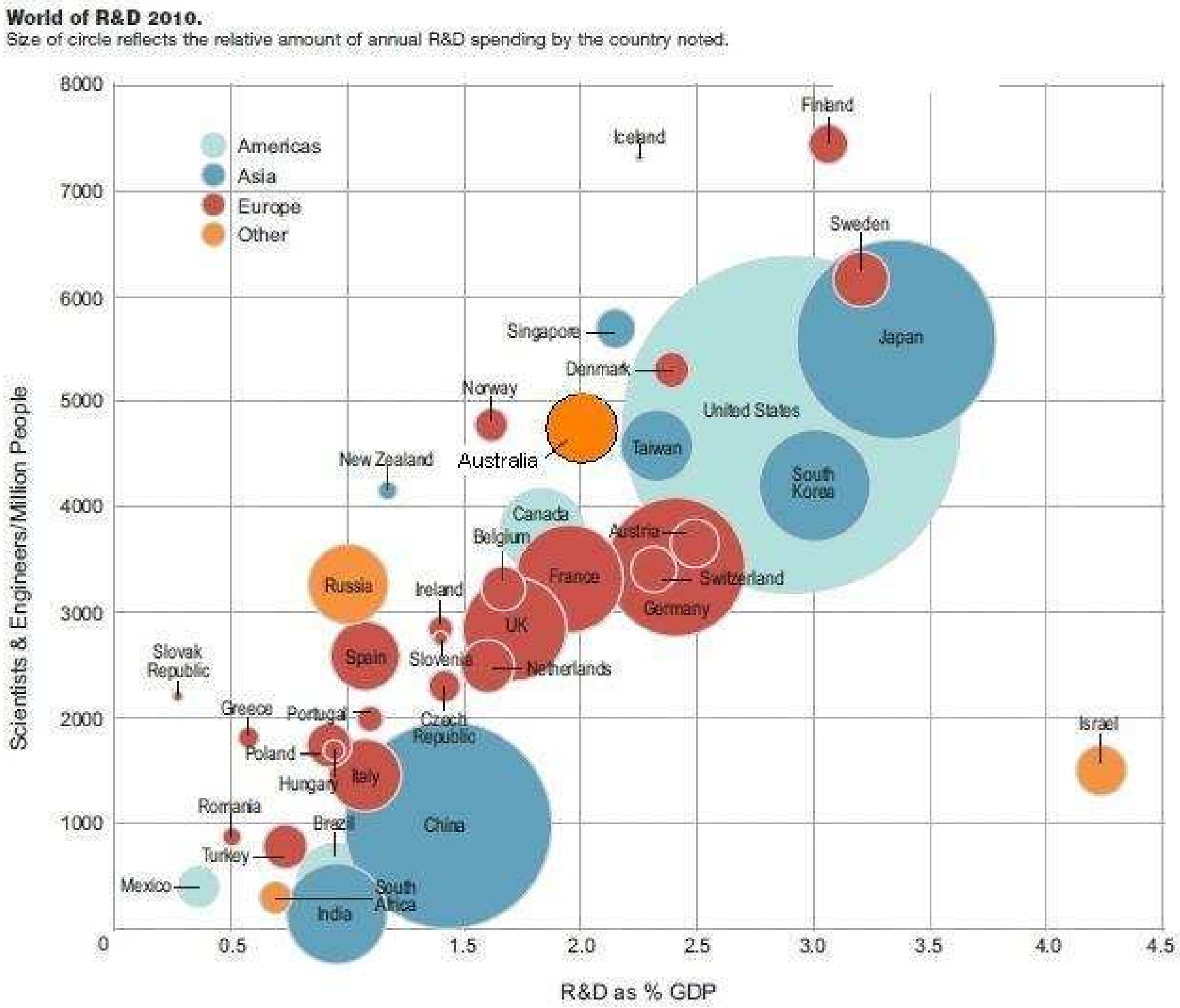

Fig. 2-1. The world of R&D investment (Ernst, 2011 p. 6 - Australian data added by the author)

Only exploration of new ideas and applications leads to economic and social progress, albeit against 'real-world' challenges, as put by Dodgson and Gann (2010 p.12):

> *"Innovation is what happens when new thinking is successfully introduced...Innovation involves deliberate preparations, objectives, and planned benefits for new ideas...It is the theatre where the excitement of experimentation and learning meets the organisational realities of limited budgets, established routines, disputed priorities, and constrained imagination."*

Edgerton (2006) makes the point that the sheer number of 20th century inventions and innovations leads to reported high failure rates, and acceptance of this enables freedom to innovate without success pressure, stating (p. 210) that: *"the key problem in research policy should be ensuring that there are many more good ideas, and thus many more failed ideas"*. Similarly we should not make the assumption that ideas are smarter simply because they come later. Söderlund and Lenfle (2011, p. 1) believe that this 'scholarly form of hubris' based on simplifications of the past is flawed, and: *"a better understanding of history might create an improved understanding of the difficulties in creating, shaping, and managing projects"*.

One attempt to assemble a worldview of large high-tech projects is captured within a recent OECD report (OECD, 2010), shown in tabulated format in Table 2-2. The reality of challenges, motivations and strategies for dealing with project complications are some of the key areas addressed within this thesis.

Table 2-2. The potential benefits and complications of large international projects (adapted from OECD, 2010 p. 4)

Potential Benefits	**Potential Complications**
Realisation of projects that exceed the funding capacity of individual countries	Delays and expenses associated with protracted international negotiations, and the requirement for (non-scientific) experts (e.g. lawyers, government officials, etc)
Optimisation of the global inventory of state-of-the-art scientific facilities while avoiding duplication	Adoption of sub-optimal technical solutions due to *juste retour* (geo-return) contracting, or multiple sources for infrastructure components
Access to a unique geographical location, or other unique local resource	Creation of sub-optimal financial or organisational arrangements due to the diverse reporting, oversight and authorisation requirements of international partners
Assembly of the best scientists, engineers, and technicians	Exclusion of certain national scientific communities whose countries are not part of the collaboration
Access to data and other project resources or outcomes	Inhibition of competition in scientific fields where it has traditionally been vigorous and productive
International experience for early career scientists and engineers	Creation of new administrative structures that may take time to operate competently

Managerial characteristics leading to success or failure is a widely researched topic, though with little focus on the managerial challenges of high-tech organisations. Management theory in this respect has matured to reflect the social structure and demands of project delivery. Nonetheless, a discriminatory set of managerial qualities remains elusive (Gadeken, 1986).[5]

A fundamental question that I explore concerns the approach taken by project management in establishing processes and systems to execute the project. High-tech mega-projects, by their nature, are high-risk endeavours having great technical uncertainties and demand skills and approaches far beyond the traditional management techniques embodied in traditional practice guides and Books of Knowledge (e.g. PMBOK® Guide, 2008). Early-stage high-tech projects (including mega-projects) are singled out by Cooper (2006) as likely to encounter difficulties in achieving technical success without an enlightened approach. Even so, Cooper warns us that commercial prospects may yet remain unclear.

There is, therefore, a clear gap in the subject knowledge where practical wisdom, gleaned from modern history and empirical research, can be applied usefully to aid project formation and review decisions, and to improve the probability of success in large science and engineering projects.

2.2 Extant literature

This thesis research is underpinned by material published from the mid 1970s to the present, an era broadly covering the professionalisation of project management, and a full cycle of strong and depressed global economic activity. Studies in this period often highlight earlier classic mega-projects such as the Sydney Opera House, the Channel Tunnel, Concorde and space missions as examples of massive time/cost over-runs or performance failure. However the dataset is rich with examples of both successes and failures to learn from.

In considering the components of project success, subject authors (e.g. Morris & Hough, 1986; Yu et al. 2005; de Wit, 1988; Williams, 1995) mention the triple constraints of scope, time and cost, and often extend this to include quality, risk, and more recently sustainability factors. Several writers add other factors such as contractor success (Morris & Hough, 1986); personal growth (Dvir et al. 1998); and project safety (Lim & Zain Mohamed, 1999).

[5] This topic is examined in depth in section 5.1.

Atkinson (1999) notes the maturing of project success factors, yet points to the paradox of projects still being judged against the 'iron triangle'. Shenhar & Wideman (1996) include client/user aspects, market share creation, and new technologies/product lines. Procaccino et al. (2002) investigate early risk factors and their effect on software project success, finding importance in committed sponsorship, and the level of confidence felt by users in the project team.

Several authors are prolific in the general subject of project success, e.g. Shenhar & Wideman (1996) on mapping success to project type; Pinto's useful Project Management Profile workbook, and collaborations on critical success factors for specific type projects (Pinto & Slevin, 1989); Cooke-Davies (2001) frequently cited work on project success; and Morris & Hough's research into preconditions of project success (Morris & Hough, 1986).

Many writers (Yu et al. 2006, Dvir et al. 1998 and 2003, Roy et al. 2003, Belassi & Tukel, 1996) have applied statistical techniques to their research to support conclusions, whereas others (Westerveld, 2003; Lim & Zain Mohamed, 1999; Winch, 1996; Erno-Kjolhede, 2000; Turner, 2004; de Wit, 1988; Rubenstein et al. 1976) investigate project success from the management theory standpoint, complemented by experiences in the application of project management techniques or models. More targeted publications (Procaccino, 2002; Weck, 2006; Ferratt et al. 2006; Pinto & Slevin, 1989; Moody & Dodgson, 2006; CSIRO, 1998 and 2003; NASA, 2000 and 2008; Hill, date unknown) have addressed project success factors specifically in high-tech projects.

The nexus between success factors, and how project success is judged, has importance in shaping project drivers (de Wit, 1988; Cooke-Davies, 2002a). Many writers discuss the multi-dimensional and multi-criteria nature of project metrics, pointing out dependencies on personal viewpoints and perceptions (O'Brochta, 2002; Crawford, 2000; Muller & Turner, 2007; Westerveld, 2003; Dvir et al. 1998). However work by Shenhar & Dvir (2007), Crawford (2000), Atkinson (1999), Shenhar & Wideman (1996), and Dvir et al. (1998) reaches consensus surrounding technical performance, project performance, and internal/external (stakeholder) satisfaction as success criteria.

Publications from the project management professional organisations (e.g. 'Books of Knowledge' or BoKs) also touch on project success, but are aimed more at project structuring and execution and are largely based on contemporary practice, not research analysis (Morris et al. 2006). Nevertheless, the Project Management Institute's Standard for Program Management (PMI, 2008) offers clear definitions of success measurement in projects, as well as mentioning the benefits of lessons learned. The widely referenced Project Management Book of Knowledge (PMBOK® Guide, 2008) also mentions the use of a 'lessons learned knowledge base' for collecting historical information. However Cicmil et al. (2006), from the Rethinking Project Management study (see below), point to omissions in the PMBOK® Guide and are critical of suggested actions in response to project perturbations that fall short of the 'lived experience' of competent project managers. Compared to the amount of project management practice guides, Books of Knowledge (BoKs), and 'how to do it' literature, written project management theory is much less apparent and perhaps more correctly described as a collection of techniques and best practice than a scientific treatment of the topic.

The US NASA organisation publishes a substantial amount of literature concerning high-technology research-based mega-projects and programs, much of it freely available from NASA websites. Importantly, NASA makes available a considerable library of lessons-learned and case study material (NASA, 2011a) concerning high-tech projects and management systems. In addition to drawing on this public-domain canon, I was fortunate in being given many documents for study purposes that further inform this thesis.

One important initiative in adding to the literature is the UK Government funded research activity called Rethinking Project Management (RPM) (Maylor, 2006). Involving a number of leading project management academics and senior practitioners from industry, the network followed a research program framed to question mainstream ideas, the output of which was published in a special issue (no. 24, 2006) of the International Journal of Project Management (IJPM). The present study cites several papers from that publication. The first paper in the compendium (Winter et al. 2006) offers a useful summary of findings and extols the need to embark in new research directions (beyond the rational and intellectual foundations often underpinned by the cost-schedule-scope (or triple constraints) paradigm) and link more directly with project management practice. Of particular note is the need for increased recognition of human issues, and exogenous factors, as potent success drivers. In looking at IT projects, Sauer & Reich (2008) concur with the RPM findings and endorse a pluralistic approach to project complexity beyond the conventional wisdom characterised in the PMBOK® Guide.

Many of the notable writers on the subject of project success consider the traits of the project manager, and the impacts these have on the overall success of the project (Baker et al, 1988; Cooke-Davies, 2001and 2002a; Disterer, 2001; Gratton et al., 2007; Grün, 2004; Morris & Hough, 1986; Shenhar & Dvir, 2007; Smith & Winter, 2010). Several authors have looked specifically at the topic over a wide range of project types (Clarke, 1999; Erno-Kjolhede, 2000; Geoghegan & Dulewicz, 2008; Laufer & Hoffman, 2000; Müller & Turner, 2007; Verner & Evanco, 2005), again linking behaviour and competence to project success outcomes. Müller & Turner (2010) look deeply into leadership competencies of successful project managers using a global questionnaire, while Keegan and Den Hartog (2004) examined transformational leadership.

The RPM initiative also notes the need for increased recognition of human issues, the social nature of projects, and resulting challenges for management. One five-year study (Crawford, 2000) foreshadowed the approach taken in this paper, by ranking project success factors from post-1995 literature in relation to project manager competence and delivered performance.

Although there is a great deal of written material concerning general purchasing strategy and approaches there is little that focuses on procurement success factors for high-tech mega-projects *per se*. Much of the extant literature resides in management texts and guides, and is centred on the transaction. Several authors (Jaakkola, 2004; Morris & Hough, 1986; Blanchard, 1990) offer solid advice regarding strategic contract policy and procurement management, linking contract management success to project and business performance. Winch and Gil (2010) go further by considering theories for complex project contracting strategies and present approaches to deal with the dual problems of contractor selection, and motivation. Tender evaluation criteria and contractor selection is an area deeply researched by Watt et al. (2009), and Zeydan et al. (2010) who offer a mathematical model for supplier selection and performance analysis. Supplier selection is described in detailed practical terms by Blanchard (1990). Both the UK National Audit Office (NAO), and the Office of Government Commerce (OGC) publish a range of business guides including the NAO's Improving Procurement manual (NAO, 2004), and OCG's Contract Management Guidelines (OCG, 2002), both containing much practical advice.

More specifically, design and execution of contracts in the engineering field is tackled by Nicholas (2004) and the published proceedings of the UK's Major Projects Association offer relevant case material. Virolainen (1998) undertakes a theoretical study of procurement strategy for industrial firms, emphasising the importance of the buyer-supplier relationship over a mix of approaches. Schill's (1979) examination of the topic in advanced technology organisations acknowledges the growing strategic and entrepreneurial importance of high-tech procurement. Carnegie Mellon's Software Engineering Institute issues the CMMI for Acquisition Technical Report (Carnegie Mellon, 2007) – a collection of best-practices for high-tech acquisition. Finally, the procurement section of this thesis is generally informed by institutional and project based material e.g. CERN's research into technological learning through project procurement (Autio et al., 2003), SKA Memo 80 on industry liaison (Hall & Kahn, 2006), and the NEON organisation Project Acquisition Plan (Ashley, 2009).

Specifically in relation to early phase project management and building resilience, Erno-Kjolhede (2000) tackles the management of research projects, addressing the underlying concepts of complexity and uncertainty at the conceptualisation phase, and the balancing of risk-taking and failure. Difficulties with early stage risk assessment in relation to over-reliance amid uncertainty are examined by Bakker et al. (2010); Flyvbjerg et al. (2003); and Geraldi et al. (2010). Project shaping as a management craft is investigated by Smith & Winter (2010) who show clear links to project success, while Miller examines episodic style project shaping as a competitive advantage (Miller & Lessard, 2000). Blanchard (1990) and Cook-Davies (2002) discuss the people aspects of new projects and the pivotal role of management a human resource, while new work by Jani (2010) asserts that self-efficacy enables resilience in IT project teams. Nonetheless, attitudinal factors for project shaping and context setting have yet to be set out in relation to high-tech projects specifically.

A number of early critical success factors (CSF) are proposed by Elenbaas (2000) who notes the crucial conditions and complex environments within project start-ups. The much referenced authors Shenhar & Dvir (2007) emphasise the need for early tailoring of project success measures and dimensions. In their examination of project peripety (an abrupt turn of events), Engwall & Westling (2001) explore assumptions around linear project processes and the limiting effects of articulating imperfect knowledge at project start-up. Lechler & Dvir (2010) offer recent work on linking project management structures to project success, arguing for serious attention to early organisational structure. Weston (2007), Fellows & Alexander (2010), and Fisher (2010) each touch on early stage risk of immature technologies and the gap in understanding between industry and institutions.

While these (and other) authors address diverse facets of early stage project conditioning, there remains a gap in the literature for an empirically based summary of early stage conditioning factors concerning resilience (the quality of robustness and the ability to recover from adversity) within high-tech projects.

2.3 Defining high-technology mega-projects

Archibald (2003, p. 4) defines the high-technology project as: *"a complex effort to produce certain specified, unique results at a particular time and within an established budget for the resources that it will expend or consume"*. Further, he qualifies this by saying: *"the project is not the end result [but] the process of creating a new end result"*. Cooper (2006, p. 24) emphasises the special nature of high-tech projects in industry, provocatively describing them as: *"the breakthroughs, disruptive technologies and radical innovations that create the huge growth opportunities and superlative profits."*

The precise parameters of very large projects (also known as 'mega', 'macro' or 'giant' projects) are not specified in this thesis, except to say that these endeavours typically have multi-million or even billion dollar budgets, time-frames measured in years, and attract a high level of public and/or political attention. Moreover, they often exert a substantial direct and indirect impact on the community and the environment. With one smaller exception (LIDAR), the case studies examined on-site ranged in budget between $50 million and $6 billion and comprised a construction life of typically 5-10 years. Apart from the IRIDIUM program, all were institutional endeavours in the physical sciences and technologically innovative.

Such endeavours may seem to have little in common with mass production projects (Miller & Lessard, 2000) but the economics of large engineering/science global projects (e.g. the Square Kilometre Array, Large Hadron Collider) are now setting aside this division. High-tech mega-projects add complexity by involving research and development, a reliance on IT/science/engineering effort, and having a significant infrastructure requirement.

Flyvbjerg (2008, p. 1) sets a useful framework for mega-projects by stating: *"mega also implies the size of the task involved in developing, planning, and managing projects of this magnitude. The risks are substantial and cost overruns of 50% are common"*.

Sykes (1990, p. 160) offers a comprehensive description of what he terms 'macro-projects', applying the characteristics paraphrased below:

- Owned by government or business consortium (or both) by nature of size
- Inevitable involvement of major government due to impact on the economy and/or environment

- Shortage of experienced senior people, leading to diminished chance of success. This is not widely, or well, understood
- Generally indivisible endeavours
- Construction period is > 5years, following investigatory/approval period of >4 years.
- Located in remote, harsh places, yet requiring large, skilled workforces
- A strain on suppliers and transporters, and due to sudden, brief supply demands, may cause absorption problems in the market
- Sheer size and complexity imposes special risks, most notably on the proponents
- Vulnerable to economic recessions and storms that can massively increase costs
- Difficult to finance.

The above definitions usefully frame the general characteristics of large high-tech projects in a mechanistic sense, but fail to provide a real world view of life within these very large enterprises. I present a brief word picture of such projects below, illustrating some dissimilarity between industrial and institutional approaches.

Mega-projects that are bid, developed, executed and supported by industry (e.g. defence prime contractors) are managed within a very strong budget-schedule-milestone environment (BAE SYSTEMS, 2009). Reporting of project status is frequent, with brief 'traffic light' type updates at team meetings, and numeric/milestone data generated through corporate project management IT systems. Earned value management systems (EVMS) commonly underpin progress payment claims to the customer (Boeing, 2004). The project office may be centralised at the delivery site, or for dispersed projects, corporately headquartered. Either way, these are very busy places, with project teams highly mindful of delivery commitments, and staffed with an experienced core group (Fig. 2-2) including the Project Manager, and Project Engineer, and supported by functional managers in charge of technical competency within their disciplines and for executing project tasks relating to their functional department. (Nicholas, 2004). Disciplines typically will include a mix of engineering, science, project management and control, finance, and production, as driven by the needs and character of the project.

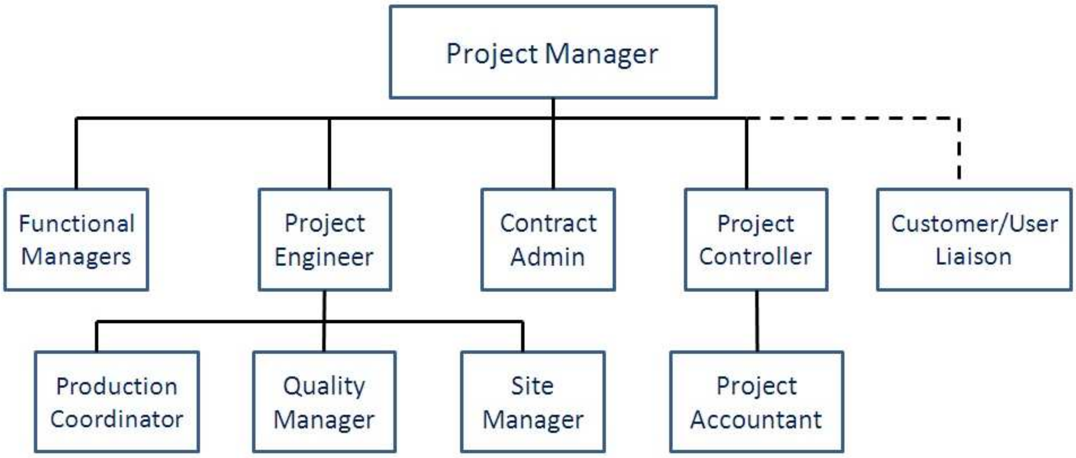

Fig. 2-2. Typical make-up of the project office (after Nicholas, 2004 p. 492)

Contractual and legal negotiations are practiced very formally, often by embedded professionals. Commercial project leaders/managers operate largely autonomously, and quickly establish both formal and informal communication channels to ensure prompt and reliable intelligence. Project audits and reviews are seen as serious procedural events, not only as a measure of achievement against plan, but also as a reflection of team reputation. Failed 'gate' reviews may result in pausing, or terminating the project (BAE SYSTEMS, 2009). Under-performance within industry projects is tackled swiftly (strategically where appropriate), and under close scrutiny of senior management. Satisfactory performance is celebrated, often including team rewards.

Large institutional high-tech projects funded from the public purse (e.g. nationally funded science) exhibit a somewhat different nature. High technical risk is inherent, with the project organisation (which may be a collaborative entity) being responsible or involved in the engineering design concept development, in response to extensive consultation driven by the science goal(s). The innovative character of new high-tech mega-projects implies that many new technologies and components need to be developed. To mitigate risks (especially cost-risk), a firm technical understanding of core components and their influence on the whole system may be required (European Commission, 2010). A substantial preparatory phase is necessary to deliver this understanding, sometimes undertaken by academia under blurry funding arrangements that can complicate in-kind support claims. Continuation of funding itself can temporarily dominate effort, unlike commercial projects (SKA, 2010). Central project authority is aspired to, but often largely titular, with major participants maintaining highest allegiance to their own institute or department. Nevertheless, a highly consultative culture is inherent, and frequent international face-to-face meetings require a robust project/institutional travel budget. Budget and schedule importance is acknowledged, but stretch-type goals are the strongest drivers, meaning that late design improvements may be accepted at the cost of adherence to a delivery parameter. Project reviews are also seen in a different light to their industrialised equivalents, being less procedural, usually led by experts drawn from project stakeholders, and less demanding in terms of formal corrective action (SKA, 2010). Project termination is rare though descopes may occur. A feature of institutional mega-projects is the perceived lack of consequences by the collaborative teams in cases of non-conformance (e.g. to delivery promises) – a consequence of weak project authority.

However, institutional mega-science projects have a notable discriminator - the higher proportion of exceptional people who work in them. An early feature that emerged from the casework for this thesis, conducted across 17 large scientific and engineering projects in Europe, Chile, South Africa, and Australia (see Table 1-1), is the formidable intellect and practical ability of the managers and teams involved. Without exception, the people both observed and interviewed displayed professional respect and outstanding technical rigour, though usually missing the benefits of formal project management training that notably lifts industrial scale project performance. While the prioritisation of home-institution tasks over promised deliverables can cause irritation at project headquarters, one cannot question the enormous goodwill and project spirit exhibited.

Unlike industrial project development which mostly relies on expert contractors to produce physical components, much of the technological apparatus for institutional projects is designed and fabricated in-house, drawing on combinations of co-located specialist skills. Examples from radio-astronomy are shown in Figs. 2-3a and 2-3b, illustrating the standards of quality and precision required for both mechanical and electrical fabrication. A further notable characteristic among team members is the ability to bridge the science-engineering gap, with scientists well-informed in relation to the engineering challenges (often contributing to the technical design), and many of the engineering staff adept at understanding the science challenges in terms of practical design of experiments and equipment (ATCA, 2008).

Fig. 2-3a. CSIRO’s ASKAP receiver interface bulkheads. ASKAP Newsletter #153, Nov 2010

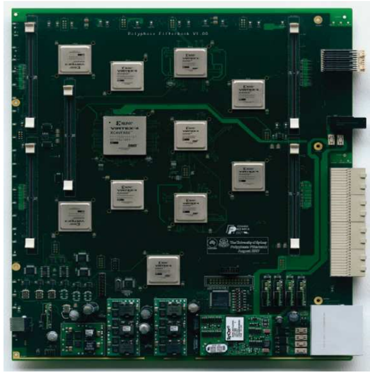

Fig. 2-3b.CSIRO’s SKAMP FX correlator board. ASKAP Technical Update Sept 2010

2.4 Characterising success

2.4.1 What is success?

To expose the key drivers for project success, we must understand what is meant by success, and its underpinning factors. The search for critical success factors (CSFs) began in the 1960s in response to the management crisis wrought by the speed of organisational change. The concept is usually credited to by D. Ronald Daniel of McKinsey & Company, USA. European publications discussed success as a project management topic in the late 1980s, with North American publications introducing the concept a decade later, soon followed by the Scandinavian school which started to define project success within a more granular framework (Jugdev & Müller, 2005). The quest to distil a definitive set of CSFs still occupies investigators, practitioners and organisational theorists (Dvir et al., 1998) and much has been written post year 2000 with results continuing to disappoint stakeholders. As Ika (2009, p. 7) succinctly puts it: *“Arriving at a definition of project success would appear to represent an enormous challenge to investigators”*. In the context of this thesis, CSFs are broadly defined as: *“those levers that project managers can pull to increase the likelihood of achieving a successful outcome for their project”* (Westerveld, 2003, p. 412). Success is achievement of stated success metrics.

2.4.2 Success, and critical success factors (CSFs): a deeper perspective

Papke-Sheilds et al., (2010, p. 651) examine CSFs from a project management perspective, and endorse Milosevic and Patanakul’s definition of *“characteristics, conditions, or* *variables that can have a significant impact on the success of the project when properly sustained, maintained, or managed"*. Papke-Sheilds et al. also note the well reported correlation between the presence of CSFs and successful project performance.

Fortune and White (2006, p. 53) adopt Rockart's seminal descriptions of CSFs including:

> *"...the few key areas where things must go right for the business to flourish.*
> *... areas of activity that should receive constant and careful attention from management.*
> *...the areas in which good performance are necessary to ensure attainment of [organisational] goals".*

In considering project success, many writers and practitioners begin by referring to the triple constraints of scope, time and cost (commonly termed the 'iron' or 'golden' triangle) and often extend this to include quality, risk, and more recently sustainability factors. Recent authors add other useful information such as contractor's commercial success (e.g. profit or new business); personal or team development; and project safety. Shenhar & Wideman (1996) list 13 success dimensions, including several client/user aspects such as the extent of customer use, customer satisfaction, market share creation, and new technologies/product lines. Procaccino et al. (2002) suggest that success for one stakeholder (e.g. project management) is not necessarily success in the eyes of another (e.g. the client) thereby illustrating a need to consider, or at least align, the project goal or mission as a CSF. A failed high-tech mega-project can draw little comfort from running a well managed project administration that may mean nothing for the public funder or user.

Several researchers (O'Brochta, 2002; Munns & Bjeirmi, 1996; Wateridge, 1998, de Wit, 1988, Cooke-Davies, 2002a) highlight the difference and juxtaposition of project success, and project management success, further complicating what is actually meant by success in projects. When discussing the success assessment of projects, Meskendahl (2010) suggests that this should cover both the execution performance, and the result. Dvir et al., (1998, p. 920) write: *"the success of defense projects, and possibly of all kinds of projects, should be evaluated only, or mostly, by the benefits to the customer and by meeting design goals"*. This stance is supported in the present study on the basis that it is operational outcomes that matter most within the context of large and expensive high-tech projects. Decoupling real or apparent management success from project failure offers no sanction for the practitioner. *"The projects profession is hazardous. An argument that 'I have done my duty and followed the procedures' rarely has much leverage in a discipline where failure is inevitable followed by the search for culprits and scapegoats"*, says Smith (2007, p. 11).

In seeking to understand success in high-tech projects, we must also look at whose opinion matters. Differing viewpoints were investigated by O'Brochta (2002) who notes the widely differing perspectives about project success from a survey of American CIA (technical) project managers. At the portfolio level O'Brochta finds that project reviews and decisions are made with reference to contribution and risk for the organisation's program, whereas departmental managers often link success with meeting the delivery schedule. On the other hand, individual managers view projects more personally, with success linked to possible career advancement. Variability of opinion is illustrated by the case of the 1960s U2 spy plane project, often touted by American historians as a huge success in terms of its development and mission accomplishments. However the downing of a U2 over Soviet territory and subsequent international embarrassment over American truthfulness could be interpreted as mission failure. The final answer is that it was both a success and failure (Wateridge, 1998), depending on whose opinion is being sought. This dichotomous view is shown to be common among high-tech mega-projects, where a period of successful service life can sway opinion. As Jugdev and Müller (2005, p. 24) state: "*Once the project is complete, short term memories fade and the focus shifts from completion criteria , 'are we done?' to the satisfaction criterion, 'are we happy?'*"

Black Knight was Britain's first ballistic rocket launched in 1958. None of the launches were considered a failure although many went wrong; the root cause being the difficulty of replicating the hostile space environment when testing on the ground (Hill, 2007). High-tech mega-projects face equivalent challenges today in terms of stakeholder acceptance that experimental 'pathfinder' work must inevitably include stage-failures that themselves shape the success trajectory of the project.

Fortune and White (2005) undertook a review of 63 publications that examined CSFs from a mix of theoretical and empirical studies embracing successful and unsuccessful projects. While their research accords well with the conclusions of this thesis in terms of ranking success factors, Fortune and White's work did not show similar alignment *within* the study itself, with only 17% of the reviewed publications citing all three top ranked CSFs - this lack of consensus among researchers and authors being noted by many (e.g. Papke-Sheilds et al., 2010; O'Brochta, 2002, Cooke-Davies, 2002a), and emphasising the wide range of views regarding which CSF actually matter.

Fortune and White also concur with Pinto and Slevin (1989) when pointing out two further criticisms of the CSF approach. First, by presenting a list of CSFs, there is a tendency for practitioners to view them as discrete challenges, and perhaps miss the inter-relationships. Second, it ignores the potential for an individual factor to have different levels of importance across the project lifecycle, against which the authors offer a conceptual Formal Management System as a framing device to aid practitioners in overcoming these problems (Fortune and White, 2005). The application of CSF frameworks to project phases over recent decades is shown in Fig. 2-4.

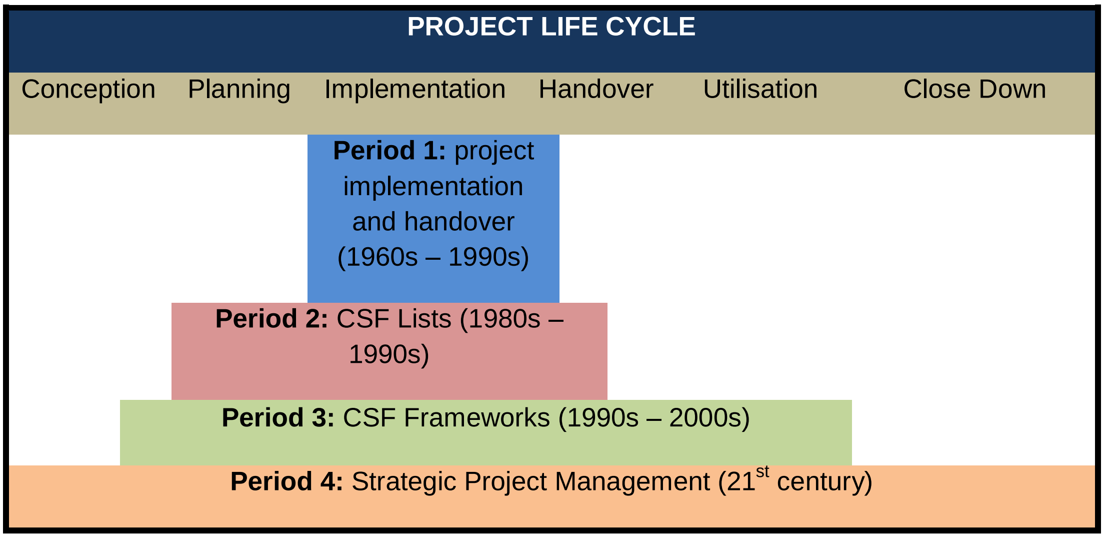

Fig. 2-4. Measuring success across project phases (Jugdev and Müller, 2005 p. 23)

Another dimension to consider is the continuing validity of success indicators as the high-tech project dynamically changes from experimental design to realisation routines. Organisational theory describes the main difference between a project and a pure repetitive operation in terms of resolution of uncertainty by decisions in the former, and standard, stable and repeatable tasks in the latter (Davies et al., 2009). Megaprojects are organised to (a) minimise the risk of known uncertainties from occurring, and (b) perform project routines to manage predictable and known operational circumstances; each requiring specific success markers. Davies et al. (2009 p. 11) continue: *"a megaproject must also be organised to provide innovative and unique solutions to unknown events or unique happenings that cannot be predicted at the outset, but must be resolved...[for]... successful completion."*

Ika (2009) also undertook a study of peer-reviewed journal articles on project success published between 1986 and 2004 and finds diversity in success characterisation. Ika's work shows an emphasis in the literature on success factors rather than criteria, but as Fortune and White (2005) discovered, fails to fully explore the links between the two. Nevertheless, despite Ika's (2009) conclusion that the study of project success defies consensus and is ‘ambiguous and multi-dimensional’, he notes the continuing effort of management science to improve our understanding of CSFs. He also endorses future qualitative type research that involves in-depth interviews and experiential input that supports my approach in this thesis.

Grün (2004, p. 68) takes a strategic view of CSFs in complex organisations, pressing for success factors which: *“avoid disasters, emphasise the interests of the project owners, influence the causes of failures, and do not overtax the capacity of the project owners and the project management”*. In this context, Grün joins Jugdev and Müller (2005) in arguing to purposefully limit the number of CSFs, and suggest just four subject areas to address:

- Goal formulation and change of goals
- Basic design (of the project)
- The socio-political environment, and
- Management structure and capacity

Pertinent to the international scope of the present study is the work of Atsu et al., (2009) who examined the success factors of ICT projects in developing nations, especially noting the relevance to Sub-Saharan African nations which is relevant to the SKA mega-project. Their largely qualitative (interview based) research of 30 projects demonstrates that some of the success factors widely agreed to be most important in the developed Western world, ranked relatively low in the study (e.g. user involvement, clear requirements, formal project methodology, and risk management). Conversely, training and motivation ranked third and fourth respectively, behind availability of funds, and top management support.

The importance of ‘soft’ goals which underpin sustainable social and economic development is emphasised by Khang and Moe (2008) in their review of success criteria and factors for international development projects. They point out the difficulties in measuring success in development projects where goals have a degree of subjectivity, however they present a generalised table of success criteria and factors derived from a questionnaire survey (n=368) mapped against project life-cycle phases. Kang and Moe’s results highlight the importance of competency (highest ranked), inter-relationships and mutual understanding (consultation), and needs fulfilment, in project planning and execution, together with effective resource mobilisation and institutional capacity. Their statistical analysis also reveals the importance of sustained outcomes on *perceived* success judgement. Risk management does not appear, corresponding to the low rating presented by Atsu et al., (2009).

There is little extant work on project success factors specifically within large high-tech projects (except IT projects), however Dvir et al., (1998) examine 110 recent defence projects covering electronics, computers, aerospace, and munitions as part of a study into a typology theory of projects. By employing multivariate analysis, they find project-specific managerial variables critical to the success of industrial projects (though of varying potency), concluding that any list of success factors is dependent on project type. For example software (SW) projects are shown to be very sensitive to *a priori* factors, whereas technical and operational specifications, and project control, are crucial for hardware (HW) projects. Interestingly, they also assert that prototypes, while important for customers, have minimal impact on meeting large HW or SW project design goals. Human processes leading to success in research projects are examined from a theoretical standpoint by Ernø-Kjølhede (2000) who emphasises the importance (to project managers) of freedom to self-manage. Moreover, the creation of mutual trust between stakeholders provides a confidence framework that underpins the project manager's credibility, especially in environments where official authority is weak or missing (e.g. universities, collaborations, etc.).

The topic of success being a matter of perception in high-tech projects is raised by Müller and Turner (2007) and by Crawford (2000) whose review of historical CSFs identifies measures beyond schedule and budget performance as components of the project success construct. Using a 'break-point' of the mid-1990s, Crawford determines that the personal traits of the project manager (communication skills, knowledge, competence) have risen in importance post-1995, whilst technical performance has decreased in importance as a success factor. Communications, as a subset of information management is mentioned in Hyvari's (2006) study into (largely) technical projects, and noted as the highest ranked factor in project management effectiveness.[6]

Information technology (IT) projects present particular challenges around defining and achieving success, with one UK study into IT project management (RAE, 2004) reporting only 16% of projects as successful. Frese (2010) looks further into IT project success research, and finds general concurrence with the frequently cited Standish reports that list user involvement as the first ranked contributor to project success, and the lack of user involvement the top indicator in 'challenged' IT projects. Wateridge (1998), in a survey of 132 IS/IT project managers, sponsors, users and analysts across 12 projects, discovers a significant discrepancy between what project managers believe to be important (basically the

[6] A topic revisited in section 4.3.3.

‘iron triangle’) and what users consider important which relies less on meeting precise budgets and schedule, and more on satisfaction with the functionality.

IT projects also present particular problems due the rapid expansion of technology platforms, complexity of applications, and consequent difficulties in managing scope and cost. Jiang et al., (1996, p. 49) found the pressures facing the system development manager quite daunting, provocatively adding that *“addressing all of the factors leading to success may not be feasible in the current development environment”*. Their study postulated 13 success factors which were then sent to 78 IT professionals to rank by importance. As might be expected, clearly defined requirements came out as the top factor, followed by personnel factors. Factors concerned with user involvement ranked centrally, with programmatical factors ranked lowest.

The high scoring of management and team issues underlines the ‘people-centric’ nature and needs of high-tech IT projects – an aspect not always intuitively recognised. De Bakker et al., (2010) conducts a meta-analysis (n=29) of the value of risk management (RM) to IT project success as reported in journal papers of the last decade. They are critical of a generally narrow understanding and practice of RM within the IT project genre, and note the discord between wider definitions of success by practitioners, and those factors reported in the literature. De Bakker et al. (2010), conclude that attention paid to RM is seen as more influential on project success than following a RM process, a finding unsupported by an earlier survey of Australian software developers which found no correlation between managing risks and project success (Verna & Cerpa, 2005). The benefit of formal risk management to IT projects therefore remains theoretically undecided; however two examples of failure illustrate the practical cost to projects. The first concerns the well-reported loss in 1999 of NASA’s Mars Climate Orbiter spacecraft, brought down by a rudimentary software interface failure (NASA, 2000). The second incident, eight years later, concerns the US Air Force’s F22 Raptor jet fighters that lost all navigation capability at the moment of crossing the 180th meridian – the International Date Line. The failure was traced to a ‘partial line of code’. A retired Head of the US National Guard commented that: *“It used to be [aircraft] tails falling off, now it’s [programming] typos that ground a fighter”* (O’Hare, 2009, p. 124).

Another survey of software practitioners yields a different perspective with success linked most strongly to project management competency, and behavioural factors (Verner & Evanco, 2005). Success is also positively associated with team motivation and rewarding long hours, especially in IT projects (Verner & Cerpa, 2005). From the programmatical viewpoint, complete and consistent requirements is seen as highly important, notwithstanding comment that almost 50% of respondents' projects began with incomplete requirements and encountered predictable scope changes, especially for larger projects. Applying logistical regression, Verner and Evanco (2005) conclude that 'project manager vision', and 'good requirements' are the best software project success factors, and when combined, predict 82% of successes overall. Procaccino's (2002) investigation of 21 software development projects adds useful depth to Verner and Evanco's work, especially concerning requirements. They find that neither the absence of a requirements gathering methodology, nor a change in scope, increased the perception of project success.

Casework interviews with project teams (LIDAR, 2009; MeerKAT, 2009; DESY, 2009) strongly indicate the benefits of creating a formal document to capture the agreed project success criteria, although these artefacts were missing (or captured early and dormant) in most of the field cases examined for the present study. The benefits of capturing success factors is supported by O'Brochta (2002), who adds that an early review of project CSFs for some high risk opportunities led to some projects being avoided, thus increasing net program success rates. Revisiting the CSFs at project milestones and decision gates, with stakeholders including customers, can lift team confidence, and permit formal adjustment of CSFs to better match project direction.

A final perspective is the impact on success of funding sources and mechanisms, shown to be especially important in institutional hosted mega-projects. From the funding agencies viewpoint, project success is centred on adherence to cost and schedule budgets, rather than technical performance. Discussions with Project Directors from the case studies (SKA, 2010; ALMA, 2007; CSIRO, 2008; ITER, 2009) indicate that the security of funding occupies much time and effort throughout the project lifecycle; a situation exacerbated when that process is made iterative by the funding agencies. Interview evidence suggests that this situation stems from academic administration practice, where rolling funding (being dependent on government budgets) is rarely taken as certain. Conversely, the idea of 'piecemeal' funding is unacceptable in industry, with funding implicit through high level 'gate' type reviews around the contract acceptance/mobilisation stage (BAE, 2009). Still, Edgerton (2006) asserts that academics prefer government funding and to be independent from commercial development, but is unconvinced by the widespread belief that academic research has led to the bulk of new and successful technologies.

High-tech mega-projects are difficult to finance. The long term nature of the effort, associated uncertainties, and risks of economic storms, mean that government and institutional funders especially are naturally guarded when it comes to financial guarantees. Extreme examples of big-science budget cuts are notable in the USA, where the SSC and Constellation programs demonstrate the power of Congress to cease the financial investment. Sykes (1990, p. 164) writes:

> *"The cost to commitment-point on a mega-project can be daunting. These costs typically fall within the range of 2% to 5% of final capital costs in real terms, but some projects have greatly exceeded this range. Even so, spending $75 to $150 million investigating a $3 billion project is clearly an enterprise only for the strongest".*

While this thesis offers theoretical and empirical evidence to support a set of success drivers derived from a wide range of CSFs and environmental scenarios, there will always be an overriding component of opinion that very much depends on the observer's (or stakeholder's) standpoint. Ultimately, *"there is probably no such thing as absolute success in project management: there is only the perceived success of a project"* (Ika, 2009, p. 7).

It is, of course, one thing to examine success factors essentially from a historical perspective, but quite another to conclude causality. This topic constitutes the central thrust of this thesis.

2.4.3 Project success criteria

CSFs should not be confused with success criteria – the metric(s) against which success can be measured, and from which CSFs are determined (Müller & Turner, 2007). Project success criteria are metrics based on dependent variables, may be quantitative or qualitative, and be expressed as longer term objectives, or more near-term targets.

Müller & Turner (2007) maintain that project success criteria vary from project to project, and that what may be acceptable in one project (for instance performing a hardware upgrade at a terrestrial radio telescope within 3 weeks) may be entirely unacceptable in another (e.g. an overnight upgrade of a bank transactional processing system). Stakeholders have different views of success, and have diverse positions in terms of interest, power, attitude, and requirements (British Computer Society, 2006). Each project's set of performance measures is thus unique, and cannot be considered in a generic sense. We can also learn something from Müller & Turner's work (2007) in regards to how project managers rate success criteria in terms of both project complexity and project importance. Their findings show that managers of highly complex projects rate the importance for customer, supplier and stakeholder satisfaction significantly higher than those of low complexity projects. In medium complexity projects, managers assign significantly higher importance on their own success criteria and customer satisfaction, whereas managers of high complexity projects rate their own success criteria significantly higher than medium complexity projects.

Further, Miller & Turner (2007, p. 303) conclude that:

> *"Project managers in high complexity projects, when compared with medium complexity projects assign significantly higher importance to the satisfaction of customers, end-users, and other stakeholders. Compared with low complexity projects they assign significantly higher importance to team satisfaction, other stakeholder satisfaction, and their own success criteria. Project managers in medium complexity projects, when compared with low complexity projects, assign significantly more importance to team satisfaction, other stakeholder satisfaction and self defined criteria."*

In seeking to formulate a new approach to successful project execution, Shenhar & Dvir (2007) posit that a holistic technique is required when setting success criteria. Their model involves at least five fundamental dimensions (or metrics):

- Project efficiency
- Impact on the customer: meeting requirements and achieving customer satisfaction, benefits, and loyalty
- Impact on the team: satisfaction, retention, and personal growth
- Business results: return on investment, market share, and growth
- Preparation for the future: new technologies, new markets, and new capabilities

Shenhar & Dvir (2007) assert that each dimension may contain sub-measures, and differ from project to project (due to variables such as project scope, uniqueness and complexity), an idea supported by Ika (2009) who adds the further dimension of project phases.

Success criteria in the form of objectives or targets are normally set early, and may be quantitative, qualitative, or logical. A considerable benefit in early declaration of success criteria is their use throughout the project execution phases (e.g. at project 'gates'), especially early on where project re-shaping, or even termination, is cheapest (Cooper, 2006).

Fieldwork for the present study revealed mixed attention to success measures, with general objectives more prevalent than precise targets. For example the SKA pre-cursor projects (ASKAP and MeerKAT) were clear in their expectations of system development and implementation, whereas the XFEL and LHC colliders gauged progress more by *results*. In specifically looking at high-technology projects, Archibald (2003) supports the application of concrete metrics tied to specific milestones (including *when* the project deliverables will be available), though recommending the addition of soft criteria. These, he says, should deal with the more subtle expectations of the user/customer, such as how the work will be done, skills transference, and managing the project for continuous improvement.

2.5 The complex world of high-tech mega-projects

The scientific problems, technical challenges, and logistical/environmental hurdles that face the type of projects I consider in this thesis are daunting, even for seasoned practitioners. Yet it is these very challenges, with their obstacles and interdependencies, and potential rewards, which drive nations and organisations to commit years of resources to the quest. Why? Perhaps President Kennedy's 'moonshot' speech captures a key driver: *"because [these things] are hard, because that goal will serve to organize and measure the best of our energies and skills, and because that challenge is...one we are unwilling to postpone"* (Logsdon, 2010, p. 1).

Theoretical support for the mega-project as an organisational form is based on exploitation of economies of scale (Merrow, 1998), and critical mass to deliver the undertaking. Advanced science and engineering challenges require large and complex facilities which are increasingly difficult to support by one country and which need international collaboration, commonly called "mega-science" (Matsuzaki, 1993; Johnston, 2003). More recently, the global influx of government stimulus money has seen a: *"blitz of multi-year, ultra-expensive endeavours...wrapped in promises to spur growth, create jobs and extend infrastructure. If they succeed that is* (PMI, 2011 p. 28). Flyvbjerg et al. (2003) address this last statement by identifying a "megaproject performance paradox" within their theory. Put simply, they posit that project risks remain unacknowledged by stakeholders and that project performance continues to disappoint, in spite of increasing opportunities to learn by experience.

Not all mega-projects are complex, but the large scale high-technology endeavours considered by this thesis are evidently so. Complex systems theory describes degrees of complexity ranging from highly complicated to almost chaotic, and which have components of experimentation, and collaborative leadership (see Fig. 2-5). Complex systems are defined on the basis of their different attributes, yet have practical difficulties with their theoretical modelling and simulation. Given their many interconnected components, the science of networks and network theory are important aspects of the study of complex systems (Remington, 2011).

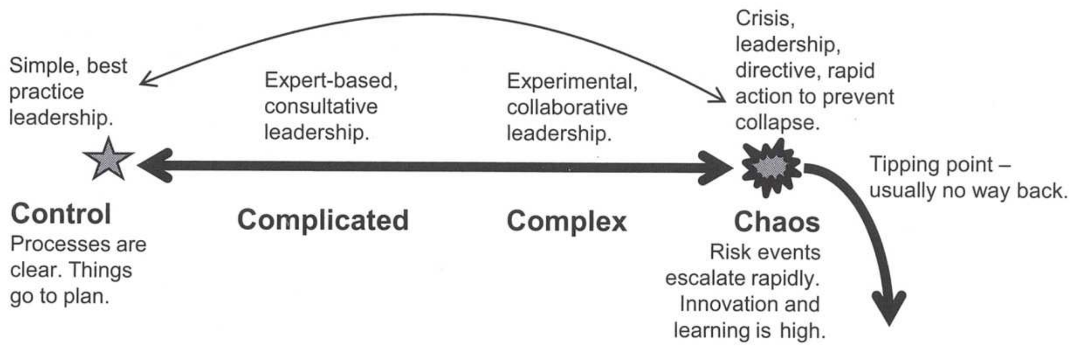

Fig. 2-5. The continuum between control and chaos (Remington, 2011 p. 18)

System complexity tends to grow in response to ever more demanding applications and science investigations, especially regarding performance, capacity and reliability. Davies and Hobday (2005) point to Whittle's original turbojet engine design with one moving part, as compared to today's complex jet engine with 22,000 parts, many of them customised, and each requiring procurement, manufacturing data, configuration management, and lifetime traceability. An equivalent picture emerges for telecommunications networks. For large high-tech projects that embody a site requirement (e.g. nuclear plants, ground-based telescopes, particle colliders, etc) institutional factors begin to add material complexity, as well as stakeholder interests (Helmsman, 2009). A report from the International Complex Project Management Task Force (ICCPM, 2011, p. 18) characterises complexity as: *"embodying uncertainty, ambiguity, dynamic interfaces and significant political or external influences. Such projects also tend to run longer than the lifecycle of the technologies involved."*

The extent of project complexity itself shapes the character of the project. While the project office may hold the status of project integrator, the prime contractors too must be capable of complex project management in support of the detailed design, systems engineering, and subcontractors. For cutting-edge programs, the system integration activities alone pose serious challenges in terms of industrial skills and capabilities for project realisation. Much of this how-to knowledge is not codified. Remington and Pollack's (2008, p. 1) study of complex projects revealed that: *"there is a growing recognition amongst highly experienced project practitioners and academics that particular projects seem to be much more than just difficult;* [they] *have special characteristics that pose extraordinary management challenges."*

Hector (2011) points to a deeper challenge, arguing that modern engineering practice is to construct models without challenging the validity of underlying scientific theories, and is *reductionist* in character – tending to reduce complexity to produce a workable design. He also describes engineering practice as *inductive* – extending existing systems on the assumption that theories hold true, and tending to exclude non-technical influences (e.g. the extended project environment). This general approach is classed as *logical positivism* by Hector (2011) and introduces flaws around interrelated systems and values that can disrupt major engineering projects and are only addressed through a new philosophy of engineering. At the outset, there are clear points of tension in big projects where the engineering team must design and build a machine which is partly experimental.

Sometimes badged as CoPS (complex product and service) projects, Davies & Hobday's (2005) definition includes any high-cost, engineering-intensive, system or subsystem, network, software system, or high technology service, supplied by a temporary project-based organisation. Thomas and Mog (1997) concur with Williams (2004, p. 274), who holds that: *"a complex system is one in which the behaviour of the whole is difficult to deduce from understanding the individual parts"*. In other words, it is not intuitively obvious how the impacts on a complex project may affect the outcomes. While much data is known, true understanding is elusive without modelling the causes of dynamic behaviour. Discussions with system engineers at Boeing's Iridium Sat-phone control centre (IRIDIUM, 2008) revealed the difficulty of forecasting precise consequences when unanticipated changes occur to one or more of the 77 orbital communications satellites – each an autonomous system within a networked constellation. One damaged satellite, for example, might trigger a load shedding sequence highly dependent on the spatial relationship and individual trajectory of the entire constellation at the precise moment, and is inherently unpredictable.

As Hobday (1998) describes, complexity has its origins in the military literature, with Hughes first grouping products into assemblies, components systems and arrays (Table. 2-3). An assembly is a mass produced stand-alone product which performs a single function unless connected by a network. By contrast, a component is always part of a larger system. Systems are defined by three characteristics: components, a network structure and a control mechanism. An array (or system of systems) is a collection of interrelated systems, each performing independent tasks but organised to achieve a common goal (Shenhar and Dvir (2007).

Table 2-3. Project complexity levels, after Shenhar & Dvir (2007)

Complexity Type	**Descriptor**
Assembly Projects	Single component, device, assembly. Single function project performed by small team in one location. Limited formality. *Examples include: GPS receiver, stand-alone software application, residential solar power system.*
System Projects	More complexity than assembly projects. Entails product or facility itself, plus training systems, test equipment, maintenance tools, and detailed documentation. Uses a single Project Office with links to subgroups and contractors. *Examples include: Bespoke communications network, military missile, national radio astronomy interferometer.*
Array Projects	Highest complexity with dispersed collection of systems that function together. A system of systems geographically spread, possibly across several countries. Large in scale, evolutionary in form and development. Project is run under an umbrella organisation responsible for administration and execution, often a public institution. A central masterplan controls executions and operations. Documentation is comprehensive. *Examples include: GPS orbital network, Broadband system roll-out, Channel Tunnel.*

2.5.1 What makes a project complex?

Managers of multi-dimensional and multi-aspect projects may generically label their work as complex, however true complex projects exhibit particular features that cause defined reactions. Investigations by Cook (2000) at the Cognitive Technologies Laboratory, Chicago, reveal characteristics of complexity, and the human response to it, as paraphrased below:

- Complex systems are defended against failure *(the high consequences of failure lead to multiple layers of defence e.g. back-ups, training, regulatory measures)*
- Catastrophe requires multiple failures *(overt complete failure occurs when small, innocuous failures join to create opportunity for systemic accident. Most failure*

trajectories are blocked, usually by operators but the potential for catastrophic failure is ever present)

- Multiple flaws are always present *(these are regarded as minor factors during operations. Eradication of all latent failures is limited and probably futile)*
- Complex systems always run as broken systems *(the system runs because it contains many redundancies and because people make it function despite flaws. System operations are dynamic with components failing and being replaced continuously)*
- Attributing failure to a root cause is fundamentally wrong *(because of multiple faults there is no isolated cause. The seeking of a root cause reflects a cultural need to blame specific forces or events for outcomes)*
- Hindsight biases post-failure assessments *(knowledge of the outcome makes it seem that events should have appeared more obvious than was really the case. Hindsight bias is the primary obstacle to failure investigation, especially when human performance is involved)*
- All operator actions are gambles *(overt failure often appears to have been inevitable and the result of wilful disregard. However all operator actions in complex systems are actually gambles in the face of uncertain outcomes)*
- Human operators are the adaptable element of complex systems *(operators and front-line management actively adapt the system to maximise performance, on a moment by moment basis. Large complex systems require constant tuning)*
- Human expertise in complex systems is constantly changing *(human expertise in system operation changes in character as technology changes, and to replace experts who leave. Training and skill refinement is actually one part of the complex system)*
- Change introduces new forms of failure *(low failure rates may offer confidence to introduce changes to further reduce low consequence sub-failures. These changes actually create opportunities for new, low frequency- high consequence failures. Because these new events occur infrequently, it makes it hard to see the contribution of technology to the failure)*
- Post-failure remedies limit the effectiveness of defences against future failures *(because remedies for 'human error' are predicated on blocking events that can cause failures, these end-of-chain measures do little to prevent future failures. In*

fact the likelihood of an identical failure is already low because the pattern of latent failures changes constantly)

- People continuously create surety *(failure free operations are the result of activities by people who work to keep the system within the boundaries of tolerable performance. These activities are part of normal operations. Human operator adaptations create system surety form moment to moment, sometimes through de novo creations of new approaches)*
- Failure free operations require experience with failure *(Failure recognition requires intimate contact with failure. More robust system performance is likely to occur in systems where operators can discern the 'edge of the envelope')*

Armed with this broad picture, a comparative view can provide context – such as the complexity assessment model offered by the Helmsman Complexity Scale (Helmsman, 2009). The tool is empirically derived from research across multiple industry sectors and underpinned by scientific and technical rigour. The scale (see Fig. 2-6) is based on complexity data which is normalised through forced ranking, ranges from 1 to 10, and mimics the Richter Earthquake scale in terms of significance. The Helmsman scale has been successfully used to evaluate the Australian Defence Project portfolio. It clearly places international high-tech mega-projects such as the SKA in the highest levels of complexity ranking.

Helmsman Scale	Level	Project Characteristics	Examples
< 4	Minor/ Micro	One person may be full time, designated team	Build new custom home
4 - 5	Organisationally Simple	Often performed by professional project teams on regular basis	Product maintenance and competitive enhancements to ongoing business operations
5 - 6	Organisationally Normal	Standard core projects in the top 50-100 organisations	Regulatory, environmental, business upgrades. GST, Y2K, Clean fuels
6 - 7	Organisationally Complex	Most complex projects commonly undertaken across the top 50-100 organisations	Merger integration, core system replacement. A380 introduction
7 - 8	Nationally Complex	Most complex projects commonly undertaken in the Nation	BHP Olympic dam, Broadband Rollout Some defence projects
8 - 9	Nationally significant	Creates significant impact on national economy	Snowy river scheme, Olympics, Collins
9 - 10	International	Significant multi-national project	Hadron Collider, Apollo, Joint Strike Fighter, BASEL II
10.0 +	Global	No truly global project has yet been executed	Joint Global Warming project

Fig. 2-6. The Helmsman Project Complexity Scale (Helmsman, 2009 p. 18)

The International Centre for Complex Project Management[7] offers a Project Complexity Assessment (PCA) tool designed to create broad awareness at the early stages of projects of an organisation's capacity to deliver. The PCA tool comprises an online questionnaire of 100 statements, and is designed to include Second Order dynamics exhibited in complex project management, where additional approaches are needed to understand the wider project environment. These include adhocratic leadership, complex contracting models, outcome management, system integration management, and experiential learning. Following consensus analysis, the grouped questions are then weighted to evaluate their contribution to the general complexity drivers and project specifics, within the framework of complexity characteristics or questions.

From these weighted outputs a scatter diagram is produced identifying responder feedback along axes of competence and complexity. This provides a collective understanding of the consensus around the likely success of the project. This scatter diagram is then overlaid with a complexity assessment matrix dissected in to four quadrants ranging from 'Buy In', 1st Order PM, Exit or subcontract to 2nd Order PM. The matrix allows the practitioner to gain an understanding of the cost effectiveness of potential alternatives for project activities.

Mathematical models for project complexity are looked at in a white paper by Sessions (2009), who expresses both the dangers and opportunities of IT complexity. He estimates the annual world cost of IT failure at around US \$6.18 trillion, or over US \$500 billion per month (he shows his workings). Sessions attributes this frightening sum largely to software complexity which he relates indirectly to functionality via Glass's Law, (that for every 25% increase in the complexity of the problem space, there is a 100% increase in the complexity of the solution space.) Through his equations and extrapolations, Sessions shows an almost linear relationship of complexity to failure rates. His formulae for calculating system complexity begins with defining a standard complexity unit (SCU) i.e. a system with only one function – the least complex system possible. His principal equations are shown below:

For a given system with bf number of business functions, and cn number of connections, the number of Standard Complexity Units (SCU) is shown by:

$$\mathrm{SCU} = 10^{3.1 \log(\mathrm{bf})} + 10^{3.1 \log(\mathrm{cn})} \qquad [2\text{-}1]$$

[7] Headquartered in Canberra, Australia - www.iccpm.com.au

As Sessions points out, most systems are actually 'systems of systems' and arranged within a Service Oriented Architecture (SOA) with multiple services, each with a complexity rating. Therefore, for a given SOA with m number of services, total complexity (in SCUs) is shown by:

$$\text{SCU}= \sum_{i=1}^{m} 10^{3.10 \log (bf_i)} + 10^{3.10 \log (cn_i)} \qquad [2\text{-}2]$$

Where bf_i = number of functions in the ith service and cn_i = number of connections in the ith service.

Running the above equations with real data offers a straightforward way to compare the complexity of system architectures. If one solution gives an SCU score of 1000, and another 500, the first is twice as complex as the second, and Sessions claims, 'twice as likely to fail'.

Thomas and Mog (1997) tackled the question of why complex engineering systems are so hard to build, defining complexity as resulting from the interactions between system components, rather than from the components intrinsic complexity. Thus their approach to a quantitative metric of system development complexity derives a return on technology investment, based on system interactions over time plus technology readiness and programmatic risk. Their equations include:

$$\lambda(t) = \sum_{i=1}^{n} W_i\,(t) E[r_i(t)] \qquad [2\text{-}3]$$

Where $\lambda(t)$ = a (time dependent) technology development complexity/maturity function, representing a payoff rate for investing in a certain level of technology.

In Equation 2-4, programmatical risk is represented by $\sigma(t)$. $C_{ij}(t)$ is the covariance between technologies i and j over the development duration.

$$\sigma(t) = \left[\sum_{i=1}^{n} W_i\,(t) \sum_{j=1}^{n} W_j\,(t) C_{ij}(t)\right]^{1/2} \qquad [2\text{-}4]$$

In Equations 2-3 and 2-4, n = number of technology investments made. $W_i(t)$ = relative investment weight for technology i. $E[r_i(t)]$ = expected return on investment for technology i over the development schedule represented by t.

Thomas and Mog (1997) apply their methodology to a NASA X-ray observatory project resulting in complexity measures as functions of cost, schedule, technology, architecture, and organisation. They claim the emergence of new understanding of the efficacy of resources utilisation, and the identification of system components that are contributing the most risk relative to payoff. The application of their model is clearly non-trivial and reliability is currently untested across a range of project scales. Intuitively, the equations imply over-sensitivity to some inputs. Nevertheless, the example is included here to show perhaps an extreme method of grappling with quantifying system complexity.

Complexity is apparent in projects in many dimensions. Bosch-Rekveldt et al., (2010) present a useful TOE (technical, organisational, environmental) framework to group the elements of project complexity, especially at the start-up phase (see Table. 2-4). They also note the influence of increased uncertainties as a complexity factor, with its attendant impacts on budget and schedule. Indeed without uncertainty, a project could only be described as complicated. Table 2-4 identifies dependencies and interdependencies adding a further complexity dimension that Grossmann (2010) highlights as an important issue for the ITER project. He asserts (p. 7) that conventional project scheduling simply does not account these dependencies, which are only overcome through: *"value-based coordination practices, leading to structured information architectures, sustainable activities, and system level awareness"*, and shows how this approach quantifies the tightly coupled nature of complex projects.

Table 2-4. The elements of complexity in high-tech mega-projects (adapted from Bosch-Rekveldt et al., (2010).

Technical	**Organisational**	**Environmental**
No. of goals	Project duration	No. of stakeholders
Clarity of goals	Size in CAPEX[8]	Stakeholder perspectives
Size of scope	Size in engineering hrs	Political influence
Uncertainties in scope	Size of project team	Internal support
Quality requirements	Size of site area	Required local content

[8] Capital Expenditure

No. of tasks	No. of locations	Interference
Variety of tasks	Resources, skills availability	Climate and weather
Dependencies between tasks	Experience in parties	Remoteness of site
Uncertainty in methods	HSSE[9] awareness	Experience in the country
Interrelations between technical processes	Compatibility between methods & tools	Dependencies on stakeholders
Conflicting Standards	Contract types	Strategic pressure
Innovation level	No. different nations	Project stability
Experience level	No. different languages	Level of competition
Technical risks	Cooperation JV partner	Environmental risks
Technical dependencies	Interfaces between disciplines	
	No. of financial resources	
	Trusted relationships	
	Organisational risks	

Other dimensions of complexity include multiple goals and risks, a multiplicity of stakeholders, and successful project knowledge transfer (Bakker et al., (2010). The many stakeholders typical of large science/engineering projects add *"an inherent level of unpredictability* [driven by] *divergent interests; long time scales and vulnerability to external environmental changes; and internal interfaces* [ripe] *for technical surprises"* (Pavlak, 2004a, p. 3). This latter point brings in technical complexity that captures factors which affect project duration e.g. the testing plan, additional resources for technical coordination, and managing technical uncertainty (Cao & Hoffman, 2010).

IT projects, by their nature tend to mask complexity from the programmatic view since, unlike (say) science infrastructure, there is no tangible artefact to observe being constructed or changed (ABC, 2011). A British Computer Society (2006) report asserts that complexity in IT projects goes beyond the technology – extending to the organisational, micro-environmental, and macro-environmental project landscape.

2.5.2 Complexity in large high-tech projects

The International Centre for Complex Project Management lists the demands of complex project management as: *"vision and motivation; empathy; attention to relationship building;*

[9] Health, Safety, Security & Environmental

the ability to take a holistic view; consummate communication skills; practical application of experientially-derived wisdom; and perhaps most of all, ...the courage to speak the truth, and take good risk" (Cavanagh, 2009, p. 4).

The 'needs statement' above is useful in understanding the nature of complex projects, but too broad a description to draw conclusions regarding inherent high-tech project complexity. A more compelling test is to apply Sykes (1990) descriptors of mega-projects (refer section 2.3) against the complexity elements presented by Bosch-Rekveldt et al., (2010) (refer section 2.5.1). By determining sufficiency of match (through comparative judgment) high-tech mega-projects are shown to be inherently complex (see Table 2-5).

Table 2-5. Matching of descriptors for high-tech mega-projects, and complexity.

High-tech mega-project descriptors (from Sykes, 1990)	**Elements of complexity** From Table 2-4, (*adapted from Bosch-Rekveldt et al., 2010)*	**Sufficiency of match** (✓ = *Yes)*
Owned by government or business consortium (or both) by nature of size	Political influence. Size in CAPEX. Size in engineering hrs. Size of project team. Cooperation JV partner. Dependencies on stakeholders. Organisational risks	✓
Major government involvement is inevitable due to impact on the economy and/or environment	No. of stakeholders. Stakeholder perspectives. Political influence. Interference. Dependencies on stakeholders	✓
They suffer form a shortage of experienced senior people, leading to diminished chance of success. This is not widely, or well, understood	Resources, skills availability. Experience in parties. Experience in the country. Interfaces between disciplines. Trusted relationships	✓
They are generally indivisible	Size in CAPEX. No. of locations. Interfaces between disciplines. Technical dependencies. Dependencies between tasks	✓
Construction period is > 5years, following investigatory/approval period of >4 years.	Project duration. Resources, skills availability. Trusted relationships. Internal support. Dependencies on stakeholders. Project stability. Environmental risks.	✓
Located in remote, harsh places, yet requiring large, skilled workforces	Quality requirements. Experience level. Size of site area. No. of locations. Resources, skills availability. HSSE awareness. No. different nations. No. different languages. Required local content. Climate and weather.	✓

	Environmental risks.	
They impose strain on suppliers and transporters, and due to sudden, brief supply demands, may cause absorption problems in the market.	Quality requirements. No. of tasks. Conflicting Standards. Size in CAPEX. Size in engineering hrs. Contract types. Trusted relationships. Required local content. Level of competition	✓
Sheer size and complexity imposes special risks, most notably on the proponents	No. of goals. Size of scope. Uncertainties in scope. Interrelations between technical processes. Innovation level. Technical risks. Size in CAPEX. Organisational risks. Stakeholder perspectives. Environmental risks.	✓
Vulnerable to economic recessions and storms that can massively increase costs	Size in CAPEX. Size in engineering hrs. Size of project team. Resources, skills availability. Contract types. No. of financial resources. Project stability	✓
Difficult to finance.	Uncertainties in scope. Technical risks. Size in CAPEX. Experience in parties. No. of financial resources. Dependencies on stakeholders. Project stability. Environmental risks. Organisational risks	✓

2.5.3 Can high-tech mega-projects be too complex?

Given the inherent complexity of high-tech mega-projects, the question may be posed – can they be unmanageably complex and therefore become '*wicked*' problems? First defined by Horst Rittel and Melvin M. Webber in 1973, wicked problems seem to defy rational description or solution. Indeed, each attempt to create a solution changes the understanding of the problem and therefore cannot be solved in a traditional linear fashion, thus showing some affinity to extreme software engineering. Partridge's (1981) definition of wicked problems may be summarised as:

- Every wicked problem is essentially novel and unique.
- Every solution to a wicked problem is a 'one shot operation'
- The problem is not understood until after the formulation of a solution.
- Solutions to wicked problems are not right or wrong.

- Wicked problems have no given alternative solutions.
- Wicked problems have a ‘no stopping’ rule. The problem solving process ends when you run out of resources.

While the above list contains features of all high-tech mega-project challenges, a more analogous picture is presented by Russell Ackoff, an American organizational theorist and pioneer in the field of operations research, systems thinking and management science. Ackoff (1974) writes about the difficulties of complex problems, explaining that every problem interacts with other problems and becomes an interrelated set, or a system of problems. He defines this concept as a ‘mess’ (a descriptive, not disparaging term). The *“messy organisational realities of innovation”* are included in Dodgson and Gann’s (2010, p. 27) theoretical explanations for complex innovation. Horn and Weber (2007) unpack this further, saying that complexity - systems of systems – make messes resistant to analysis and, more importantly, to resolution. These authors present the following characteristics of messes which I place into two groups:

Group A

- No unique “correct” view of the problem
- Different views of the problem and contradictory solutions
- Most problems are connected to other problems
- Data are often uncertain or missing
- Multiple value conflicts
- Ideological and cultural constraints
- Political constraints
- Economic constraints
- Numerous possible intervention points
- Considerable uncertainty, ambiguity

Group B

- Consequences difficult to imagine
- Great resistance to change
- Often a-logical or illogical or multi-valued thinking, and
- Problem solver(s) out of contact with the problems and potential solutions

The present study suggests that the items in the Group A list above resonate closely to the high-tech case studies examined in this thesis. The SKA, with its pseudo-competitive precursor instruments (ASKAP and MeerKAT) are certainly ‘messes’, but can be distinguished from wicked problems that often come from the areas of public planning and policy: e.g. global climate change, and nuclear energy.[10]

2.5.4. Implications and management of complexity

While the number and scale of complexity factors is shown to generally indicate project execution difficulty, several interviewees from the case study facilities mentioned positive aspects coming from these dimensions such as; team diversity, spreading of risk, and varied sources of experience (ALMA, 2007, ATCA, 2009, DESY, 2009, LOFAR, 2009). These findings aligned with an Australian study of large Defence projects (Helmsman, 2009) that looked at project performance against complexity factors in terms of schedule, budget, outcome, and reputational damage (see Fig. 2-7). Clearly an understanding of specific complexity factors and their likely challenging, or indeed positive, effect is helpful in realising success in terms of project performance.

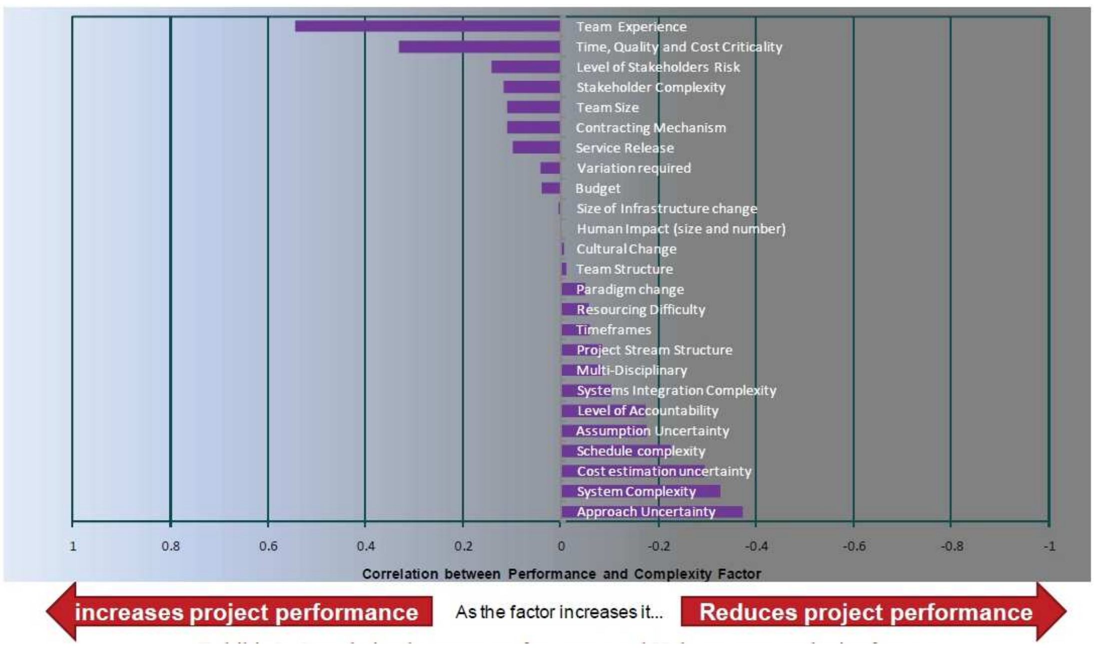

Fig. 2-7. Correlation between project performance and complexity factors (Helmsman, 2009, p. 11)

[10] One example of a wicked high-tech problem is the AU$1.3 billion desalination plant project for Sydney, Australia which continues to test Government decision-makers by uncertain and conflicting data concerning adequacy of water storage levels, rising planning and design costs, undecided court hearings regarding land acquisition, undeterminable future water prices, and demands and losses in public water consumption.

Koppenjan et al. (2010) investigate management approaches to large engineering projects and reason that complexity has two distinguishable aspects – structural and dynamic. Structural complexity refers to the interacting technological parts, and dynamic complexity describes the project elements subject to change. They find that the reality of managing a complex project requires a synthesis of Type I management – *predict and control*, with Type II style – *prepare and commit*. The practical impact of these approaches is shown in Table 2-6, and provides a basic palette from which to select strategies to suit project profiles.

Table 2-6. Predict-and-control versus prepare-and-commit (Koppenjan et al, 2010 in print)

	Type I	Type II
	Predict-and-control	Prepare-and-commit
Terms of reference	Blueprint	Functional
Task definition	Narrow for best control	Broad for best cooperation
Contract	Task execution	Functional realisation
Incentives	Work-task based	System-output based
Change	Limit as much as possible	Facilitate as much as needed
Steer	Hierarchical	Network
Information management	Limited, standardised	Open, unstructured
Interface management	Project management task	Shared Task

One avenue to meet the growing demand for improved high-tech project performance is to attempt to better prepare project managers for complexity through educational programs. Thomas and Mengel (2008) looked at new perspectives and concepts for advanced project management training, especially in dynamic and complex project environments. Their findings show that (a) the professional institution training and certification programs (e.g. PMI) do not go beyond their practice guide (e.g. PMBOK) level, (b) practitioners usually discuss complexity as a state or condition, rather than a complex systems theory, and (c) managers pay insufficient attention to emerging small changes and non-linear subtle changes that demand new levels of competency. Thomas and Mengel suggest training of project managers to a Master level is required, including the ability to diagnose situations, adapt tools and techniques, and learn continuously – competencies above that required of the merely competent project manager.[11]

[11] The topic of project complexity is further touched on in section 3.3.3.3, and again in relation to project manager characteristics in section 5.1.4.5

2.6 The challenge of international collaborations

Large, high-tech projects are most commonly collaborative enterprises, often involving multinational groups to share and exploit resources in order to execute projects that are beyond any single participant organisation's financial and/or technical capabilities (Sykes, 1990). Intuitively, this pooling of knowledge and resources should ease the path to project success, yet often proves troublesome.

Collaborations may be formed as project consortia, joint ventures, alliances, and strategic partnerships, and can even occur between different organisational departments (institutional or industrial) as well as between organisations and suppliers (Matsuzaki, 1993; Davies & Hobday, 2005). By overcoming the difficulties of physical and perceptual distances and effectively engaging participants the project may be enriched through sharing of knowledge, resources and responsibilities (Aronson et al., 2010).

However multiple parties also introduce an uncertainty factor associated with the project management infrastructure and achievement of project performance. Atkinson et al. (2006) highlight this in their exploration of project uncertainty, including specific concerns regarding; the objectives and motivation of each party; the quality and reliability of work undertaken; and the abilities and availability of the collaborators. Differing perceptions of risk, and appetite for sharing information augments the list.

Sykes' (1990) investigation into the need for international cooperation in macro projects begins by tackling the matter of multiple ownership (p. 157) which he says *"gives rise to the need for special political skills to manage what is, in effect, a major, but temporary, alliance"*. Sykes notes the challenge of collaborations to obtain simultaneous approval, coordination, and enthusiasm, needing the utmost (sometimes exhausting) dedication, concluding (p. 162) that: *"for a [collaboration] to succeed, it must be in the best interests of all key participants, i.e., it must be and <u>remain</u> superior to any other practical courses...including doing nothing"*. In other words, there must be both genuine commitment and demand – a topic exposed further in section 5.2. Khang and Moe's (2008) research into successful international development projects puts compatibility of policies and priorities of key stakeholders, and effective consultation squarely among the factors at the planning stage for achieving overall project success.

From a people perspective, research by Aronson et al. (2010) asserts that behaviour which values inclusion, and maintains a positive project spirit, is likely to engender improved collaborative responses, i.e. a sense of common purpose via interactions, and the sharing and coordination of information and activities. Moreover, Aronson et al. emphasise the importance of trained and interpersonally skilled leaders of high-tech projects with the autonomy to create project spirit. Collaborative teams by nature have different masters, making decision-making protracted, and sometimes thwarted by simply not having the right people at a meeting. Managing large collaborations is a rare skill within project management (Sykes, 1990). Work by Gratton and Erickson (2007) on collaborative teams reveals an interesting paradox. Large, virtual, highly educated and diverse teams are found to be crucial to success, yet those same characteristics tend to undermine progress by preferring to work autonomously and without shared goals.

International collaboration in mega-science is only sparsely represented in the literature. One document that does contribute to the subject of structuring big-science facilities is the ASPERA report 'Linking of existing infrastructures' (Katsanevas et al., 2009). It offers much sound advice referenced later in this thesis, yet opens (p. 3) with a caution that structural linking of science projects should not be mistaken as a method to force cooperation, and that:

> *"Collaboration building for a large science project is a process that should be initiated by the researchers themselves and be followed by funding agencies to assess whether the collaboration is able to build the project. Many successful projects ...demonstrate that this process works and funding agencies should intervene only in difficult situations."*

Matsuzaki's (1993) paper addresses similar 'hard' issues of collaborative high-tech organisations including the start-up process, and management problems concerning the leverage of decision-making power though financial shareholding. He finds that a one-vote, one-country system (equal voice) creates negative attitudes by large nations towards small countries, and suggests an expense-percentage arrangement as being preferable. Whilst an analysis of financial models and schemes to ensure fair return (e.g. *juste retour*) to the collaborative partners is beyond the scope of this thesis, it is clearly a success sub-factor, and worthy of further research.

Experience drawn from contemporary casework demonstrates the real-world challenge of managing high-tech collaborations. A lessons-learned workshop conducted by the Gemini telescope collaboration (NRC, 1999) confirmed the need for an active management approach to address cultural issues of differing importance according to differing countries. Similarly, perceptions of equal status are important, though capabilities vary. A ‘soft’ or neutral language tone from the project office is shown to be beneficial, as are periodic surveys of partner satisfaction levels. The SKA project (SKA, 2010) found Domain Specialists frustrated through a *laissez-faire* approach by project collaborative teams in relation to information exchange activities e.g. teleconferences and meetings. Institutional project partners not receiving payment for specific tasks (in other words providing in-kind contributions) are often described as unmotivated to deliver promised output in terms of product and/or schedule (SKA, 2010; HIPER, 2010; ITER, 2009).When pressed, interviewees speculated that the cause for this apathy is largely the lack of real consequences or penalties.

Collaborations with industry are shown to be fruitful, as demonstrated in Australia by the Australia Telescope Compact Array and the OPAL reactor, indicating an industrial model of project management is likely to be more successful overall (CSIRO, 2008; OPAL 2009; LOFAR 2009, TOPSAT, 2010). Projects with a large proportion physical equipment provided through an in-kind collaborative arrangement are prone to schedule upsets through interdependencies (ITER, 2009; ALMA, 2007). Finally, a report addressing US decadal science planning (Fellows and Alexander, 2010), explored the cost risks in relation to international collaboration, noting NASA’s decision (as a risk mitigation tactic) to rely less on European contributions. The report also refers to the Galileo spacecraft, noting the cost impact of the purely German propulsion system against the international team responsible for the Huygens probe success. The report authors express concern that outsourcing of technology development between countries lessens domestic capability, however make the point that international collaborations achieve science benefits beyond matters of cost.

Samuel (2009) looks specifically at the SKA mega-project, finding that collaborative challenges in institutional mega-science projects were broadly similar to commercial counterparts, with three interesting exceptions. First, she found mega-science projects more accepting (some even welcoming) of individualism, with survey respondents associating this as a positive attribute aligned with drive and vision. Second, mega-science is almost always funded through the public purse, as against shareholder capital. Lastly, Samuel (2009, p. 5) posits that the construction of science mega-project facilities usually lasts at least a decade, and remarks that: *“Commercial projects have a more immediate need for meeting deadlines and delivering a return on investment on projects...thus affecting the speed at which these progress”*. This conclusion hints that, other factors being equal, a commercially focused project will deliver faster and better outcomes.

The interlinked nature of high-tech collaborations is addressed further in section 2.8; suffice to say here that the dimensions and flows around mega-projects bring a dynamic quality to the problem of management. The operations of inter-firm R&D projects (utilising *e-transactions* and *e-delivery*) is examined by Weck (2006) through the lens of five collaborative R&D projects within the telecommunications industry. Weck finds a fairly conventional list of difficulties associated with commercial collaborations (conflicting planning and management methods; poor joint governance and reporting; differing interpretations; and unclear responsibilities). More interestingly, the theoretical framework adopted for the research shows that well-scoped customer needs lead to a genuine win-win outcome for all parties, and this in turn increases the anticipation of value among participants. Moreover, knowledge heterogeneity is derived from integrating both market and technical knowledge, though this is strongly dependent on complementary knowledge bases.

Collaborative R&D projects offer lessons-learned beyond the common *a priori* project success factors. The development of a true win-win situation is shown to lead to additional cooperation after the R&D project is complete, and an integrated approach to the work (using parallel phases) pays dividends through enhanced iterative interaction. The quality and fit of knowledge-based resources means that project partners engage in mutual cooperation and learning[12]; another success factor for large high-tech projects (Weck, 2006, Cooke-Davies, 2002a).

2.7 High-tech project funding

Once the legal form of the high-tech mega-project is established, and the total budget agreed, the vital matter of the partner contributions must be settled. For institutional projects, the technical and sovereign deliberations surrounding this extremely important (and often complex) step are likely to be protracted and usually conducted at Ministerial level in government. In the commercial arena, funding is commonly from a Board approved capital allocation, or from the customer (e.g. Ministry of Defence).

Funding and contribution arrangements are complicated through issues surrounding procurement rules, inflation, currency exchange, attitudes to contingency, personnel

[12] Approaches to collaborations are further in section 5.1.3.3.

placements, and geo-return (*juste retour*)[13]. A detailed coverage of this complex and specialist topic is outside the scope of this thesis; however the following outline offers the main points where a shared understanding reached early can avoid later confrontations (adapted from OECD, 2010):

- Agreement for provision and deployment of cash or in-kind contributions, and valuation of in-kind contributions.
- Agreement for deciding the scale of partner contributions (e.g. a formula)
- Agreement on the instruments that represent the partners' shareholding (shares – possibly computed to an accepted variable such as GDP, with minimums and maximums specified)
- Agreement on the currency used for defining shares, possibly a 'project currency' (e.g. ITER 'kIUA' Units) with an agreed exchange world rate
- Defined stages of the project (including the operational phase) aligned to calls for contributions, and the consequences for defaulting partners
- A clear statement of financial risk to inform participants of the probabilities and consequences of potential perturbations
- Any special contributions or discounts falling to particular partners (e.g. the host country)
- How cost efficiencies will be implemented in terms of global spend, split procurements, and dispersed procurement
- Processes and controls to drive financial robustness and guard against delays and overruns
- Processes to supervise financial governance (e.g. through a common fund), and accounting for any *juste retour* (economic benefit approximating a nation's contribution)
- Expectations regarding national benefit(e.g., non-project benefits, local R & D, access to IP, human capital growth, *juste retour*)

Casework for this thesis shows that *juste retour* (or geo-return) is strongly coupled with the cash/in-kind ratio, in the sense that partner organisations that suspect weak commitment to *juste retour* policies will naturally argue for increased in-kind contribution to better assure domestic economic returns. Moreover, it may be that an in-kind contribution is the only pathway to gain approval from a national government to participate, due to a treasury policy of funding science and engineering endeavours only through institutional allocations. In-kind

[13] the principle of '*juste retour*', means that member states or institutions get approximately the same benefits back as the funds they contribute,

support does carry risks however, since the central project office is effectively dependent on the contributing partner to deliver as promised – a situation that has negatively impacted the ITER project where 90% of the contributions are in-kind (ITER, 2009). The classification, and valuation, of in-kind support in the form of personnel can expose a thorny problem, and rates should be agreed up-front, including on-costs such as pensions, relocation costs, etc.

2.8 The principal actors

Delivery of a successful high-tech giant project is dependent on a complicated and competent network of inter-related players, activities, and flows (see Fig. 2-8). Typically, the project office will receive (or at least manage) the capital allocations, and distribute funding directly to contractors, or via project partners tasked with defined work packages. Some arrangements provide local funding to project partners as a component of in-kind project support. Goods and services flowing from funded groups are delivered to the project facility location, in some instances via the project partners, or even through the project office itself.

Customers (or users) gain access to the facility after commissioning, however it is typical in high-tech projects for the users to be involved in the development, testing and commissioning processes, possibly as part of an in-kind contribution. Section 3.2.4.4 introduces possible permutations for contracting arrangements.

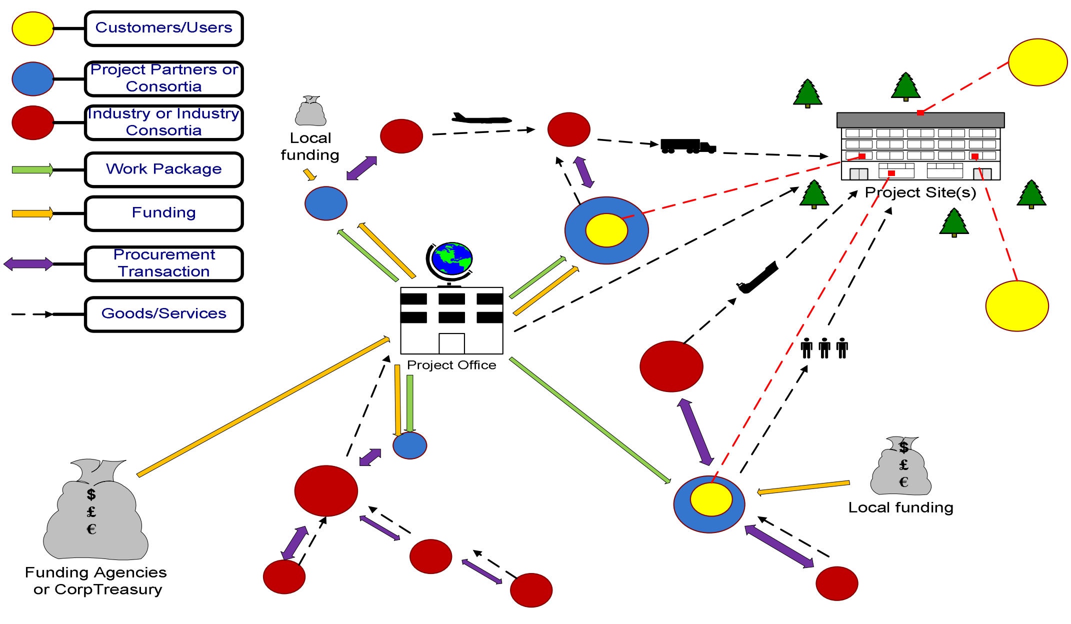

Fig. 2-8. The inter-related network of players, activities, and flows in a high-tech mega-project.

Fig. 2-8 illustrates the central importance of the project office in managing and coordinating workflows and associated information exchanges. Robust mechanisms for tracking project information and data and coordinating supply logistics are crucial, and of equal importance to good systems engineering in terms of maintaining project control (see section 3.3.4.3).

The degree to which the project office can be centralised is a fundamental issue for each project, and not unconnected with 'empire building' (Archibald, 2003). Certainly there are some functions concerning overall processes, systems, tools, etc that clearly require centralised control, but the planning and control of sub-projects, their reporting relationships, supporting services, and local schedules can be more successfully managed closer to the work execution.

Samuel's study (2009) of global partnerships surrounding the SKA project includes a stakeholder map shown in Fig. 2-9, which illustrates the potential decision-making influence of Governments and funding agencies. When interviewed, SKA Program Director, Prof. Schilizzi (SKA, 2010) expressed the view that *"there is no doubt that the funding agencies want to feel they are influential and being heard, especially so in early technical meetings"*. However the present research found no substantive evidence of funding agencies influencing the technical success of high-tech projects *per se.*

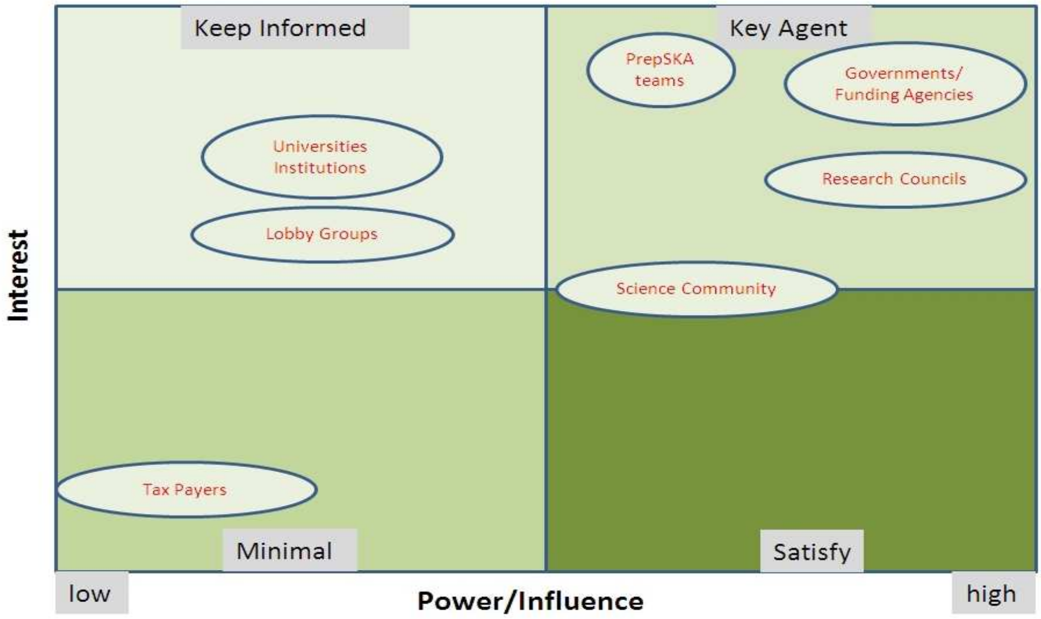

Fig.2-9. Stakeholder map for the SKA project (after Samuel, 2009 p. 79)

2.9 Chapter Summary

In this chapter I have introduced research context by describing the how understanding of success parameters has changed through the modern history of mega-projects, yet success itself remains uncertain regardless of global R&D investment.

There is substantial literature covering project success and failure, and much practitioner material concerning science/engineering project management. However there is a gap relating to the combined characteristics of large, high-tech projects, of the type that involve large infrastructure. This thesis defines that niche, and attempts to fill the gap.

Success was examined as a parameter, and as an outcome of defining critical success factors, measured against success criteria and metrics. High-tech mega-projects are shown to be inherently complex whether assessed by scale comparison or mathematically, and that complexity influences project performance.

The way large high-tech projects are supported by effective collaborations, and the challenges this can bring, was reviewed. The benefits of an industrial project execution model were shown, and the impact on success of funding approaches, *juste retour*, and project stakeholder relations was presented.

In the next chapter, I look at project inception, operating structures (including the important procurement function), and shaping high-tech projects for resilience.

Chapter 3 – Pre-cursors of high-tech mega-project success

3.1 Project inception

High-tech mega-projects usually begin life as a notion, discussed informally among scientists and engineers, and often gaining a unique designator using an appropriate acronym. As the concept and technical challenge gains interest and attention, groups are formed to steward more formal discussions, draft technical papers, and canvass institutional participation. These early stages are funded, in effect, by the employers of the early participants and volunteered time.

At some point, assuming the proto-project is neither dismissed nor shelved, it must become recognised as a potential real enterprise – a process known as *projectification* (Smith, 2007). The timing for this can be crucial so as to ensure controlled delivery without damaging creativity (Smith & Winter, 2010). In the case of projects procured from the industrial sector (e.g. a defence or civil mega-project) a tender specification is prepared and released and the winning bidder or consortium executes the project according to contractual terms and procedures most often through a conventional entity and standardised project structure. Mega-projects prosecuted through national or international institutional arrangements are less straightforward; characterised by the presence of at least one funding agency, and the absence of a traditional customer. Nonetheless, a legal entity and organisation must be designed and formed to realise the project goals.

3.1.1 Operating entities for high-tech mega-projects

In terms of an entity, a recent European (ASPERA) report investigating the potential benefits of linking new science endeavours with existing infrastructures (Katsanevas et al., 2009) conducted a useful study to better understand the initial conditions required to efficiently start a big science project. The report investigated both international infrastructures (CERN, ESO, ESA), and laboratory facilities in 11 nations, as well as project efforts linked between the two. Despite the European emphasis, the report offers a useful general portrait of workable entities.

The creation of a legal identity is a pre-requisite for any complex high-tech project, in order that staff may be employed, procurement undertaken, and premises secured. Legal arrangements for assurance of agreed partner contributions of funding, components and effort (and for enforcing performance penalties) are also required (Matsuzaki, 1993). Such legal identities can be formed as inter-governmental (treaty/convention), or inter-agency, agreements; a subsidiary body; or a stand-alone corporate entity. The latter option permits several structural choices depending on laws applicable in the country selected for incorporation; some offering favourable taxation arrangements, speedy set up, and flexible operating arrangements. The ASPERA report (Katsanevas et al., 2009, p. 41) describes the practical advantages of linking to an existing organisation, arguing that: *"Setting up a completely new organisation will always be a substantial task, the more so when a number of participants have to reach agreement on every aspect of its structure and operation"*. This advice is echoed in a study of Australian participation in multilateral mega-science projects (Johnston, 2003, p. 57): *"building on existing resources can avoid many potential problems and costs"*. The same study posits that formal Treaties, with their long gestation times, do not offer any meaningful advantages over an MoU[14] enabled at significantly lower direct and indirect costs.

Nevertheless there might be good reasons to establish some form of new independent organisation, despite the probable lengthy delays until the agreements are signed by all the partners, including the tasks assigned to governments and their agencies (Sykes, 1990). In 'Taming Giant Projects', Grün (2004) writes about Multi-Organisation Enterprises (MOEs), claiming these to be the most demanding of project categories, made highly complex through involvement of various constituencies, and prone to erosive competition limiting project learning. The inherent goal conflicts require the creation of a project-specific company, shared by all project owners. This has the added benefit of separating project risk from the parent organisations. The formation of the legal entity not only gives the project identity, it also enables practical transactions and is recommended to occur sooner rather than later. The Giant Magellan Telescope chose to incorporate early (GMT, 2011)[15]; whereas the SKA project office (SPDO) is hampered by its host agreement under the University of Manchester.

3.1.2 Engaged partnerships

Having a formal entity in place does not by itself make collaborations effective; something only enabled through tangible involvement, commitment, and investment by full members. Johnston (2003) describes this as 'deep influential engagement' requiring nothing less than a

[14] Memorandum of Understanding – a document describing the promised intent of the parties, though not usually legally binding.
[15] As the GMTO Corporation, a not-for-profit corporation established in the US state of Delaware.

seat at the Board table. More colloquially, case study interviewees couch this as ‘skin in the game’

Johnston (2003, p. 58) makes the salient point that: “*mega-science agreements are driven, and operate in practice through, a shared commitment to scientific objectives and the excitement of scientific progress. If these are not present, no amount of careful wording can make the agreement work*”. Even so, finding the right legal framework is a difficult problem requiring consultation of legal and administrative experts.[16]

The topic of what makes effective partnerships was raised at the Gemini telescope ‘Lessons Learned’ workshop (NRC, 1999, p. 25), which listed the following items as most important:

i. focus on needs/wants
ii. agreement on approaches
iii. clear, common expectations
iv. well defined budget, schedule, deliverables
v. appropriate sharing of costs, risks, benefits (buy-in)
vi. contracts to record obligations, expectations
vii. frequent ongoing contact, collaborations, communication
viii. effective project management
ix. professionalism (delivery)
x. periodic surveys of partner satisfaction levels
xi. post project impact evaluation.

While many items in the above list are intuitive, item (*vi.*) is especially interesting. It hints that past contractual documentation was deficient in properly scoping the exact responsibilities and anticipated performance between the partners, and highlights a potential critical weakness.

Fieldwork interviews for this thesis (ILC, 2009; VISTA, 2010; ALMA, 2007) revealed that the initial partners in most big (institutional) high-tech projects tended to be self-selected, i.e.

[16] For discussion concerning the legal entity of the SKA see Chapter Seven, Table 7-1.

the employers or host institutes of the project proponents. From this core group other organisations are invited by invitations channelled through professional relationships; these often developed through past collaborations. Sykes (1990) notes that some technically achievable and financially sound mega-projects fail to be launched, essentially due to the (large) number of key participants. Interviewees shared the view that there is likely a point where the number of participants (and therefore interfaces) detracts from optimum efficiency, and compatibility. The consensus view numbered this between 10 and 20.

3.1.3 Funding through collaborative contributions

High-tech mega-projects managed in the commercial world are generally assured of funding when procured through government agencies (e.g. Defence, Infrastructure, etc), or private capital sources when risk and return is justified. Giant institutional (and often multi-national) projects however, must convince participating organisations to commit to years of funding, often in an environment of competitive national resourcing. Without tied funding, no project of any size will be supported for long.

The machinations surrounding collaborative funding of big science and engineering endeavours are complex, prolonged, and usually political in nature. Matsuzaki (1993) compares the case of the HERA colliding accelerator with the Superconducting Super Collider (SSC). HERA is shown as setting an effective example of consultation with scientists who were influential in their own countries in order to obtain international financial commitment. In contrast, the US government moved to construct the SSC largely autonomously, seeking financial support after construction commencement, and eventually abandoning the project.

The ASPERA report (Katsanevas, 2009) concludes there is no single best way of dividing contributions among international collaborations. Amounts based on GDP have been used, though the method neglects national aspirations and strategic interests. Setting contributions using a percentage of project budget (e.g. ESO) has advantages for the project office accounting, but brings uncertainties for those partners who sign up early, and carries exchange rate risks. An alternative approach is to require fixed contributions in one currency. In-kind contributions have their place, although valuation of effort can be problematic, and too high a proportion of in-kind contributions can result in insufficient working funds. Considered an initial strength of the ITER project, the kIUA credit units have led to poor cost/value propositions, and the partners (known as Domestic Agencies) show little accountability for in-kind contributions (Grossmann, 2010). To counter this in any multi-lateral project, a cash reserve amount known as project (or risk) contingency may be established.[17]

An underlying feature that can impinge on the contributions of collaborative partners is the principle that the value of contracts awarded within a member state should closely reflect the amount of money that it subscribes. Known as *juste retour* (or geo-return), the principle is enshrined in ESA's terms of reference where it completely differs from other European collaborations such as CERN that are free to award contracts purely on merit.[18]

Having access and control of the project purse (i.e. in the manner of commercial mega-projects) is shown to be highly desirable to strengthen management control in institutional projects. Interviewed in 2010, SKA Director Professor Schilizzi lamented the decision of the Executive Committee to permit the SKA Consortia to self-manage their project support (by means of institutional effort) rather than formally contribute cash to a central fund, saying: *"Any sense of obligation to deliver against agreed requirements was highly diluted, leaving the [project HQ] with no real power to demand compliance to agreed action plans"* (SKA, 2010). A similar situation occurs in the ALMA project early construction phase, where money from the partnership agencies flows around the central Joint ALMA Office, not through it (Schreier & Webber, 2010). The fractured management structure of ALMA continues to frustrate the organisation.

3.1.4 Project structures

Project structures, in terms of hierarchy and interactions most often portrayed as organisational charts, are multifarious and at the detailed level unique to each project. Investigation of the specific positioning of roles and departments and their respective interactions is a research topic outside this thesis, however both the literature and case experiences offer useful intelligence when considering the formation of governance and working structures for high-tech enterprises.

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[17] This is further discussed in section 3.3.4.4.

[18] *Juste retour* is defined, and discussed further in section 2.7.

Institutional mega-projects (e.g. formed under an MoU) will require a Governing Board (or Executive Committee) to serve as the principal decision-making body, although the MoU itself may not confer legal powers to the Governing Board (Katsanevas et al., 2009). A secretariat function, either separate or co-located with the project host, embodies the necessary legal entity, and is headed by a Director whose responsibilities are set out in the MoU. The relationship between the collaborative project and its host country are established through a country agreement. These relationships are shown in Fig. 3-1.

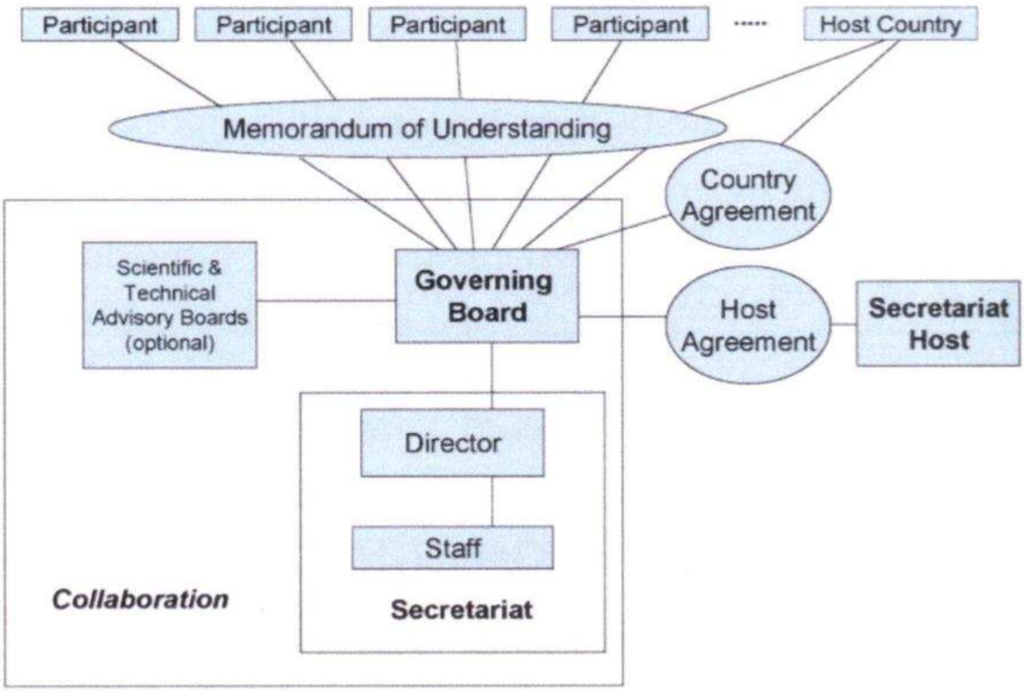


Fig. 3-1. The relationship between governance elements of an international mega-project (ASPERA, 2009, p. 44)

Large domestic high-tech projects can take advantage of leaner top level structures, especially when the project integration task is placed with a single contractor e.g. Australia's OPAL project, and the US National Ignition Facility- NIF (NASA, 2011b). The NIF was implemented through an existing Department of Energy Management and Operating contract, and considered so successful, it won 'Project of the Year' from the Project Management Institute.

Governance activities are often informed by a project Steering Committee which requires very careful establishment and framing if it is not to be dysfunctional. A Steering Committee can be a strongly beneficial arm in maintaining alignment of the project team and stakeholders, and in cohesive direction setting. Non-institutional project organisations may refer to such a group as a Core Team, described by Graham and Englund (1997) as essential to effectively executing the project, minimising project cycle time; often with dramatic results. Governance Bodies of institutional big science projects frequently enunciate their intent to execute their programs along such 'industrial lines', then proceed to appoint 'status' members, or worse, establish a notional but disempowered Steering Committee that simply creates a burden for the project. In response, a noted IBM project manager offers high-tech project managers the following (adapted) descriptors for successful Steering Committees (Elenbaas, 2000):

- The project sponsor/project champion is represented, and some key business people who must play an **active** role on the project
- There is representation from experts in all critical project domains, including programmatics
- The project manager controls the agenda and preferably chairs the meeting
- The main role is to arbitrate on issue/change/decision management, on issues raised and supported by the project's key stakeholders, including overall change control for scope, schedule, cost, quality, risk, and performance reporting
- The Committee is a forum where open, honest and frank discussion can occur, based on the **real** project picture (which may not always be pretty)
- Meetings are scheduled frequently, more than monthly.

Allied to the project Steering Committee, and certainly within the purview of the Project Manager, is the concept of the project Task Force(s).[19]

At the project execution level, the interrelationships between departments and personnel are normally set out in a project organisational chart (or organogram). Over the past decade there has been a general movement away from traditional functional-based organisations (Fig. 3-2a) with largely vertical reporting and control and ostensibly only limited ability for project ownership by functionaries, towards matrix style structures (Fig. 3-2b). Conceived in the 1960s within aerospace industries, matrix management was a response to the need for a project oriented system that linked 'horizontal' project resource groups directly to top management, essentially forming orthogonal lines of command and communication, with

[19] Task Forces are discussed further in section 5.1.4.2.

many staff coming under both a department head (or functional manager) and a project manager (Kuprenas, 2003).

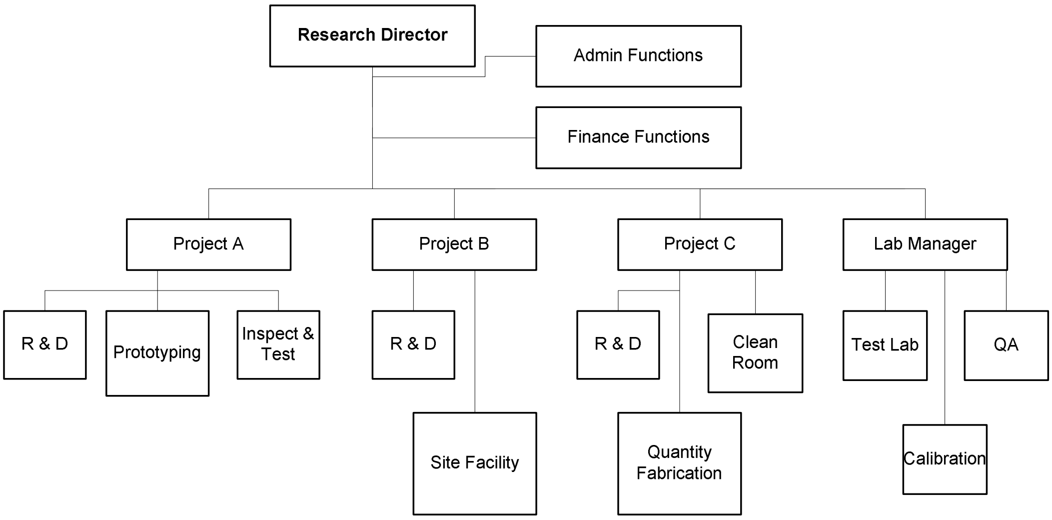


Fig. 3-2a. Showing traditional styled project organisation structure.

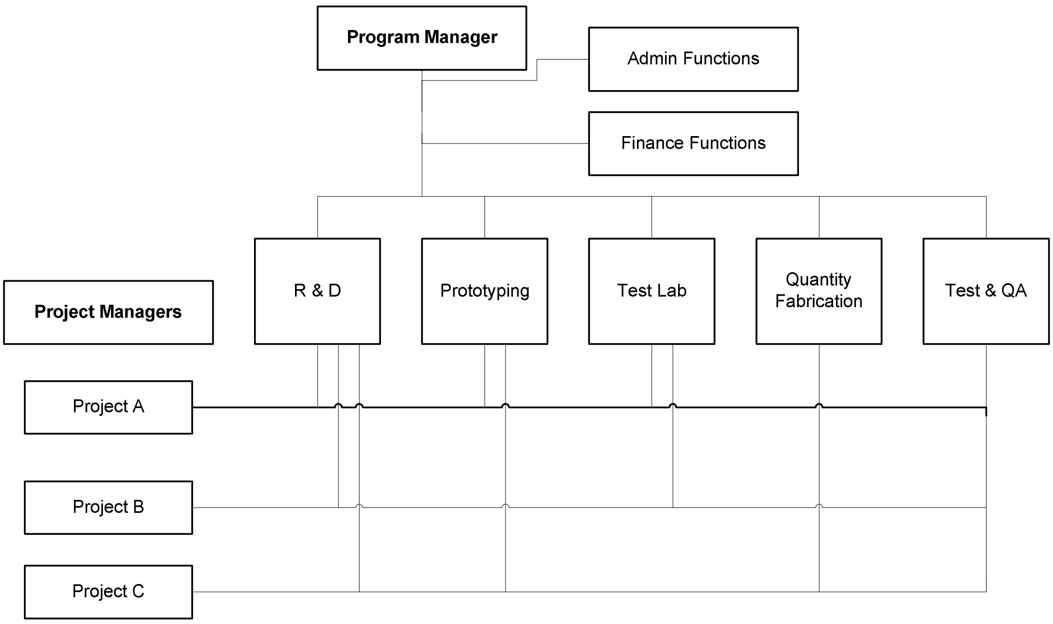


Fig. 3-2b. Showing matrix styled project organisation structure.

While theoretically the matrix organisation should deliver a suite of advantages including; improved ability to access resources, better coordination across the organisation, faster decentralised decisions, and improved communication and coordination, these are difficult to quantify. Work by Kuprenas (2003) found increased communication and flexibility while maintaining organisational accountability in engineering firms, as well as reduced unaccountable time. He also found performance benefits in the public sector harder to define, with no measurable difference at the project level, although 50% improvement at the program level. Graham and Englund (1997) found more problems than benefits for projects under a matrix model, their main complaint being the perceived marginal change from the traditional (hierarchical) model, leading to conflicting priorities and reward systems mismatched to organisational goals. In fact, the matrix should represent a whole different way of managing projects, and requires reinforcement through two dimensional information systems and managerial behaviour to support dual reporting relationships (Nicholas, 2004).

The choice of which organisational design to apply need not be purely binary. When considering an optimised design for high-tech organisations where expertise is critical, Galbraith (1971) posits a fully sliding scale for cross-functional forms (see Fig. 3-3), while recommending the functional authority structure to be most applicable.

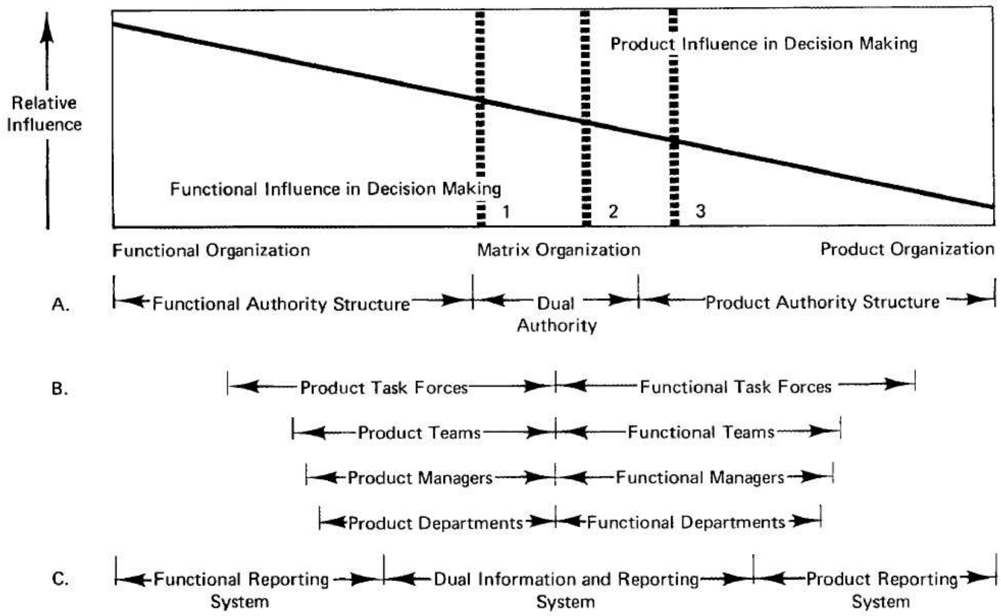


Fig. 3-3. The range of alternatives of a matrix organisational form (Galbraith, 1971 p. 37)

Research for this thesis revealed a further intriguing design for a cross-dimensional organisation. Referred to as a Solar Organisational System (see Fig. 3-4), it originated from a 1971 paper discussing management practice at The Manned Spaceflight Centre at Houston. Although shown here as a novelty, it does bring forward the idea that there are organisational representations for projects yet to be explored. Moreover, the concept of groups as planetary systems offers a revived view that may resonate well in the high-tech/aerospace sector.

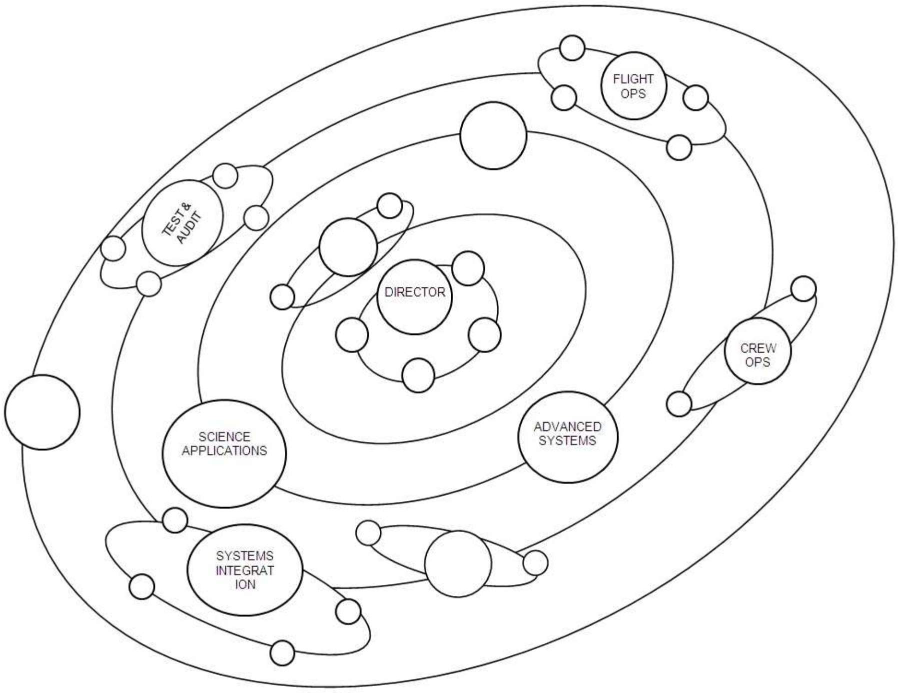


Fig. 3-4. Manned Spaceflight Centre solar organisational system (after UAI, 1971)

Many large high-tech organisations now adopt the concept of Integrated Project Teams (IPTs). IPTs are cross-functional teams formed for the specific purpose of delivering a project or product, or main component of same, for an external or internal customer. IPTs are staffed by groups with complementary skills and committed to a common purpose for which they hold themselves mutually accountable. While endorsing the benefits of IPTs in supporting the defence acquisition process, a UK Ministry of Defence report (MoD, 2002) recommended a review of best practice in IPT roll-out, learning lessons from comparator organisations, being rigorous in setting hard and stretch targets that are robustly reviewed, and a continuation of implementing an IPT Maturity Model to identify and promulgate success factors for IPT performance. The ASKAP project found inconsistent reporting quality from IPT leaders, indicating some form of calibration is required (ASKAP, 2010). The MoD report clearly identifies that establishment of IPTs must be complemented by a continuous improvement process based on lessons-learned – a theme that pervades this entire thesis.

Within the high-tech projects investigated for the present study, it is clear that teams at all levels were diverse in the sense of age, nationality, cultural background, training and experience. Tony Spear, project manager NASA's successful Mars Pathfinder, described his team as: "*a mix of scarred veterans and bright, energetic youth*" (NASA, 2011b, p. 27). These observations accord with the norms for international projects, where talent is recruited primarily on the basis of qualifications and capability, and the expectation that the people who seek the challenges of big science and engineering endeavours, are willing to relocate to participate. Anecdotal evidence from interviewees was strongly positive regarding the social and innovation benefits of working in an international team (ALMA, 2009, ATCA, 2008, LHC, 2009). In terms of cognitive diversity (varying education, cultural values, and attitudes) the response was more mixed, with some caveats concerning perceived status equality. Australians, for example are generally very egalitarian, whereas team members from an Asian background may be more deferential by nature. This view is supported by research showing that cognitive diversity can interfere with knowledge transfer, or hinder adoption of advanced processes (NASA, 2010c). The solution rests with proper integration of skill sets, respect for diversity, and team knowledge.

Alongside the setting out of organisational structures and teams, responsibilities and authorities must be clearly set out, and be commensurate with the position. Saunders et al. (2003, p. 367), investigating management success predictors in space projects, conclude that: *"responsibility, authority, and accountability need to be matched, and the decision-making process clear to all...many development problems can be attributed to confused lines of authority."* Overall day-to-day project control and organisation falls to the person commonly titled Project Manager or Project Director (although some projects distinguish between these labels). NASA is most clear that: *"the single greatest contributor to a project's success is the person on whom final responsibility rests, the project manager. He or she is responsible for executing the project within the [organisation's] guidelines"* (Nicholas, 2004, p. 45). There is consensus among the case studies for this thesis, and within project management articles, that shorter, co-located, management chains, work better. A re-baselining of the US NIF project after major cost and schedule deficiencies were exposed, eventually led to creation of a Federal Project Director designation being established. This move compressed the authority lines between the government and the project contractor, and improved focus on project priorities (NASA, 2011b).[20]

Responsibilities, and associated authorities and accountabilities are naturally devolved through the project structure, and crucially, must be formally documented, and announced throughout the project organisation. Special effort is required to communicate delivery responsibility and information control authority to any collaborative partners, since experience shows that distance from project headquarters can dilute perceived obligations in terms of strict project procedural compliance and observance of deadlines. A study of ICT

[20] The skills and qualities demanded of such a role are deeply examined in section 5.1 of this thesis.

success factors in developing nations (Atsu et al, 2009) offers evidence that 50% of the project office personnel surveyed do not take full ownership responsibility for the project, citing lack of motivation associated with non-empowerment to exert the necessary authority because of the bureaucratic organisational structure. A similar frustration is expressed by the Domain Specialists within the SKA Program Development Office (SPDO).

3.1.5. Project location

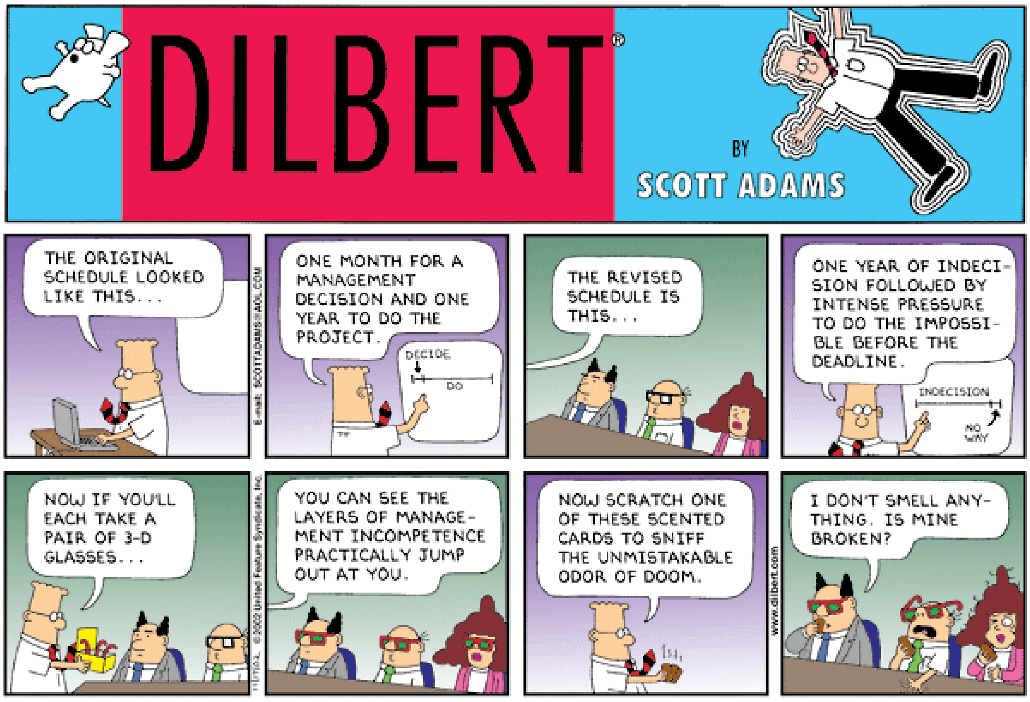
The need to access competencies and funding, and realise institutional inclusivity, drives multinational collaborative high-tech project ventures, especially in science, aeronautics, automotive, and telecommunication industries. Siemens, for example, handles more than 1,000 projects in a distributed mode at any one time (Bourgault et al., 2008), and almost all mega-science endeavours are multi-national. However dispersed projects create challenges for effective decision-making and processes do not always adapt well when applied globally. One quantitative study of success determinants in distributed teams (Bourgault et al., 2008), clearly demonstrated a link between successful management of dispersed project groups, and team autonomy in executing project activities. Moreover, the quality and formality of project decision-making processes are both highly important to a successful outcome.

The physical location of high-tech project infrastructure may be determined by the location of the principal protagonist (e.g. LOFAR), pre-existing infrastructure (e.g. LHC), or by the special needs dictated by the science goals (e.g. LIDAR, ALMA). Giant science and engineering projects with multi-national partners may decide to locate the governance offices, and in some cases the project headquarters, in a different location to the project infrastructure itself (e.g. SKA). Again, Elenbaas (2000, p. 5) offers his experience with big, high-tech industry facilities, describing the physical location as an ‘extremely high’ impact factor for shaping success, and suggesting that:

> *“Projects are about communication, communication, communication. At the very least, try to bring sub-teams/key team members together in close physical proximity (this includes key business people). Spend big money on temporary relocation if necessary (you’ll save much of it on reduced travel costs and it will pay huge dividends.) Don’t get fooled by modern communication media – nothing replaces face-to-face contact, and e-mail is a slow media for a high traffic communications link.”*

3.1.6 Power and discipline

Like any very large enterprise, the world of high-tech mega-projects is never straightforward. While project management texts may convey an idealistic, aspirational picture of calm and steady progress through staged milestones towards a satisfying outcome, the reality is much closer to the edge of chaos depicted by Smith (2007) and illustrated through the raw realities of the project manager struggling with disorder, disruptions, and complexity. The seemingly endless task then of the project manager is to unflaggingly revise forward plans, attempt to create order, and constantly steer the project within the realm of control.



Adams S, Dilbert cartoon series. Originally published 2001. Retrieved on 29 Aug, 2011 from: http://search.dilbert.com/search?day1=17&mth1=11&yr1=2002&day2=17&mth2=11&yr2=2002&x=25&y=4

The human element of projects that contributes significantly to the unpredictability of events and responses is mostly observed in the social interactions of project 'tribes'. Smith (2007) posits that understanding tribal groups and their characteristics, as viewed through the lens of a social model, can aid our understanding of what is really going on within projects. He offers a table of tribal categories reproduced as Fig. 3-5, which is useful in understanding the interests and personal drivers of project teams and individuals.

Category of Tribe	Who Are They?	What Are Their Characteristics?
Project directors	The group seeking to impose project working within an organization.	Driving a central agenda of accountability and control, promoting management by projects as a way of life.
Strategists	Agents of central policy makers, using projects to deliver a strategy.	Concerned with creating projects, while preventing peripheral and non-essential activities. May act as the formal project 'sponsor'.
Project shapers	The project designers, negotiating and setting the agenda of individual projects.	May be an explicit tribal group, but is often an ad hoc group negotiating between interested parties. Some project managers see involvement in this function as central to their role. Others deny any interest in the subject.
Project deliverers	The group who take responsibility for delivering a project (or part of a project).	Individual project managers will belong to this tribe as a long-term home, while acting on behalf of a temporary team for a specific project.
Priesthood	The groups who act as custodians of project management knowledge.	The group that sets the standards. They include in-house expert practice groups, independent standards organizations, associations that claim to be professional bodies and universities.

Fig. 3-5. Categorisation of project tribes, and their characteristics (Smith, 2007 p. 33)

Smith and Winter (2010) view the topic of tribal power through the perspective of projects emerging through the manoeuvres of diverse groups, each with disparate agendas. In multinational projects, power is diffuse and negotiation is required to satisfy power imbalances. For example government targets might over-ride the creative efforts of knowledgeable teams and individuals in order to meet a bureaucratically based time limit. In other cases the technical tribe may be over-ruled by the powerful finance tribe. Energy expended in tribalism saps project vigour, a situation only met by: *"the project shaper [acting] as an expert player in this social world, endeavouring to facilitate and create projects with a [common] drumbeat"* (Smith & Winter, 2010, p. 54).

Finally in this section, I consider the relative merits of professional background and experience for those leading the high-tech mega-projects. Should the governance and project manager role fall to well known and respected scientists, previously associated with like-projects, and mainly interested in optimising performance? Or a professional engineer with formal project management training and who is likely to apply a programmatical discipline to deliver against specified criteria, budget, and timescale?

This dichotomy of culture for project leadership is addressed by Riordan (2001) through an examination of the Superconducting Super Collider (SSC), and epitomises the problem. The issue at stake is whether physicists, or engineers, are best placed to manage the construction phase of large scientific projects and thus be able to influence the quality of relationships between the project execution teams and the laboratory.

As Riordan tells it, (Riordan, 2001) under wartime conditions, control of the workplace had been ceded to engineers. Physicists may have made the crucial intellectual contributions to building weapons technology, but they ultimately reported to (or through) the engineers and project managers in charge. However at the Stanford Linear Accelerator Centre (SLAC) and the Fermi National Accelerator Laboratory (Fermilab) this relationship was reversed in the project structure. From the outset, physicists designed, built, and managed these successful high-energy physics laboratories; they stepped into important engineering roles or occupied the key decision-making positions, and the engineers reported to physicists. These past power wrangles erupted between high-energy physicists and engineers hailing from the military-industrial era, during the abortive construction of the Superconducting Super Collider (SSC) and became another episode in this continuing struggle. At the multibillion dollar scale of the SSC, powerful forces came back into play that had not figured at the hundred-million-dollar scales of Fermilab. The impact of these influences continues to appear in contemporary mega-projects above a certain scale, and is a salient reminder of where conflict can arise[21].

3.2 Contractual (procurement) arrangements[22]

3.2.1. Introduction

In the world of science and engineering mega-projects, the breadth and pace of technology advances and demands for improved success brings new importance to professional management of procurement. This challenge embraces technology identification and access, supply channels, cost control, and industrial relationships (Schill, 1979).

[21] The characteristics of mega-project managers are further explored in section 5.1

[22] This section is drawn from the author's peer reviewed paper published as SKA Memo 129, Crosby, P., (2011). *Procurement strategies enabling success in high-technology mega-projects: Preparatory work for the SKA*, SKA Program Development Office (SPDO), UK. See Appendix K.

The procurement of goods and services for projects has traditionally been seen as largely administrative or operational rather than having strategic importance (Virolainen, 1998; Schill, 1979). However project complexity is driving a more strategic approach (Jaakkola, 2004), and recognition of forces other than purely transactional show a maturing of approach to the contracting problem (Winch & Gil, 2010).

In this section, I show that procurement strategy and practice are vital precursors to the success of mega-projects. Through a study of large scale procurement practices relating to big science and engineering projects (with particular relevance to the Square Kilometre Array project) I show that effective procurement underpins planning, acquisition, and execution processes to help assure value-for-money, and contribute to project success.

The term 'procurement' is used in its wider sense to cover the process ranging from establishing the requirements, global sourcing, placing of the contract, overseeing execution, and in some cases dealing with through-life support (Hall & Khan, 2006).

Modern procurement management in the high-tech environment is more reliant on buyer-seller partnerships than a traditional contractual based approach. These relationships tend to be longer term, ongoing, and risk-sharing, and strive for win-win outcomes at lower cost (Virolainen, 1998). Within procurement, the key task of contract management itself can be broadly grouped into three areas: service delivery management, relationship management, and contract administration. *"All three areas must be managed successfully if the arrangement is to be a success [and] good preparation and the right contract are essential foundations for good contract management"* (OGC, 2002, p. 5). Contract execution procedures, administration and specific documentation are of course vital to procurement outcomes, though beyond the scope of the present study. Suffice to say that the *"light legal touch"* suggested by Hall & Khan (2006, p22) is consistent with the key, yet simple principles offered in this thesis.

3.2.2. Scope, data sources and study method

In the following sections, I mostly address the institutional (publicly funded) procurement environment, contracting models, procurement specifications and terms, general contracting instruments, tender evaluations, supplier relations, planning, and risk. Input is drawn partly from referenced research papers, and project management texts and articles. While such literature provides useful commentary (and some practical instruction) in relation to general mega-project procurement, the finer points of procurement strategy development and execution for high-tech enterprises are effectively sourced from case experience. To this end, I have incorporated research material from my fieldwork case studies listed in Table 1-1.

The main body of this part of the thesis (section 3.2.4) adopts a discursive style in order to present the broad range of high-tech procurement issues, informed through the lived experience of project personnel. The aim of the section is to go beyond *a priori* elements of procurement, and present the essential ingredients of a sound procurement strategy for success in contracting within high-tech projects.

3.2.3. Framing procurement as a precursor to project success

Acknowledging the strategic nature of procurement means giving proper and early attention at the project preparatory stage to policies, processes, and resources. Jaakkola (2004) points out that the process of establishing contract management in an organisation can take years, and should be viewed as an on-going process designed to generate cost savings. By documenting the process, the steps and interactions may be clarified. (Refer the example shown for the SKA in Appendix B).

In considering modern procurement challenges, a Major Projects Association seminar concluded that the following questions can help organisations decide on a procurement approach through better understanding of the determining factors (adapted from MPA, 2009);

- What is vital for success?
- What is the funding (and how secure is it)?
- What are the possible risks to (procurement) success, and what risk must be managed by the organisation?
- How will those risks change, or how can they be mitigated over time?
- What experience requirements are needed for other parties to manage risk, and what reward/commitment incentives can be put in place?

These questions, and other related issues, are discussed within nine topic headings below. Each topic informs an associated key strategy as summarised in Table 3-1, and is a suggested topic heading within the structure of any ‘high-tech’ mega-project procurement plan.

Table 3-1. Nine topics of procurement success and their associated key success strategy

Topic heading in section 3.2.4	**Key Success Strategy**
The procurement office	*Establish early the procurement office structure, resources, processes, roles and responsibilities, and information management systems.*
Procurement strategy, policy and planning	*Formally approve procurement policies, strategies, and plans, and document these within a concise approved Project Procurement Plan.*
Informed contracting with industry	*Obtain full understanding of global capability scouting information, and employ appropriate approaches and instruments with terms and conditions supporting project goals.*
Contracting models	*Establish the contracting model, aligned with the legal entity. Develop relationships with principle contractors and the supply chain.*
Ensuring competitiveness	*Ensure competitiveness in contracting, through carefully planned pricing strategies, and a 'value for money' approach.*
Procurement specifications	*Apply purchasing specifications that are appropriate to the goods or services required, are flexible for optimal outcomes, and developed with input from industry.*
Tender evaluations and contractor selection	*Understand and actively manage procurement risk, including the critical early stage engagement phases.*
Procurement risk	*Evaluate and select project contractors using a fair and balanced process, executed against standardised procedures, and focussed on criteria weighted in favour of mission success parameters.*
The purchaser-supplier relationship	*Implement fair and transparent procurement processes, and exploit open strategic partnerships while allowing for evidence based supplier inspections.*

3.2.3.1 The legislative environment

High-tech mega-project procurement will almost certainly be a global endeavour, and aside from the giant aerospace/defence contractors, is likely to occur in the institutional (or public) domain.

Public funding for such science/engineering projects or programs requires that procurement complies with appropriate and agreed codes or regulations e.g. the European Procurement Directives, the World Trade Organisation rules, as well as national legislation (Hall & Kahn, 2006). In the USA, public purchasing is enshrined within FAR Part 12 (NASA, 2009c). The technicalities of global trade environments, and procedures (especially related to maintaining open competition), demand expert attention.

The self-contained treaty organisations adopt strict procurement rules. In CERN's case the FIDIC Conditions of Contract are embraced, incorporating an industrial return coefficient for member states. The legislative impact, including its taxation status which impacts directly on procurement instruments, will depend upon the legal identity of the project.

Deciding on the legal structure for international mega-projects requires expert advice to review the viable options. However useful experience comes from contemporary examples. Treaty organisations (e.g. CERN, ESO) are generally satisfactory entities although bureaucratic and take a long time to establish. The ITER treaty model with a Supervisory Council appears less effective. Similarly, the European Research Infrastructure Consortium (ERIC) entity takes a long time-to incorporate (at least nine months), and being a relatively new construction, has some uncertainties and likely difficulties for an SKA type endeavour (Chance, 2010). Whatever the final model, the governance, management, and supervisory structure must have clearly defined authorities (European Commission, 2010).

Formalised collaborations under an MoU (e.g. AUGER, HESS) are simpler and succeed in an environment of goodwill, while the ill-fated BEAGLE 2 consortium was founded on a "gentlemen's agreement" with each partner funding its own activities (ESA, 2004). Commercial-like structures such as LOFAR (formed as a special limited partnership under Dutch law) and XFEL (established as a German limited liability Company) enable a legal trading entity to be quickly created (DESY, 2009). Research by ASPERA concluded that 'high-tech' collaborations are complicated and lengthy to realise, and linking between unequal partners is intrinsically difficult; it may be more cost effective to link to an existing organisation (Katsanevas et al., 2009). One independent (commercial-in-confidence) study concluded that (i) a Dutch foundation (*stichting*), (ii) a UK company limited by guarantee, or (iii) a US not-for-profit corporation in Delaware, are equally suitable for the purposes of effectively executing an SKA-like project (Chance, 2010).

3.2.3.2 Global sourcing

Rendleman and Faulconer (2011, p. 20) discuss the importance of: "*closing the gaps between available technologies and customer needs before beginning an acquisition* [so as to] *put programs in a better position to succeed.*" Schill (1979) also points out the strategic liaison role played by procurement to ensure that suppliers remain competitive and at the forefront of technology, as well as realise better cost and product performance. Moreover, he assigns strategic responsibility for materials and technology identification both to the buyer, and the market – an important tactic identified in the SKA Capability Assessment Model (Crosby, 2010). This approach addresses the concept of 'scaling up' in terms of industry capability, where science-based mega-projects may demand hundreds or thousands of an item previously produced only as a speciality part. Even so, there may be no ongoing commercial market.

The strategic identification, stimulus, and utilisation of global capability (Virolainen, 1998) may be 'kick-started' by a formal scouting process which may itself be coupled to preliminary vendor screening; the focus being on determining which suppliers are (actually or potentially) qualified, and have the capacity and/or talent to perform the work (Blanchard, 1990). The NEON organisation identifies this phase as 'pre-solicitation/evaluation' in their technology procurement plans (Ashley, 2009.

3.2.3.3. Internal-external procurement

In high-tech projects many of the outcomes are entirely dependent on high risk, new technologies that must be demonstrated to 'proof of concept' level (e.g. the SKA pathfinders) before production quantities can be considered. Even then, commercial factors may limit procurement choices. For example, a lifecycle cost/benefit analysis should be conducted between the alternatives and/or competitive offers to determine the best option for specified performance at least cost (perhaps including a 'make or buy' feasibility decision) without jeopardising other project interests or resource priorities. Due consideration must be given to intellectual property ownership, as well as the long term cost-benefit impacts of ‘high-tech’ outsourcing.

In NASA’s case, most of its funding is spent on contracts; however its strategic plan outlines the need to maintain institutional capacity and core competencies through having its workforce perform some of the hands-on work. The advantages and disadvantages between in-house and contracted work was recently reviewed for the MMS spacecraft project, with the conclusion that both approaches have significant strengths and weaknesses, while acknowledging clear benefits in maintaining a level of in-house competency (NASA, 2009a).

3.2.4. Strategies for high-tech mega-project procurement

Rendleman and Faulconer (2011, p. 51) write frankly about aerospace acquisition programs, claiming problems to be endemic, and intrinsically linked to high-tech project failures. They characterise the ‘acquisition death spiral’ (see Fig. 3-6) as: *“a rapid compounding of external influences, systems engineering, and management failures.”*, and emphasise that project managers must be able to spot and counteract the early signs of project downfall which they list as (adapted from Rendleman and Faulconer, 2011, p. 55):

- Failed systems engineering;
- Unrealistic funding realities, including incomplete budgets or volatile program funding;
- Unreasonably pushing the technology envelope, with unstable requirements;
- Overly optimistic planning estimates, with weak program cost and schedule reserves;
- Launch vehicle selection driving program complexity;
- Unreasonable “sunk-cost” arguments;
- Government/customer is not acting and thinking strategically;
- Faltering industrial base;
- Stunts being used as a substitute for mission value.

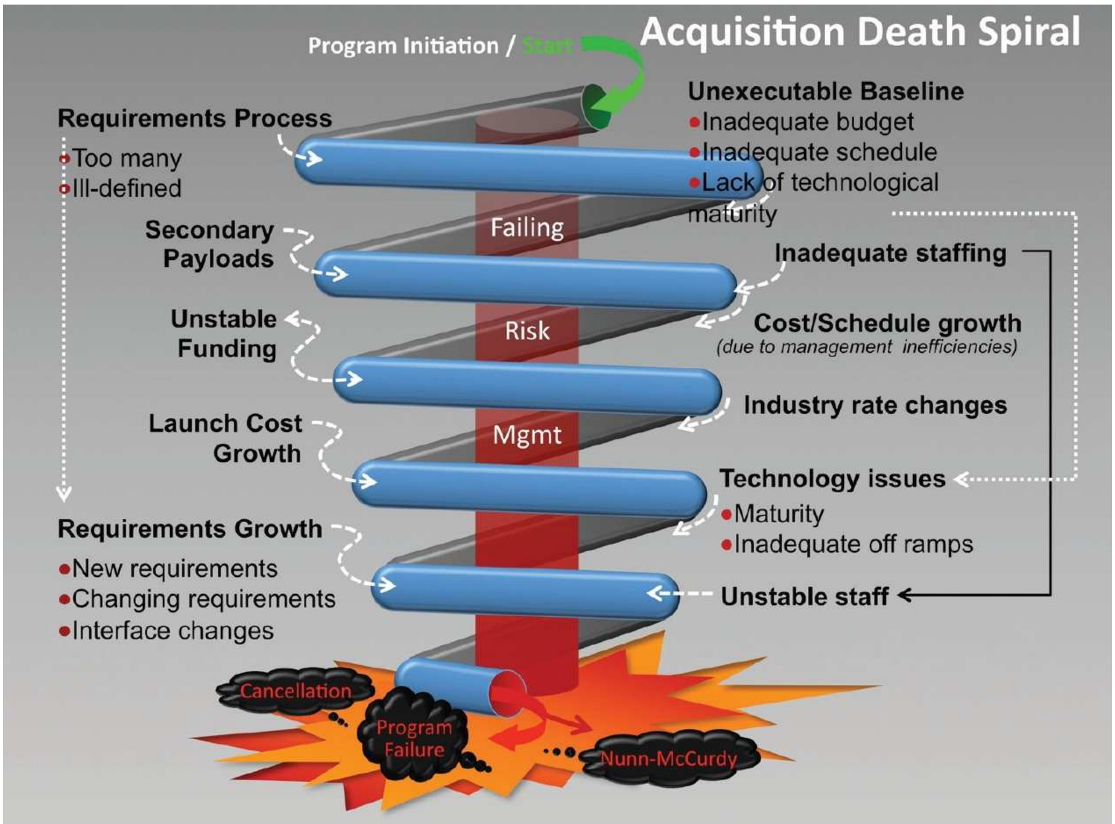


Fig. 3-6. The acquisition death spiral (Rendleman & Faulconer, 2011, p. 55)

The huge financial investment, and long lifetimes of high-tech mega-projects mean that strategies necessarily enacted early have both short-term tactical influence, and long term ramifications, and are clearly important to get right. The following topics describe key areas where wisdom from subject authors and case-work experience can help shape strategies for procurement success, as a precursor to project success.

3.2.4.1 The procurement office

Given the lead times involved with high-tech mega-projects, the establishment of a functional procurement team should be considered early. Underpinning the strategic arrangements, Jaakkola, (2004, p. 1) states: "*The first step is simply to get the basic contract management operations established. These include…a centralised contract repository, appointment of person(s) responsible…a contract management handbook, contract templates*". The procurement system, in terms of software tools and processes integrated to the project management, also require early and careful selection and management.

Roles and responsibilities require definition and approvals assigned, ideally with an individual assigned as focal for each major contract. As the UK Office of Government

Commerce (OCG, 2002, p. 7) advises: *"The importance of contract administration to the success of the contract, and to the relationship between customer and provider, should not be underestimated"*. The American styled Integrated Project Teams (IPTs) model has showed functional success in procurement for the Australian SKA pathfinder (ASKAP, 2010).

Successful management of any enterprise relies on effective communication and no less so in procurement, especially between the procurement department and design team during the early phases. The conveyance of information concerning emerging technologies, forecast changes, financial analyses of upfront costs and investments, and cash flow risks, when added to the more traditional price and delivery schedule data, ensure strategic value for the project.

3.2.4.2 Procurement strategy, policies and planning

Procurement strategy provides a management framework for obtaining products and services via contracts. Sometimes it is necessary to probe outside sources in order to gather sufficient information to formulate an acquisition strategy. This may be some form of active capability scouting, or by issuing a Request for Information (RFI) to industry and other parties. The aim is to obtain information about technology maturity, technical challenges, capabilities, price and delivery considerations, and other market information that can influence procurement strategy decisions. NASA's System Engineering Handbook (NASA, 2007a p218) contains much detail to inform high-tech procurement processes, and suggests the acquisition strategy should include:

- Objectives of the acquisition—capabilities to be provided, major milestones;
- Acquisition approach—single step or evolutionary (incremental), single or multiple suppliers/contracts, competition or sole source, funding source(s), phases, system integration, Commercial-Off-the-Shelf (COTS) products;
- Business considerations—constraints (e.g., funding, schedule), availability of assets and technologies, applicability of commercial items versus internal technical product development;
- Risk management of acquired products or services— major risks and risk sharing with the supplier;
- Contract types—performance-based or level of effort, fixed-price or cost reimbursable;

- Contract elements—incentives, performance parameters, rationale for decisions on contract type; and
- Product support strategy—oversight of delivered system, maintenance, and improvements.

The overall approach to the high-tech acquisition program is captured in the procurement plan; itself linked to the project master plan/system timeline. The procurement plan sets out top level policies for sourcing, tender management, contract evaluation and approvals, *juste retour*, as well as the regulatory environment, responsibilities and authorities, procurement strategies, and pointers to detailed procedures and guidance. The procurement plan may be in the form of a public document (Crosby, 2008a), enabling industry and other stakeholders to understand and prepare for project opportunities, and possibly an internal version created for the project (Hall & Kahn, 2006).

Strategic planning of mega-project procurement will include research and monitoring of lead times of major system components (see example Appendix C), and relating this information to the procurement timeline (see example Appendix D). This is crucial for all stakeholders understanding. Procurement plans may be complemented by national or international industry participation plans describing the intent of procurement policies in relation to fair competition, strategic capacity building (regional development), and local involvement (Crosby, 2008b).

Such plans need not be large documents, an example being the NEON Project Acquisition Plan, covering references and scope, procurement strategy, functional responsibilities, and procurement plans succinctly within its nine pages (Ashley, 2009). LOFAR's plan covers similar topics in 11 pages (de Geus & Kahn, 2002). Plans for specific type acquisitions can be referenced and separate, as can general institutional purchasing manuals, regional rules, and Conditions of Contracts.

3.2.4.3 Informed contracting with industry

The level and method of industry interfaces will vary according to the stage of the project e.g. preparatory and construction phases, through to operations. Perna et al. (2009, p. 21) suggest four ways in which industry may be engaged at the early stages:

- *"High level engagement, at the concept level, to discover new technologies or industrial information and skills*
- *R & D contracts for prototyping & design*
- *Global price enquiries for COTS requirements*
- *'In-kind' contributions of personnel, tools, technical services, or other resources"*

These engagement options, and later construction phase activities, will normally lead to selection, approval, and a contract using instruments such as a collaboration agreement, Request for Information (RFI), Request for Quotation (RFQ), or Request for Tender (RFT). These processes build on, and are informed by, the global industry 'scouting' process which takes account of the regional/country capabilities to the appropriate extent. Mega-projects may choose to be more proactive; ITER for example, pre-announces each year's intended procurements for next 24 months (ITER, 2009).

Although RFTs may be restricted to project member institutes/states, open RFTs are most common for science/engineering supply acquisitions (as used in ESO). This method more likely guarantees both the largest number of industry enquiries, and a fair approach in gathering industrial information, and supply offers. Price enquiries and R&D contracts performed via open tenders provide the following advantages (Perna et al., 2011):

- guarantee of full access to a worldwide market to identify the best available technologies, free from any geographical boundary restrictions;
- continuous monitoring by project stakeholders for fairness in the industrial involvement.
- the ability to look strategically at regional capability for possible 'chunking', bundling or split of contracts, or to address *juste retour* issues.

The contents of RFTs and other issued documents are normally closely scripted by institutional templates validated by legal professionals. However experience gained from CSIRO's ASKAP project means that care is needed to ensure that standardised language and text does not mask or generalise either the specific need or overriding objectives of the procurement (CSIRO, 2009).

RFTs will ordinarily require bidder details concerning product, price and performance, however Blanchard (1990) identifies several issues for which tender documentation should solicit an expanded response from the contractor;

- A detailed plan of execution (to ensure the scope is understood)
- An overall staffing chart, and project schedule with critical path defined
- A 'labour force' load chart indicating committed and available resources
- Resumes of key staff with at least one alternative each
- A choice of contractor's project manager
- An estimate of the number of engineering plans to be supplied

Whilst open requests for information or offers have advantages, and are usually a legislated requirement in public procurement for high-tech mega-projects (LHC, 2009; OPAL, 2009; VISTA, 2010), there could be benefits in a more direct approach. Partnership sourcing, where the buyer and supplier develop a close and long term relationship resulting in lower total costs, can enhance dependability and overall supplier quality (Virolainen, 1998). The arrangement encourages early strategic supplier engagement and recognises distinctive value. Blanchard (1990, p. 113) also promotes direct negotiation through the question: *"When a company is seeking to convert a concept or idea into a reality...why not get the best [firm] that is available?"* Once that vendor(s) is known, discussions can begin early, and eliminate much of the time and cost of the competitive bidding process. Blanchard (1990, p. 113) continues: *"administrative niceties have crept into the execution of projects...and are indicative that we may have lost sight of the real objective – to convert a concept...into a reality and to begin returning the investment as rapidly as possible".* Whichever mode is selected for supplier contracting, it should be subject to cost-benefit analysis, and risk of long term innovation and costs being sacrificed for expediency.

Terms & Conditions - Contractual terms and conditions (T&C) will largely be set by the governance model adopted, and with advice from project funding agencies. Nevertheless guidance can be drawn from documented experience generally, and also from many of the major contemporary science and engineering facility projects. Below are set out certain contractual aspects of particular relevance to high-tech mega-projects:

Penalties – While penalties are commonly applied to contracts at the general level, or against specific deliverables, some care is required with their construction. The nature of mega-science programs usually entails both design modifications and unexpected events that can cause delays which may (even inadvertently) trigger penalty clauses invoking liquidating damages within supply chains. Expert legal advisers are needed to draw up such clauses so as to reflect the collaborative nature of the contract, yet ensure retention of power to act in circumstances of supplier failure. Notably, T&Cs for the OPAL nuclear research project required that disputes are not permitted to delay delivery of contracted goods or services (OPAL, 2009).

Delivery Timing – Procurement programs will be based on project master plans that will almost certainly be amended over time. Contractual documents will therefore need to incorporate some avenue to adjust schedules of procured goods and services (particularly within 'just-in-time' arrangements). Failure to do this may lead to delivery of goods at incorrect project phases, causing delays or requiring storage, and resulting in cash flow problems from unsynchronised contractor billing.

Payment – Extended contracts will usually incorporate payment milestones. Ideally, payments should only be made against measurable, and tangible deliverables, or otherwise verifiable earned value (RAE, 2004).[23] Field interviews suggest that clawing back over-payments is a very management intensive task, and leads to breakdown of goodwill across the supplier base.

International Pricing – To facilitate proper competitive procurement, and ensure fair evaluation, contracts should require price offers to be in a single, universal currency. To enable this, a foreign exchange (FX) conversion methodology will be required, and directions given regarding the application of duties and tariffs. An alternative is to implement some form of project currency unit, with published FX rates for all project collaborator currencies.

Guarantee – Contracts stating or requiring guarantees against goods or services performance, delivery dates, or compliance need to be very explicit regarding the extent of the warranty issued, and remedies for failing to meet it. Compensation must not only include rectification of the fault or breakdown, but also any costs or associated effort on the part of the buyer's organisation to restore performance. In the case of large, high-tech mega-projects, systems and components may well approach or exceed their advertised warranty period prior to entering service. Procurement contracts should seek to delay the commencement of the warranty period until the goods are operational, or extend the period to cover any such delay.

[23] 'Earned value (EV) is the amount of money that should have been spent to produce what has been achieved – if a project is completely on target, EV will equal actual costs.' (RAE, 2004 p. 27)

Ethical standards – Not all countries and regions have equivalent ethical standards. These should be overtly stated in contractual documents and made clear in all dealings. This is especially important concerning hospitality, gift giving, and passing of information. It is not suggested that such policies should prohibit social customs or observance of business courtesies, merely that these customs be conducted openly, be of an acceptable scale, and transacted without prejudice.

Environmental awareness – The project may consider taking an official position on global impacts and environmental standards by incorporating a 'green' policy (as per GEMINI) into its procurement function. This could take the form of addressing issues such as anthropological climate change, landfill, and pollution through business policies concerning packaging, shipping-miles, favouring firms employing sustainable systems, and using fully electronic purchasing systems.

Subcontractor conditions – Contracts must address the topic of subcontracting, stating clearly the conditions and approvals required. (E.g. ESO's contractors require authorisation before subcontracting). Ideally, any subcontracts will be 'back-to-back' with the prime contract for all terms and conditions, and be especially clear on the requirement to mirror quality assurance and performance requirements fully down the supply chain e.g. CERN (LHC, 2009). Subcontractors must be identified within tender offers, and their credentials verified.

Intellectual Property (IP) – The management and treatment of foreground, background, and project generated IP and copyright material should be addressed through a project specific IP policy. This must take into account international legislation, and be known, practiced, and conveyed to suppliers through the procurement process. This is especially important to allay the tensions over IP ownership reported by industry when dealing with research institutions such as universities (Hertzfeld et al., 2006).

3.2.4.4 Contracting models

Various contracting arrangements are possible for SKA-like projects, and several models are shown in Appendix E, Figs. a-f (adapted and extended from Morris & Hough, 1986). The actual structural links between the project organisation and suppliers may vary over project phases, and in accordance with contract size, geographic spread of members, funding shares, and the legal entity structure.

The prime contractor–subcontractor relationships shown in Appendix E also embrace the concept of supply chains, where suppliers can usefully engage with SMEs to exploit niche capability.

Contractual relationships are unlikely to remain stable over the entire project, being subject to company buy-outs, change of key personnel, and even change of business focus. Procurement documentation needs to be contractually robust to ensure continuation of supply.

3.2.4.5 Ensuring competitiveness

High-tech mega-project acquisition both enables and benefits from market competitiveness framed by the strategic approaches described previously. However a cautionary note comes from Rendleman and Faulconer (2011, p. 13) who reason that, due to the skyrocketing value of aerospace contracts, the US government effectively fosters ‘death bids’ from firms who find *“it is better to be on contract and under bid than on the street”*, thus creating viability risk. Nevertheless, there is good experience for high-tech mega-projects to learn from, as presented in the project procurement policies and initiatives, as described below:

Pricing - The offered price for any good or service reflects the contractual risk involved, and is therefore to some extent influenced by the buyer’s policy. *“If the risk is large (say more than about 10%) the price becomes unnecessarily high, especially if there is no real competition*”, say Hall & Kahn (2006, p. 20). They further explain that if the risk is under-estimated, cost-cutting can ensue, thus working in a highly detrimental way for complex scientific projects, and most dangerous when the contract was won with an artificially low bid dependent on profit recovery through post-contract variations. These concerns are also voiced by Nicholas (2004) who describes ‘fixed price with determination’ to counter the tendencies described above. Blanchard (1990) posits that risk and contingency for uncertainty should not exceed 5% of the total expected cost for fixed price contracts.

Even under a stated ‘best value for money’ procurement approach, price remains a key discriminator among tender offers. This is true whether a competitive contract is ‘cost-plus reimbursable'[24], a fixed-price basis, or somewhere in-between. Since bidders will build contingency in their offers commensurate with their perception of the risk, each offered price will contain a combination of costs, profit margin, and risk money. In R&D type projects (e.g. aerospace) it is not uncommon for early contracts to be on a cost-reimbursable basis, and later production or site execution orders to be firm price contracts – the latter requiring much lower procurement management effort (Winch & Gil, 2010).

Fixed price contracts are most common in mega-projects (ESO, VLT, and LOFAR) generally, though Morris & Hough (1986, p. 217) argue they are *"clearly inappropriate in high risk situations,"* Contracts may incorporate financial incentives for achieving or exceeding defined project objectives e.g. delivery date, performance, etc. Damages may apply for failed performance, but as shown in the VISTA project, and in MoD reports, are not always effective (MoD, 2009). Buyer-driven changes in scope can be accommodated, but generally at a cost, with a premium value attached for any contract variations.

Cost reimbursable contracts involve payment to the contractor for legitimate expenses for completed work, plus a profit margin. Financial incentives may be applied. This type of contract is useful for flexibility in directing the contractor when the precise scope of work cannot be defined at the start, and may well be applicable to a mega-project environment. Moreover, some price certainty is possible with cost caps in place. Simplified cost reimbursable contracts are often useful for R&D work and are conducted on a 'time and materials' reimbursable basis using a pre-agreed schedule of fees.

Economic price adjustments, tied to a reliable financial index, are commonly applied to large project procurements that span a period of years. A special provision is included allowing for pre-defined changes to the contract price due to changed conditions e.g. inflation, exchange rate variation, or changed commodity values (e.g. CERN's Contract F template).

A novel approach taken by some large scale technical integrators is to take the stance of price-setter rather than price taker. Referencing Dell Computers as an example, Gans (2006) describes this method for modelling competition for orders prior to procurement negotiations. In this case the tender documents will include either (a) fixed price per item, or (b) a variable price per item based on quantities offered, or (c) a price cap representing the maximum price that will be paid, encouraging competition beneath that figure.

[24] Sometimes known as 'cost-plus', this is an arrangement where the contractor is compensated for all its costs (often based on an offered rate table) plus an agreed profit margin.

Split buying - For procurement of high quantity parts, split-buying offers the advantage of spreading the production risk over two or more suppliers. This can be appropriate in cases where each supplier indicates an individual production capability beneath that required by the project, and especially where sharing of tooling is practical. Apart from raising competitiveness, split-buying is also appropriate where the purchaser has a policy preference of not becoming the dominant or exclusive customer of the supplier. Counter to this, spreading a quantity order over too many suppliers will reduce any economies of scale.

COTS Purchasing - Another way to encourage competitiveness is to specify Commercial-off-the-Shelf (COTS) products (where possible) within tender documents. The GEMINI telescope project experience tells us that COTS products are always cheaper to acquire, support and upgrade, and are often available from several sources, sometimes via global channels (NRC, 1999).

Industry Consortia - To better understand and potentially service the needs of major high-technology projects, local or global industry consortia may be formed, either as regional (possibly government) initiatives, or encouraged by the project itself. Such teaming arrangements are usually beneficial in allowing industry to more efficiently work together to address mega-project needs, as well as spawn spin-off collaborations or opportunities to service adjacent markets.

Mega-projects should be alert to the formation of cartels, especially where there are restricted numbers of bidders. A cartel is a formal organisation of suppliers that agree to coordinate prices, marketing and production, and are anti-competitive. The EU's competition law explicitly forbids cartels and related practices in its article 81 of the Treaty of Rome. Long Term Partnering Arrangements (LPTAs) with key vendors offer strategic pathways for global procurement.

Broader Outcomes - Overlying project acquisition strategies for capability deployment, and application of *juste retour*, may modify price-based decisions in terms of allowing for the non-financial benefits of technology transfer and exploitation, and regional capacity building. The importance of this latter item is recognised for the SKA project, and explored and reported through a recent COST initiative (COST, 2010).

Value for money (VfM) comes from the effective, efficient and economic use of resources. Getting value for money means optimising the ratio between value and cost, and may be numerically or subjectively quantified (OGC, 2002). A VfM bid assessment not only provides lower overall cost benefits, but also the common ground for very different offers to be compared. The simplistic 'lowest price' criterion is unable to grant neither the lowest total cost of ownership (costs over the whole life cycle) nor project life performance. The VfM decision criteria must consider project quality and performance, in relation with other requirements including economic value, reliability, supportability, purchase risk, and price (Perna et al. 2009).

3.2.4.6 Procurement specifications

The purchase of products, materials, software, tooling, systems, and other tangible needs for complex high value projects requires focused attention on defining the specification. This can be done through (a) documented designs (blueprints), controlled engineering drawings and notes, prototype examples, and supplemented by part numbers; or (b) a detailed performance specification where the inputs, outputs, design constraints and tolerances are stated, but not the precise physical design. Both approaches are validated with test plans against performance criteria. In the former, the contractor will be expected to deliver an exact version in every respect to the designs provided. In the latter, the contractor has some latitude to develop and construct/create the item(s) as long as the performance criteria and design constraints are met. It is not uncommon for both approaches to exist within high-tech mega-projects.

Linked to this concept is the notion of manufacturability (or 'design for manufacture'). It is essential that designs intended for large scale production are developed with input from industrial experts so that contracts can be issued with the benefit of knowledge from practical production techniques and limitations. The procurement function has an important role facilitating this, as well as ensuring that industrial specifications are established and approved for fabrications – even when it is expected that accepted professional standards will apply. By way of illustration, a combination of ineffective chafing guards and an abundance of flammable materials contributed to the fire that killed three astronauts at Cape Canaveral, despite the contractor being a recognised and highly experienced aerospace firm (Young et al. (1969).

Another vital consideration is 'upgradeability' – the application of production expertise to ensure that future production runs can be modified to accommodate improvements in the design at low cost. A relatively small increase in the initial procurement cost may lead to great savings later. A procurement policy is also required to cover the specification requirements of professional services.

Contemporary cases offer useful advice. CERN commend flexibility and innovation in procurement, suggesting for example that sets of spares should be procured initial as part of the construction procurement to avoid potential commissioning delays. CERN's LHC project leader, Dr. Evans, expressed in interview: *"If a strategy doesn't work as planned because of unforeseeable conditions, you have to be prepared to change strategy. Be aware of possible 'grab and run' attitude by suppliers" (LHC, 2009).*

Australia's OPAL program mostly used a performance specification, and noted that a pre-solicitation 'scouting' process reduced cost and time overall. LOFAR experience from the Netherlands warns of underestimating the specification difficulties of mass production and systems integration. A general recommendation was that the combination of processes forming the leanest model that meets the requirements of the project is best adopted.

3.2.4.7 Procurement risk

The procurement process and fulfilment of the contract may be endangered by several kinds of risk as listed below, only some of which are within the provider's control (adapted from OGC, 2002, p13);

- Poorly drafted contracts
- Inadequate resources assigned to contract management
- Customer team not matched to the supplier team in terms of either skills or experience (or both)
- Wrong people put in place, leading to personality clashes
- Context, complexities and dependencies of contracts not well understood
- Failure to check supplier assumptions
- Unclear authorities or responsibilities relating to commercial decisions
- Lack of performance measurement or benchmarking by the buyer
- Focus on current arrangements rather than what is possible or the potential for improvement
- Failure to monitor and manage retained risks (statutory, political and commercial)
- Lack of supplier capacity, or scope creep beyond ability.

- Loss of supplier's key staff
- Change of supplier's business focus
- Financial insecurity and *force majeure.*

Risks are heightened by procurement itself, with a dependency on one or more external providers, leaving the buyer with reduced ability to command and manage variables (Schill, 1979). Even when a risk is notionally subrogated to the supplier it cannot be dismissed: "*transferred risks…cannot be forgotten about simply because the contract obliges the provider to deal with them. A key point is that business risk can never be transferred to the provider"* (OGC, 2002, p. 25)

In discussing advanced technology organisations, Schill (1979) specifies nine specific risk areas; concluding that high-tech procurement is especially prone to a wide risk front when requiring development of new materials, components, or equipment. He cites time overruns of some 180% and cost overruns of 200-300% on R&D Government contracts.

Risk of pre-competitive relationships (lock-out)
(adapted from Hall & Khan, 2006)

As a general principle, potential bidders should not be given foreknowledge of contractual requirements and it is good practice to avoid direct contact between contracting personnel and potential bidders once a purchase action has commenced. In high-tech mega-projects, this is not always easy, as there is often contact between project personnel and industry; nevertheless policies must be observed and a culture of internal discipline is required. Such a policy poses major problems for large scale, long term projects with considerable R&D, since public procurement rules are not always in sympathy with the specific needs of such projects.

An example is where a company is involved in an early (and vital) stage of the project there is a risk that the (potential) bidding firm might be excluded from subsequent participation precisely because of its prior knowledge (also known as 'lock-out'). This could mean exclusion of precisely those organisations that have specific relevant knowledge or skills from the early stages of a project. This situation creates difficulties for the strategic engagement potential for early involvement in multi-million Euro 'high-technology' projects (such as the SKA).

Another extreme example is when one of a number of potential bidders for a contract has already been given a contract for a prior phase of the work. The advantages are obvious and include a better understanding of what will be needed, reduced costs through familiarity of system interfaces, and the possibility of customer developed hardware.

However, it *is* possible to operate properly within the rules and still do what is technically and scientifically necessary (as shown by ‘real world’ examples) but it does require a lot of care, forethought and advance preparation regarding the procurement scheme.

In practice, the LOFAR project found success with software correlator development largely because of effective nurturing and management of industry collaboration with IBM (LOFAR, 2009). The ALMA radio telescope also features pre-competitive engagement with industry mostly via conventional contracts.

Some of the approaches that projects can take include:

- Crafting the legal entity, so that specialist contractors can be legally engaged.
- When placing a study or technology development contract, do this on the basis of a competition, thus providing a justification for continuing relations with the contractor.
- Assign the study or R & D work with provision for the results to be made available to all potential bidders for the main contract.
- Employ parallel competitive studies. These can sometimes produce better results, as well as justifying the further selection of one contractor, though cause added expense.
- Seek contractors for early stage work who do not have the capacity or desire to engage in large scale manufacture. A contractual condition can be that the contractor agrees to be available as a potential sub-contractor to any future potential main bidder.
- In extreme circumstances a developed technology that is regarded as vital can be treated either as customer furnished equipment or as an imposed sub-contract. This has the disadvantage that it entails considerable customer responsibility for the results.

3.2.4.8 Tender evaluations and contractor selection

The evaluation of potential contractors for public, high-tech mega-projects demands close attention, especially for high value prime contracts. Blanchard (1990) favours a two-stage process, pointing out that tendering imposes costs on all parties, and limiting the ‘full and final' offers to a few qualified firms narrows the choice and lifts the quality, though possibly results in higher prices. He suggests the compromise is to restrict tender invitations to four or five for very large projects, but no less than three.

Practitioners agree that effective contractor evaluation requires an approved, transparent procedure, and should be conducted against pre-determined criteria (Hall & Kahn, 2006). The application of the ISO 9000 Quality Management Systems has seen useful standardisation in this, and advocated for space satellite projects by Saunders et al., (2003). However while supporting the principle, Crosby (1996) calls for sensible application of such standards, particularly in the area of approved supplier lists, where completion of a questionnaire often falls well short of the intended diligence. Project Directorates should ensure that funding is allocated for an appropriate level of quality audit as well as technical compliance checking for each major procurement contract, and that this 'mission assurance' aspect is documented within tenders and acknowledged by bidding firms.

The process by which the main contractors for any high-tech mega-project are evaluated requires careful attention, transparency, and adherence. Appeals by dissatisfied vendors can absorb valuable resources, as can probity audits (ASKAP, 2010). Scrutiny of the much lauded Apollo program by Young et al., (1969) revealed falsehoods over the selection of North American as the first choice contractor (the fabricator of the fatal 012 capsule). The company's bid of $400 million was ultimately a ninth of the final sum paid.

A study undertaken by Watt et al. (2010, p. 59) contributes interesting data from 222 engineering project cases concerning the relative importance of tender selection criteria. Their research shows that: *"past project performance and technical expertise were of almost equal importance, but twice that of tendered cost. These, coupled with project management expertise contributed to a combined importance >85%"* of the nine measured criteria. Blanchard (1990, p. 47) concurs, saying: *"Nothing can replace the experience with suppliers as a determinant of the probability of on-time delivery"*. Experience from the GEMINI project recommends active checking of past work and competency, not simply relying on contractor assertions (NRC, 1999).

3.2.4.9 The purchaser-supplier relationship

A close partnership style relationship is crucial for publicly funded science/engineering procurement where economic benefits flowing to the community through contracts are viewed as equal success indicators to project outcomes. Nonetheless, the procurement activity must be impartial, formal, and transparent, and with the expectations of each party clear and actively managed.

In long term mega-project contracts, where interdependency between buyer and provider is inevitable, both parties have an interest in a fruitful relationship, though the profit motive must not be overlooked. The three key factors for success are trust, recognition of mutual aims, and communication (OGC, 2002). In discussing information flows in procurement, the UK Office of Government Commerce argue strongly for a change of paradigm in information sharing and suggest that fear of exposing the buyer's thinking, position, or concerns should be modified by adopting: *"a realistic balance between openness and reserving negotiating positions"* (OGC, 2002, p. 30).

The relationship between some suppliers and the project often begins at the project inception and early R&D phase where technologies and niche capabilities are being investigated, products tested, and experiments conducted. Companies (particularly large ones) are sometimes open to (or volunteer) early stage collaborations or other strategic synergies such as personnel exchanges, expert advice, or free/loaned tools and technology. The procurement department needs to be aware of these pre-contract arrangements to ensure that 'lock-out' situations don't develop (see section 3.2.4.7), and that such opportunities are agreed to fairly and are transparent to the industrial community.

Once contracts are awarded in the construction phase, the relationship between suppliers and the project must be formalised under a contractual framework that maintains this positive interaction and openness. This is especially vital concerning inspections and acceptance of work which lessons-learned from major high-tech projects suggest can be a defining point in procurement success. ESO asserts the right to inspect and verify goods anytime, whereas both ITER and CERN undertake planned inspections of work at suppliers (VISTA, 2010; CERN, 2009; ITER, 2009). OPAL participates in witnessing of hold points defined in test plans, and collaborates in commissioning (OPAL, 2009). LOFAR emphasise close relations with suppliers; using the process to guarantee quality (LOFAR, 2009). Their procedures include installing inspectors in suppliers' factories. CERN goes further, swapping inspectors between suppliers and choosing not to rely on ISO 9001 certification or supplier's QA records (CERN, 2009). However close and positive the relationship, the VISTA project found that contractors always need help regardless of any contract conditions (VISTA, 2010).

Another important aspect to supplier relationships is the amount of dependency involved, and a project policy decision is required regarding limitations to the size of order in respect to any given company's size or turnover. This decision will take account of the balance between desired level of reliance of the firm on the contract, and the buyer risk attached to highly geared contracts. CERN takes the standpoint of preferring not to be >20% of the supplier's business (CERN, 2009), while NASA (NASA, 2009c) promotes multiple suppliers as both a risk mitigation strategy and competition driver.

A point made strongly by the UK's National Audit Office report 'Improving Procurement' (NAO, 2004) is the need for sound client capability, particularly senior management leadership skills, and paying particular attention to enhancing key aspects of procurement capability. These are:

- raising commercial awareness, having better, more up to date management information particularly on current market prices
- more joint purchasing between departments, and more proactive management of suppliers
- managing the risk of relying on too small a number of suppliers for key commodities, and
- developing procurement expertise and better targeting of value-for- money improvements.

3.2.5 Recommendations and conclusions

In fast changing technological situations, effective acquisition strategies can help decrease risk, shorten lead times, reduce investments, and improved response to project needs. An informed, holistic approach to procurement can improve the effectiveness of the process, and underpin more productive and open relationships with suppliers. In particular, nine key strategies are suggested as being necessary in order to position the procurement function as a precursor for high-tech project success. These are shown in Table 3-1 above.

Competent procurement management is vital to the success of mega-projects, being both shaped, and the shaper of, the high-tech environment, and influencing how much R&D vendors do. Schill notes US Air Force Commander Schriever's comment: *"The pacing factor in acquiring technologically-based modern aerospace systems is <u>management</u>, not science and technology"* (Schill, 1979, p. 299).

3.3 Project shaping and building resilience[25]

In this section I argue that project success, unlike project planning, (Flyvbjerg et al., 2003) is not indeterminate by nature, and that undertaking certain activities, coupled with application of particular policies and launch conditions at the front end, positions a project for success and resilience. As Archibald (2003, p. 31) puts it: *"the seeds for success or failure are frequently sown in these early phases, but the outcome often is not known until the project nears completion."*

3.3.1 Introduction

Although the project management literature touches on success factors identified throughout this thesis, evidence of continued failure (e.g. Standish, 1995; Proccacino et al., 2002) indicates that a deeper examination of project practice is warranted. A recent task force report (ICCPM, 2011, p. 33) claims that: *"resilience is the reward for maintaining diversity within the PM system"*, referring to the tension between efficiency initiatives (Just in Time, Lean Systems, etc) and less vulnerable processes and practices. The aim of this section is to present research into nine areas that are shown to contribute to early stage project shaping, robustness and resilience. This section focuses on high-technology (hi-tech) mega-projects, and draws on both recent literature and fieldwork to distil a fuller understanding of the more subtle factors behind project success beyond the basic 'givens' of project structure, requirements, funding, tools, and plans.

Resilience is defined here as being akin to robustness in the sense of building strength and the ability to recover from, or adjust easily to, misfortune or change.

3.3.2 Study approach and methodology

In this section I draw from peer-reviewed papers, books and reports, largely published between 2000 and 2010. Discussions at relevant conferences and workshops offer further

[25] This section is drawn from the author's peer reviewed paper titled: Crosby, P. In print. (2012). Building resilience in large high-technology projects: front end conditioning for success, *Int'l Journal of Information Technology Project Management, 3*(4)**.** See Appendix K.

insights; in particular the topics of peripety, optimism, and mission assurance which were prominent at the 2010 NASA Project Management Challenge, an annual best practice networking event.

As described in section 1.3.2, I also undertook research into mega-project management at several large scientific projects in Europe, Chile, South Africa, and Australia. These projects typically have specialised infrastructure, > US$100 million budget, and a science goal concerned with astro, particle, or nuclear physics. I conducted formal interviews with project management representatives, each typically lasting 3-5 hours and loosely structured to permit the gathering of salient learning aspects from each case. The fieldwork study list is shown in Table 1-1. Following comparative analysis of themes and trends, the data gathered enabled the lived experience of project practitioners to be benchmarked against the literature sources.

This research effort focuses on eliciting resilience factors beyond *a priori* programmatical processes, resources and artefacts (such as execution plans, project funding, Work Breakdown Structures, etc.). The findings are grouped into three 'attitudinal' factors, and six 'conditioning' factors described in Sections 3.3.3 and 3.3.4 respectively, and defined as 'special' factors to distinguish them from traditional programmatical factors. Attitudinal factors are those which require an intellectual stance or approach, whereas conditional factors are realised through purposeful activity.

Finally, having resolved these 'special' resilience factors, they are examined empirically against three contemporary mega-science cases in section 3.3.5, and the findings used to inform the conclusions of this thesis.

3.3.3. Attitudinal project shaping

3.3.3.1. Balancing enthusiasm with realism.

A necessary component of any high-tech project funding bid is the enthusiastic belief by the protagonist(s) that it can be executed on time, on budget. This often leads to inaccurate estimates, most disappointing when over-selling is used to win favour with funders. Grün (2004) talks of project proponents, project managers, contractors, and planning experts who may form 'over-optimism-coalitions'. He further defines over-optimism (p. 41) as the:

"tendency to underestimate the difficulties of achieving the technical goals… the operation & maintenance costs, and the costs caused by the changing of technical goals."

Evidence of optimism is not hard to find. A lessons-learned workshop from the Gemini telescope project revealed that the effects of science drivers on cost and schedule led to overly optimistic estimates, resulting in a 300% over-budget in one instrument (NRC, 1999). Observations in a radio astronomy technology White Paper describe overly optimistic cost and development time estimates as the most frequent cause of project de-scoping (Fisher, 2010) – the JWST being the latest gross example (Siegel, 2011). In the early 1980s, a four nation Euro-consortium announced the commencement of the Eurofighter jet, expected to cost $20 billion and be flying by 1997. After 20 years of technical problems and unexpected costs, project costs had risen to $45 billion by 2003 (Lovallo & Kahneman, 2003), with production aircraft not delivered until 2008. A recent UK defence report lamenting a £205 million cost increase over 20 projects admitted: *that "on far too many projects, the Department is over-optimistic and sets unachievable cost, time and performance objectives"* (MoD, 2009, p. 5). The procurement function can be similarly affected, with aerospace acquisition failures linked to overly ambitious technical readiness and resources estimates, as reported by Rendleman and Faulconer (2011).

The cost-schedule paradox is a formidable enemy. A US Defense Acquisition office investigation concluded that once past 15%, an over-budget program is 'highly unlikely' to recover original projections and the final overrun will get worse (Butts & Linton, 2009). Over-optimistic budget and schedule expectations are shown to inhibit project success, and are especially likely on projects with institutional difficulties (Murphy et al., 1974). IT projects appear to be especially vulnerable (Verner & Cerpa, 2005).

NASA officials, seeking to boost congressional support, sought to emphasise the Space Shuttle's apparent low development cost. Such optimism proved flawed, as the program encountered delays of three years and cost overruns of 60% prior to its first mission loss in 1986 (Shenhar & Dvir, 2007). When interviewed, NASA Director, George Morrow asserted: *"a major pitfall is being overly optimistic early in the project lifecycle."* (NASA, 2009a, p. 31).

Lovallo and Kahneman (2003) investigated this planning fallacy that leads managers to make decisions founded on delusional optimism, and attribute the phenomenon to two sources - cognitive biases, and organisational pressures. The former exhibits itself in a general tendency by people to be optimistic, to overestimate benefits while overlooking the potential for error or mistakes, and to underestimate levels of control. Why is this so? Lovallo and Kahneman (2003, p. 4) reason that:

> *"The cognitive biases that produce overoptimism are compounded by the limits of human imagination. No matter how detailed, the business scenarios used in planning are generally inadequate. Any complex project is subject to myriad problems—from technology failures to shifts in exchange rates to bad weather—and it is beyond the reach of the human imagination to foresee all of them at the outset. As a result, scenario planning can seriously understate the probability of things going awry."*

Organisational pressures are felt in every project, and are accentuated in the high-tech, high-risk ventures discussed in this thesis. As project budgets rise to reflect ever-growing challenges, so competition for contracts (ICCPM, 2011), money, and other resources becomes intense (whether from the public or private purse) and pressure to remain within cost-caps increases. This results in a cost-risk paradox where the project with the highest likelihood of budget failure (because of budget tightness) is chosen for investment. Yet the tendency to understate has always pervaded the institutional high-tech project world, as evidenced in a quotation from engineer and astronomer Robert Hanbury Brown in 1987: *"In my experience most major programs of scientific research would never have got started if the people who proposed them had not greatly underestimated the cost, time and amount of work involved"* (Robertson, 1992, p. 132). Hanbury Brown's comment reveals a further source of inherent optimism – the belief that project funding will continue unchecked, simply due to institutionalised resistance to closing a project mid-term. Thomson et al. (2011 p. 5) concur, finding a tendency in military equipment projects to respond to overruns: *"by delaying the project rather than cancelling it, thereby rewarding the optimism bias."*

How then might we recalibrate our thinking without losing the all-important project enthusiasm? Blanchard (1990) claims objectivity may be the only defence against the snowballing effect of eagerness, and suggests that, as a balancing process, project proponents should also develop a case for not proceeding. Research shown by Lovallo and Kahneman (2003) supports this stance, arguing that an 'outside view' (sometimes called reference-class forecasting), insulated from cognitive bias, is essential. Realistic estimates and plans (i.e. neither optimistic nor pessimistic) would seem a correct approach, but Erno-Kjolhede (2000) argues that this could lead to project participants failing to innovate, and result in second-best performance. He recommends a tone of 'highly ambitious', or 'challenging' planning, driving stretch goals underpinned by factual data. Flyvbjerg et al. (2003) strongly support cost estimates accompanied by a risk analysis of future cost regimes, thereby offering a realistic view to curb against 'appraisal optimism'. The Acquisitions Defence RUSI Group offers practical advice to break the 'conspiracy of optimism' including transparency, realism, de-risk programs and interfaces, and ultimately consider cancelling programs (Weston, 2007).

Butts & Linton (2009) who investigated NASA's cost estimation performance, conclude that undershooting cost and schedule projections is a well verified NASA phenomenon, being rooted in an historical practice of over-optimism. In response, their report introduces a hybrid model (the '*Joint Confidence Level - Probabilistic Calculator', JCL-PC*) for accurately estimating cost and schedule reality in complex science and engineering environments where maturing technologies are present. The adoption of sophisticated cost tools (e.g. the Square Kilometre Array Cost Engine), managed by trained and experienced project personnel, perhaps heralds a maturing attitude to cost realism.

3.3.3.2. Checking for relevant lessons learned

The value of recording lessons learned from past projects, and the investigation of experiences from like-projects during early stage high-tech project planning, seems obvious. However casework and the literature reveal little effort is applied to these valuable activities. Many of the facilities investigated for this study almost totally relied on the collective experiences of project staff and management rather than any formal survey of analogous projects, thereby failing to learn of others' mistakes (ALMA, 2010; ASTRON, 2010; CSIRO, 2009).

Authors consistently promote the need to learn from project experience, and cite this as vital for continuous improvement as well as evidence of project management maturity (Cao & Hoffman, 2010; Verner & Cerpa, 2005; Cooke-Davies, 2002b; Kerzner, 1998; Williams, 2004; PMI, 2008; Fisher, 2010). Disterer (2002, p. 512) concludes: "*only a few firms manage systematically to identify and transfer valuable knowledge from projects to following projects [so that people can] apply it to future tasks*". Smith & Winter (2010) directly link 'front-end' management with project success and promote the idea of deliberately exploring insights and implications flowing from past project perspectives, and crafting appropriate action responses.

Formal lessons learned capture mechanisms are needed to avoid 'project amnesia', including knowledge management systems. Schindler & Eppler (2003, p. 223) suggest methods for learning from experience and cite the Boeing approach of applying the results of past project investigations, thus delivering: *"the most successful and error free market launches... accomplished in the history of Boeing"*. Industry are more adept at systems to capture and retrieve previous learnings, experience put to great use in lowering costs in orbital satellite projects (TOPSAT, 2010).

Within organisations, project staff have opportunities to learn and reuse lessons (Davies & Hobday, 2005), and post-mortem results can be stored within knowledge systems, or communicated directly to other teams (Collier et al., 1996). Mapping techniques that show chains of causality are useful in transferring lessons-learned to other projects (Williams, 2004). For the high-tech planner in single project organisations effort is required to access and locate such learnings (CSIRO, 2009). Schalken et al. (2006) address this problem with a (highly qualified) method based on Grounded Theory to deal with qualitative information from project reviews. An alternative is to access public databases such as NASA's Engineering Network (NASA, 2010b), and the Software Program Manager's Network (SPMN, 2010). Whatever method is used, lessons-learned and wisdom applied from analogous projects is concluded to be a vital, though largely underused, project success factor.[26]

3.3.3.3 Embracing complexity, ambiguity and uncertainty

High-tech mega-projects are characterised by risk, complexity, ambiguity and uncertainty, not just related to technology, but introduced via multiple collaborative parties, and often a dispersed infrastructure. At project start-up, uncertainty surrounds performance levels, objectives and motivations, capabilities, stakeholder expectations, and political environments. Knight's classic work (1921) distinguishes between economic risk where the outcomes were unknown but governed by probability distributions, and uncertainty where the outcomes were likewise random, but governed by an unknown probability model.

High-tech mega-projects are always complicated, and almost always (by adding uncertainty) complex. Not only through the abundance of programmatic interfaces, but also because of the interactions between systems. Complex systems as understood in the contemporary sense are testing of management (Crosby, 2012a), and have an inherent level of unpredictability (Pavlak, 2004a; Miller & Lessard, 2000). Grasping this complexity, and preparing the

[26] This topic is addressed in more detail in section 5.3.5.

project for it, demands early stage agile and adaptive management (Shenhar & Dvir, 2007). To respond strategically, project management will likely develop more than one (possibly several) management strategies (Crosby, 2006; Pich et al., 2002), before down-selecting the final way forward. Beinhocker (1997, p. 8) supports this approach, saying: *"In a complex adaptive system, a focused strategy…is necessary for day-to-day survival, but [is] not sufficient in the long run…strategies must be robust [and] perform well in a variety of possible future environments"*. Thus project shaping is as much about keeping options open, as about trouble-proofing.

Traditional project management practice as outlined in the Project Management Bodies of Knowledge (PMBOKs) applies a rational probability-based approach to management, but is poorly equipped to deal with project uncertainty (Pender, 2001). Atkinson et al. (2006) characterise uncertainty as the incompleteness of information, a normal situation for early stage high-tech projects that requires tolerance from development teams, and may only be mitigated by trust in management.

The early stages of R&D (high-tech) projects are dominated by long periods of ambiguity where solutions (and even problems) are not clear and where change is incremental. There follows a short period of peripety (Engwall & Westling (2001), where one solution (or a set of solutions) becomes the obvious candidate as the legitimate path forward. Peripety is a turn of events leading to cognitive transition from ambiguousness into a less daunting state of uncertainty, often recalled as a time when real achievement occurred. It is not simply a change of fortune, but a change of understanding of all that has gone before (Smith & Winter, 2010).

In dealing with uncertainty, Smith (2007) invokes the pragmatic skills of 'ProjectCraft' starting with uncertainty spotting, and alerts the project manager not to delegate this to risk managers. He suggests we pose the critical questions: are we confident in our assumptions, and if wrong, could the impact be serious? Moreover he supports uncertainty workshops, stating that (p. 134): *"we must spot the potential frauds, and shake the tree to find out what is not secure"*. However the fieldwork for this thesis suggests that such analysis is rare.

Based on the literature and casework, high-tech project managers can lift confidence by addressing ambiguity through preliminary studies (e.g. pathfinders) and by using new knowledge to improve sense-making and thus refine the way forward. When interviewed, TOPSAT's project leader claimed that: *"our US$250K prototype was crucial in proving feasibility, and this success meant a lift in morale – we believed it could actually be done"*

(TOPSAT, 2010). LOFAR's Technical Support Manager (N. Ebbendorf) described prototyping more bluntly: *"So painful, it was worth it"* (LOFAR, 2009). Engwall and Westling, (2001) posit that uncertainty can only be reduced by acquiring necessary information through explicit questions, while Denyer and Kutsch (PMI, 2011) find that leaders of resilient organisations are able see the big picture, while concentrating on single operational issues.

3.3.4. Launch conditioning

3.3.4.1. Project mission & success definition

While the setting of time and budget limits at project commencement is problematic (Bakker et al., 2010), no project should start without at least a broad objective(s) aligned to stakeholder expectations and priorities. The IPMA Project Manager's BoK (Caupin et al., 2006) list objectives, mission, and project charter in its start-up guidance. However Atkinson et al. (2006) warn readers of 'premature definition' based on insufficiently defined specifications, especially in novel, one-off high-tech projects. Having a well-defined project mission was ranked #1 in the project definition stage by Hyvari (2006), and ranked #2 in a recent meta-study of high-tech project success drivers (Crosby, 2012b). When linking success to project types (including high-tech), Shenhar & Wideman (1996, p. 9) assert: *"As part of every project's front-end planning...agreement should be reached on the project's principal success criteria having regard to its project type"*. In software projects, Verner & Cerpa (2005) found that the start of a project offers greatest chance of quality improvement through better requirements setting. O'Brochta (2002, p. 1) draws on CIA technical project experience to conclude that: *"the earliest phases of the project life cycle have the most dramatic impact upon the odds that projects will be viewed as successful"*. Shenhar & Dvir (2007) strongly support project success measures to be integrated with planning at project initiation, and suggesting inclusion into the project team's charter.

The fieldwork findings I undertook for this research agreed that statements around the mission and science goals were often established early (driven by funding applications and collaboration approaches), but project success definitions were less obvious in early planning (ITER, 2009; CSIRO, 2008; VISTA, 2010), although in hindsight were considered useful.

3.3.4.2 Reporting and decision-making policies and structures

A common characteristic of large high-tech projects is the distributed nature of the technical and governance committees. In the commercial world this is evident through strategically located research nodes (e.g. Boeing's virtual PhantomWorks) and global procurement management. Institutional mega-projects frequently assemble executive and technical committees from world-wide nominations, and from a third stakeholder group – the funding agencies which pay for, but do not benefit from, the project output (Khang & Moe, 2008). This coming together of diverse people and interests to achieve a common purpose requires perceived and actual distances to be overcome, and responsibility to be shared (Aronson et al., 2010). Ideally, all this happens in a spirit of effective communication and coordination, active participation, trust, and common expectations (Samuel, 2009; NRC, 1999).

Such challenges prove difficult to meet in practice. Interviews I conducted within several of my case studies exposed tensions where operative project managers felt frustrated by a lack of decision or feedback on project shaping proposals (ASKAP, 2010; DESY, 2009; SKA, 2010). Project staff also reported irritation when committees made pronouncements or aired concerns regarding matters considered outside their remit, especially when related to early stage technology selection, and several interviewees thought their committees were too large to work effectively (DESY, 2009; SKA, 2010; LOFAR, 2009). Similarly, an independent review reporting on the ASKAP project cited the frustration of several interviewees concerning delays and confusion around decisions (Schoening, 2009).

Davies & Hobday (2005, p. 261) write: *"Different organisational cultures, problems in contractual relations and the need to integrate different domains of knowledge make collaborative projects very difficult to execute."* Recent European Government reports addressing start-ups of science infrastructures emphasise the need for clear decision-making processes with one body/person having final say (European Commission, 2010; Katsanevas et al., 2009); the latter rejecting a 50:50 sharing of decision-making (e.g. ALMA) as ineffective. Lessons learnt from the ASPERA report encourage early formation of a Management Board, supported by a core management group, interlocked to the researchers and administration through a clear (documented) decision-making and reporting hierarchy.

A frequent point raised incidentally during casework interviews for the present study was around poor understanding of decisions taken at upper levels in project organisations. Hector et al. (2009) describes such 'natural decision-making' as second-generation behavioural theory. This describes the process by which people actually make decisions amid uncertainty, and shows them to be strongly influenced by personal beliefs and values, thereby often defying logical analysis and emphasising an imperfect process.

Decision-making theory, founded on the concept of rational causality is a frequent feature within both project management and management science. Until the 1940s, decision theorists focused on how decisions should be made, rather than understanding the process itself. (Hector et al., 2009) discuss how actual behaviour was observed to be markedly different to theoretically predicted behaviour, and how these normative approaches (such as game theory and Bernoulli's notion of utility) have more recently evolved into behavioural decision theory. This emerged from the work, among others, of Herbert Simon (Hector et al., 2009) whose theory of bounded rationality places limits on human decision-making by virtue of finite time, information, and cognitive capability, thus restricting optimal choices. Remington (2011) describes work by experimental psychologists that finds that humans violate the basic logic of decision-theory, i.e. choosing among alternatives to realise an optimal outcome. She points to developments in neuroscience that are revealing greater understanding of how the brain integrates complex information in conditions of uncertainty.

Complexity is sometimes seen as a mere series of first order problems in a reductionist attempt to simplify tasks and get on with the job. This loss of granularity of information, creates side effects which can undermine decisions. A report by ICCPM (2011) finds efforts to reduce the 'noise' of extraneous information can mask many of the complex system's vital emergent properties, leading to decision-making on the basis of pre-existing belief rather than empirical evidence, and so losing the opportunity to learn lessons from the mistakes.

A review of decision-making in the (now cancelled) NASA Constellation program found that it can only be as efficient as the roles, responsibilities and authorities are clear and understood. Investigations revealed unilateral changes (including the deletion of a test flight) were rife at project start-up, and things only improved once the program integration function was operational. However in spite of attention by top management, the decision-making process remained problematic due to poor delineation of accountability and loss of multi-decadal focus, often leaving certain stakeholders dissatisfied. The lesson learned by NASA was to clearly define decision-making processes, and support this with constant vigilance, time and energy to maintain currency and comprehensive control (Rhatigan, 2011).

In establishing clear reporting and decision-making, top management can either help or hinder a project. Several authors (Hayfield, 1985; Baker et al., 1988; Rubenstein et al., 1976; Procaccino et al., 2002) give some emphasis to the negative effects of too much management, citing ‘interference’ and ‘meddling’. Conversely, fieldwork revealed protracted decisions as the only real complaint of management efficacy, with only the (German) XFEL project identifying the need for total management restructure (DESY, 2009).

3.3.4.3. Project information control

Large projects generate a vast amount of information. Much of this, especially the formal project procedures, plans, and records, is usually documented and organised within some form of centralised Project Management Information System (PMIS). Computer based PMIS not only store large amounts of data, but can intelligently manage, sort, back-up and report, timely (sometimes predictive) information of immediate use to managers. Most importantly for high-tech mega-projects, modern packages will integrate complex data relationships between scheduling and network planning, resource management, budgeting, cost control and performance analysis, and risk burn (Nicholas, 2004). As NASA has found, the ability of current technologies to deliver precise information exactly when needed is still imperfect (NASA, 2010a), however it clearly makes sense to establish a PMIS of appropriate scale and capability early, and enforce its use. Scott Samuelson from the US National Ignition Facility (NIF) believes effective project oversight actually revolves around access to current relevant data, saying: *“I got lots of numbers and pieces of paper [showing] whether milestones were being met. That’s all good. But it’s the ability to determine whether...what you’re seeing matches what’s really going on”* (NASA, 2011b, p. 58).

Case interviews (CSIRO, 2008; ASTRON, 2009; DESY, 2009; ALMA, 2007) show that the discipline required to create, register and link all relevant project documentation within a controlled environment is rarely maintained outside of externally audited (usually industrial) projects. Observations during fieldwork show a mixed attitude to centralising plans and data, with personal storage practices representing the highest risk. An independent gap analysis of one of my case study projects (ASKAP) identified the ‘sketchy’ understanding of each IPT status between project teams as the most significant finding (Shoening, 2009). This lack of inter-project communication is shown as being a serious flaw, since conflicting demands are not resolved – simply because they are not raised. Moreover, ASKAP managers are reported as unable to obtain timely information about budgets, and effort expended by work package.

Of at least equal significance to the successful project execution is the abundance of information exchanges that take place around the project, internally and externally, and often not noted or recorded centrally. Added to this, is project publicity through (often worldwide) science and engineering meetings, and project brochures – all aimed at maintaining the necessary high profile (CSIRO, 2008). Information traffic flow includes face-to-face meetings and conferences, telephone and video meetings, emails and presentations, each sometimes involving arms-length groups.

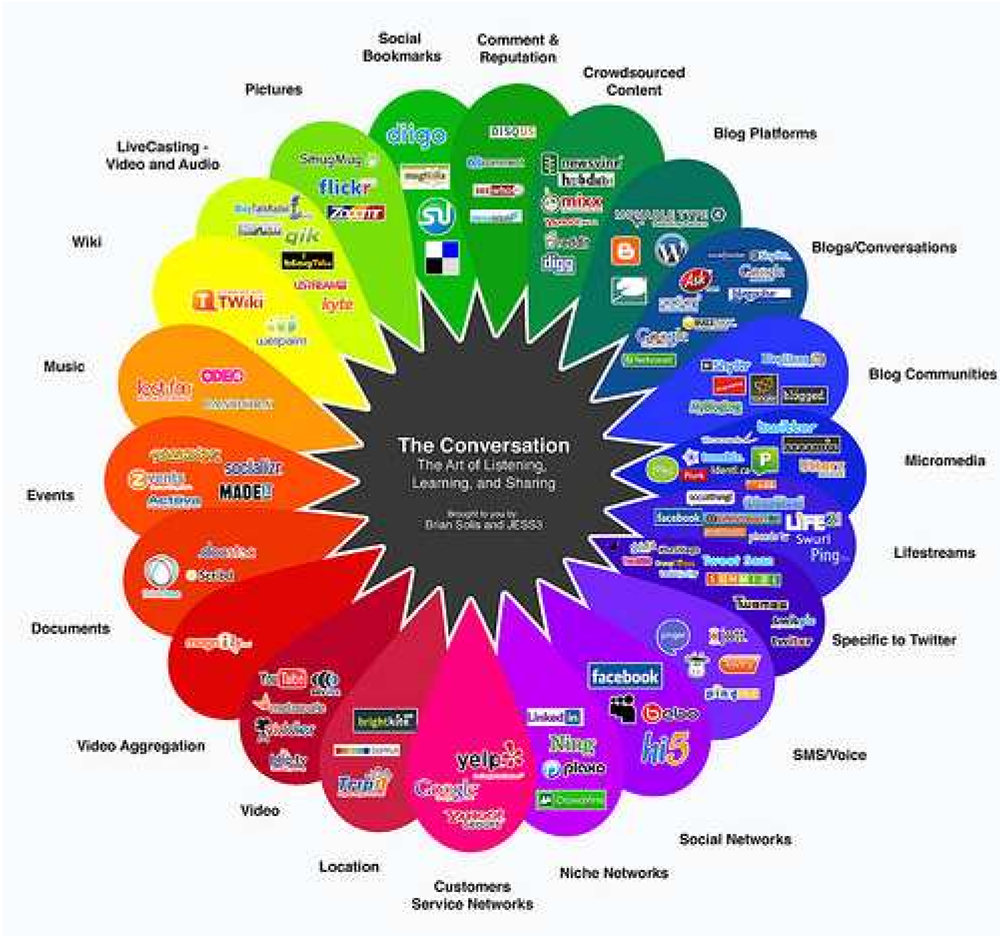


Fig. 3-7. Showing the social media Universe as at early 2011 (source: http://www.theconversationprism.com/)

The plethora of channels now used between individuals and groups (fostered by mobile communication services and devices) is daunting in terms of choice and management, and requires strong management (see Fig. 3-7).

As the project community grows through the conception stage through to execution, the risk of misalignment of working group effort, misunderstandings of priorities and changes, and misinformation to external parties grows accordingly. Moreover, exercising weak control over these 'satellite' information channels leaves aspects of the project imperfectly recorded, leading to inefficient external reviews and limiting the usefulness of central repositories as stores of lessons learned (CSIRO, 2007-2009; HIPER, 2010). Archibald (2003, 2009) identifies that customer demands, or other external stakeholders (e.g. joint venture partners) may require integration of corporate project data beyond the core programmatic metrics. An effective PMIS must be capable of linking and displaying this extended information set, especially time-related resource data.

How should early phase project managers address this situation? Implementing a project management framework based on an accepted professional guideline (e.g. PMBOK® Guide) may go some way to instilling the required practices. Similarly, implementing a certified (independently audited) management system (e.g. ISO 9001) will demand compliance with organisational procedures designed to apply control of information flows, as well as instigate corrective and preventive action for process failures.

In NASA's Constellation program, communications bandwidth was broadened considerably through two initiatives. First, 'Communities of Practice' were formed to aid communication flows in particular technical areas. Second, IT tools such as Webex, LifeSize, ICE/Windchill were used extensively to enhance information flow (Rhatigan, 2011). Communication is seen as a vital component of change management in IT projects. A British Computer Society (2006, p. 58) report puts the case succinctly as:

> *"Not only does it allow change procedures to happen smoothly, it helps trigger change by effective communication networks that encourage two-way communication about the project goals, and innovative proposals and actions to meet these objectives. It helps all of the stakeholders understand the changes that are being implemented, regardless of whether these changes are within the project, or in the macro environment."*

In this study I conclude that the most effective means of establishing a disciplined information controlled environment is to introduce it early, drive it through management example, and most importantly, dedicate resources to maintaining it. In its most mature form, this might involve a Project Information Office (PIO) as central controllers of project information, documents and data (i.e. the PMIS); and holding responsibility for arranging and recording meetings and teleconferences, moderating official on-line networks, wikis, and blog sites, and managing communication outputs. The PIO would hold authority for approval and recognition of any satellite group information needs, including the use of project templates, branding, intellectual property (IP), and single point management media interfaces. Clearly, the adoption of such a concept represents a radical move towards the industrial mode for most mega-science projects, and possibly requires a staged introduction.

As an example, the early phase UK HIPER project is already benefiting from a distinct Work Package entitled Public Relations and Communications.

Experience from the LOFAR project suggests that extensive formalisation (PIO-style) early in the project was viewed unfavourably (ASTRON, 2010). However the increasing drive for industrial class high-tech mega-projects (as opposed to technical institution models) is demanding greater rigour from the institutional sector. When interviewed, a LOFAR senior manager suggested that a balance might be struck by providing a Wiki-type document environment where early stage documents and concepts from scientists and engineers can be assimilated less formally (LOFAR, 2011).

3.3.4.4. Risk, contingency and descopes

High-tech projects have inherent risk as a consequence of their raison d'être, and higher risks must be consistent with higher contingency (Fisher, 2010). A common approach to dealing with project execution risk (seen in each of the fieldwork case studies) is a register type tool using a rating system to score anticipated risk based on the likelihood and consequences of the defined event occurring (British Computer Society, 2006; GMT, 2011; ASKAP, 2010). Residual risk is assessed after controls are considered. Management decisions are then taken to accept, mitigate, or remove those risks. Conventional approaches to risk assessment (e.g. cause/likelihood matrices) are somewhat problematic because of the perception that resilience has been instilled to deal with all unexpected events (Pender, 2001), whereas it is actually most reliant on experiential hindsight as a risk predictor. Furthermore, most attention is applied to technical risk; largely ignoring emerging environmental, social, and political risks that are just as important in terms of project success (ICCP, 2011).

Nevertheless, the approach is reasonably effective at the project start-up for the *known knowns* and *unknown knowns*, but takes little account of the *unknown unknowns*[27] – events, circumstances or outcomes that are invisible to the project, yet almost certainly will arise and are often 'outside the rulebook' (PMI, 2011)[28]. Placing the full possibilities in matrix form (Fig. 3-8), we can see that even in the absence of data or effective modelling techniques,

[27] *"There are known knowns; the things we know that we know. There are known unknowns; the things that we know we don't know. There are also unknown unknowns; the things we do not know we don't know."* Donald Rumsfeld, former U.S. Secretary of Defence, Brussels, Belgium, 2002.
[28] Recent project management jargon terms these as 'Black Swans' (ABC, 2011; Zurich, 2010)

strategies are available to at least play out scenarios for better understanding and preparedness.

	Data exists	Data do not exist
Modeling possible	**Known knowns** • Dynamic system theory • Network analysis	**Unknown knowns** • Simulation • Monte Carlo exercises
Modeling not possible	**Known unknowns** • Statistical techniques	**Unknown unknowns** • Imagination • Scenario analysis

Fig. 3-8. Options for analysis of known-unknown event combinations (Zurich, 2010, p. 13)

Work in NASA by Saunders et al., (2003, p. 369) shows that: *"all development programs will encounter unforeseen events and problems"*. One Boeing expert asserts that risk management works well provided we can foresee the risk. Unfortunately, unforeseen bad things happen (Schoening, 2009). Howell et al. (2009) link 'consequences' to risk by asserting that extreme uncertainty (chaos) equates to a 100% probability of an unexpected event.

Geraldi et al. (2010, p. 548) contend that in projects: *"it is not a question of if, but when, unexpected events will emerge"*. These perturbations may include transactional issues such as exchange rate fluctuations, market changes etc. (Nicholas, 2004). Miller & Lessard (2000) report that, on average, projects encountered five unexpected events in the formative stages and some were confronted with as many as 12. The ALMA telescope gas energy supply interruption being one example where an early assumption appeared fully reliable, only to be unexpectedly revoked.

The American approach, epitomised in NASA's Space Flight Program and Project Management Handbook (NASA, 2010b), is to derive a budget contingency against risks, including unknown unknowns, identified through integrated risk analysis. This contingency is part of the cost baseline and is separate from the management reserves for unknowns. NASA's codified processes offer the project manager several choices for managing funding reserves (a) allocate the reserve to specific subsystems and subprojects (b) hold the entire reserve at the project level but allocate it for troubled subsystems, or (c) embed the reserves in the project estimates, based on risk quantification (Rendleman & Faulconer, 2011).

As an example, NASA's Mars Pathfinder allowed for 40% of project budget to be kept as contingency against the: *"inevitable surprises and adjustments the ambitious new technology program would bring"* (NASA, 2011b, p. 26). Every element of the project was cost-capped, with no extra funds to draw on if they overspent. But even NASA can get it wrong as shown in the case of the JWST where Siegel (2011, p. 7) reports: *"the mismanagement was primarily not keeping enough cash-on-hand to deal with unexpected issues when they came up"*.

NASA's System Engineering Handbook (NASA, 2007a) comprehensively deals with processes to identify and manage risk in high-tech projects. NASA's methodology introduces risk scenarios that, along with consequences, likelihoods, and associated uncertainties, make up the complete risk triplet (with total risk as a set of triplets-scenarios). The triplet concept (see Fig. 3-9) applies in principle to all risk types, and includes the information needed for quantifying simpler measures, such as expected consequences.

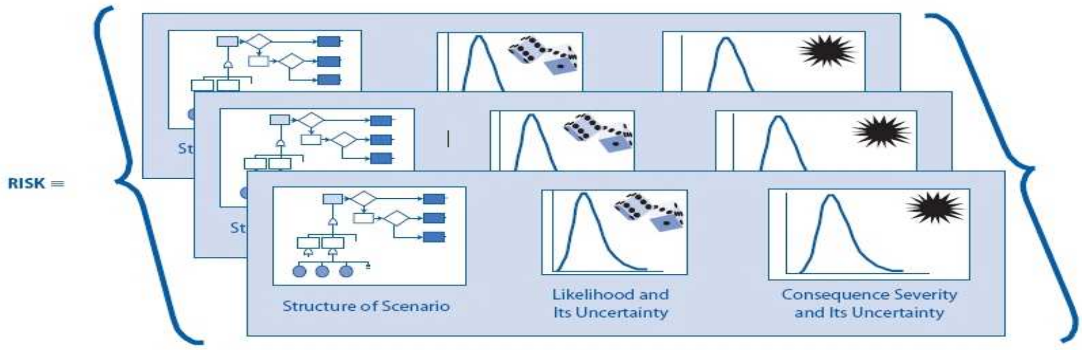


Fig. 3-9. Total high-tech project risk expressed as a set of triplets (NASA, 2007a p. 141)

If the substantive risk to the project is unknown, how might we deal with it at the project formative stage? This study suggests a dual response: applied contingency, and threat readiness.

Project contingency (rather than specific threat contingency) includes those external factors or events that cannot yet be pinpointed but will seriously jeopardise the project when they materialise. However quantifying contingency is non-trivial. The PMBOK® Guide mentions reserves and contingency but not how they are computed or applied within the project (Pender, 2001). Nicholas (2004) offers a calculator and further suggests an overrun allowance in some circumstances. NASA has developed the '*Joint Confidence Level – Probabilistic Calculator (JCL-PC)* founded on the hypothesis that a project's early phases hold many unknown risks (Butts & Linton, 2009). The GMT project takes the lowest level of the WBS to estimate contingency values, claiming this is the most effective method (GMT, 2010).

The US Department of Energy's Cost Estimating Guide (DOE, 2011) also ties contingency and management reserves to specific project confidence levels of 70-90% based on (but not limited to) risk assumptions, complexity, and project size. In their model, quantitative methods are used to objectively analyse project contingency, through an aggregation of probability and consequences of individual risk. Risk analysis of budget and schedule uses statistical modelling techniques such as Monte Carlo simulation, sensitivity simulations, influence diagrams, decision trees, and other stochastic methodologies. The results are used to establish the cost and schedule contingency for the required confidence level. Each risk is assigned a probability, each cost impact is attributed a dollar amount, and each activity is given a schedule impact. The concept is expressed as the equation below *(source: DOE, 2011, p. 51)*:

$$\mathrm{EV} = \sum \mathrm{P_{Ri}} \times \mathrm{CI_{Ri}} \ \ (\mathrm{or\ SI_{Ri}}) \qquad [3\text{-}1]$$

Where: EV = Expected value of cost impact (or duration impact) of all risks[29]

P_{Ri} = Probability distribution function of a risk occurrence

CI_{Ri} = Cost impact distribution function of a risk occurrence

SI_{Ri} = Schedule impact distribution function of a risk occurrence

For the Project Manager, the potential problem with the quantitative method above is the possible errors in the underlying assumptions, and careful analysis and testing is required for validation. Inaccurate estimates of underpinning qualitative scores (i.e. for risk impact or likelihood) will give erroneous outputs leading to incorrect values of contingency and confidence levels. It should also be clear that the unknown unknowns are not taken into account, and appropriate allowances will need to be estimated for unexpected threats from outside the project.

Whatever approach is applied, early budgeting for appropriate (cash) reserves is clearly indicated as one strategy for resilience, and reserves ranging from 20% - 25% (Fellows &

[29] Note that $\sum$ is not the summation of individual expected values for each risk, but represents a stochastic process (e.g., Monte Carlo simulation) using the collective probabilities and cost/schedule impacts for all identified risk events, and can be usefully expressed in graphic form (e.g. a bar chart) by a probability distribution function.

Alexander, 2010; JPL, 2010) upwards to 50% - 100% (NASA, 2009; ASKAP, 2009) are not considered unrealistic in the high-tech mega-science environment. Flyvbjerg (ABC, 2011) seriously suggests that firms embarking on major IT projects assure themselves of being able to withstand a threefold cost increase before approval.

NASA's Kepler spacecraft represents successful contingency management, despite the project following a disappointing but familiar path of cost increases and schedule slippages. Ultimately, when faced with yet a further funding request of $42 million, NASA Science Chief, Alan Stern refused and called for a workable plan to avoid cancellation. By reducing project length, amending test plans, and streamlining management, the original budget was maintained. Most importantly, analysis showed no increase to mission risk (Rendleman & Faulconer, 2011).

One other avenue of contingency that arose from the present study's casework, is the possibly of descoping, in terms of the project physical facilities (e.g. reduced quantity or performance of procured devices) coupled with lowered aspirations (e.g. less experiments). In the case of the BEAGLE Mars lander, system tests were even descoped to maintain schedule, almost certainly contributing to its failure (ESA, 2004). However this mode of (potential or actual) cost saving in order to fund unexpected risks or cost increases does not necessarily equate to project failure (PMI, 2011), but the quantum of saving requires careful analysis against both the loss in overall project performance, and the perception it gives to stakeholders. When interviewed, Prof. Holdaway from the TOPSAT project said: *"Descoping of science goals is the proper way to achieve budget control. [But] everybody must understand what is being achieved for the money and what is being delivered/lost"* (TOPSAT, 2010).

Saunders et al. (2003, p. 368) offer their experience from space missions: "*Descope plans are a necessary part of the risk management plan, but these should be used as a last resort. When descope plans are developed, it is very important to identify for each item the...effect on the mission"*. Descopes have their own dangers, as evident in the troubled AEHF[30] system. Budget blowouts from technical problems and launch slips caused deletion of two satellites based on the justification that AEHF would become an interim system to the TSAT[31] program. TSAT was itself first restructured, then cancelled (Rendleman & Faulconer, 2011).

[30] Advanced Extremely High Frequency Satellite System
[31] Transformational Satellite Network

The NASA Space Flight and Project Management Handbook (NASA, 2010b, p. 34) offers further practical advice:

> *"Descopes must not cut a project below the minimum success criteria needed to carry out the missions in the program. If a descope is invoked, it is necessary to take a systems view to ensure that all potential interactions are identified. It is important to identify potential descopes early and to get sponsor buy in. It is also important to identify the risk associated with taking potential descopes. Many potential descopes are possible and beneficial when taken early in the program life cycle but may be much less useful or even increase overall program or project risk when taken late in the life cycle."*

Confirmation of project scope at any point in the project lifecycle is paramount; however an early period of grace may be appropriate for high-tech projects where the final performance is highly dependent on some nascent R&D. Once agreed (or changed), the project scope must be documented, announced, and defended. The LHC project leader, Lyn Evans, put it bluntly to me at an on-site interview: *"scope creep is your biggest enemy"* (LHC, 2009).

Since the unknown cannot be planned in detail, an alternative method is to plan for everything (the Napoleon approach) expecting that something will go wrong and that a solution will be needed as the challenge emerges. When referring to the aggressive, revolutionary high-tech F117 Stealth Fighter program, Nicholas (2004, p. 325) writes: *"Expecting the unexpected is often better preparation for coping with risk than preparing extensive plans and believing that the unexpected has been eliminated."*

General managerial alertness is clearly required to scan broadly for potential threats. Smith (2007) describes 'uncertainty spotting' skills; the early seeking out and challenging of threats and assumptions. An expert gap analysis of the ASKAP project identified lack of planning for 'really bad program events', and suggested the same preventative approach though appointing specific people, who are only loosely connected with the project, as sentinels against trouble (Schoening, 2009). In their study of tools for complex projects, Remington and Pollack (2008, p. 4) discuss non-linear risk events requiring early decision-making about communications and governance, so that even if managers cannot directly predict the source or possible ramifications, an *"atmosphere of preparedness develops"*. Certainly, being watchful, and informed by timely and accurate trend-type data, is indicated as a key project success strategy.

Coupled with this are task force response teams (aka 'tiger' or 'cheetah' teams) that are shown to operate effectively to contain and direct events (Crosby, 2012b). The strength of the task force lies in their combined expertise, detachment from the project, and freedom from project bureaucracy (LHC, 2009). Power is concentrated through limiting numbers and very careful participant selection (Pavlak, 2004b). However, task forces take time to establish and become effective. Ibbs and Kwak (2000) found, when investigating risk management approaches, that such groups are formed after the problem has arisen, which is too late. Rendleman and Faulconer (2011) describe a 'tiger team' formed to address cost blowouts at Falcon Air Force Base, explaining that the project overrun was around $1 billion by the time the task force was assembled. I posit that one or more task force panels might be anticipated, assembled virtually during project start-up, and periodically offered a project 'health' report so that a dormant state of readiness is maintained. In the event of an unforeseen disruption, a panel of previously enrolled experts are far better placed to begin problem solving than a bricolage type response.

In addition to applying contingency and maintaining a quiescent threat readiness, wise project managers will practice skilful early stage planning to try and avoid unplanned events. Howell et al. (2010) warn us of the spiralling effect of plan deviations, leading to hasty replanning, improvisation, and ad-hoc responses, resulting in yet more uncertainty and surprises. Activities including response readiness, stakeholder negotiation skills, avoidance of panic and over-reaction, and speedy approval processes, all serve to strengthen resilience (Geraldi et al., 2010).

3.3.4.5. Project environment

Whatever their size or structure, projects exist within a larger financial, geo-political, and governance framework (project environment) that can both enable and constrain the enterprise (Blanchard, 1990; Archibald, 2003). The high-tech projects considered in the present study generally require physical space for infrastructure, often in underdeveloped areas prone to host site sensitivities. Gaining approvals for large engineering facilities, often involving decades of operations, can be a slow process fraught with challenges. Merrow's (1988, p. vi) study of 52 mega-projects concludes:

> *"Cost growth and schedule slippage...are driven primarily by conflicts between the projects and host governments, i.e., institutional problems relating to environmental regulations and opposition, health and safety rules, labor(sic) practices, and*

procurement controls. The importance of institutional factors clearly distinguishes mega-projects from their smaller cousins."

Projects encumbered by excessive government restrictions or involvement showed a strong negative relationship to success in a study by Murphy et al. (1974), while Pinto & Mantel (1990, p. 274) add: *"change in the project environment beyond the control of management"* as a cause of project failure. A high level European Commission report alerts project managers to the consequences of decisions inspired by political considerations rather than technical and scientific requirements (European Commission, 2010). Large IT projects are similarly vulnerable (British Computer Society, 2006).

Systematic periodic scanning of the high-tech project environment is strongly endorsed by Archibald (2003), who presents a comprehensive pie-chart to help guide the strategic engagement process (see Fig. 3-10). The idea is to identify both the key actors, and the key factors, that may exert a great influence on the project in terms of risks and enablers.

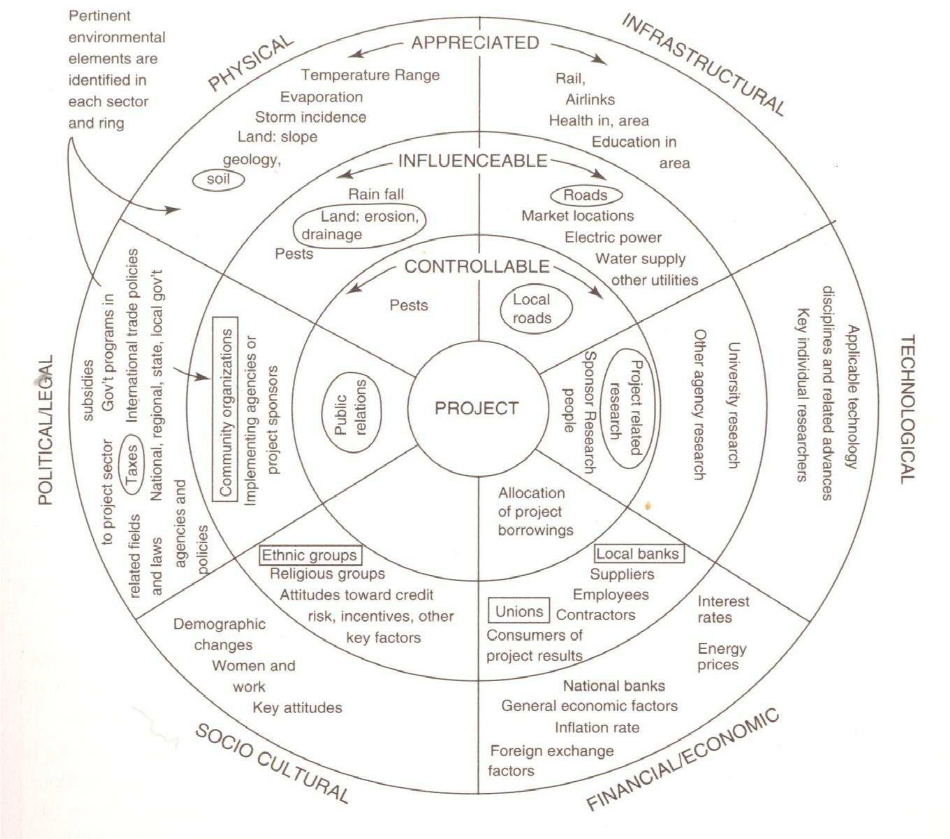


Fig. 3-10. A pie-chart of project environmental factors with potential to affect project success (Archibald, 2003 p. 51)

The project environment may also prove challenging in terms of recruiting talent. Assembling the best people at the facility site, or even in a less remote headquarters office, must inevitably mean consideration of visa, tax status, spouse and family issues (employment and school), insurance, and pension provisions. Mega-projects frequently have the critical mass to negotiate privileges such as tax advantages and certain immunities, thus offsetting the upheaval of relocation and impacts on personnel lifestyle (OECD, 2010).

There is advantage in establishing the project within known, coherent and mature institutional arrangements. Miller & Lessard (2000, p. 23) write: *"Projects shaped in incomplete and shifting arrangements have a hard time taking off: they require deals and agreements that may not stand for long"*. In the $3bn Accelerator Production of Tritium (APT) project, project management successfully adopted the concurrent engineering approach, integrating design, planning, and operations teams early on, and conducting up-front analysis driven by environmental (NEPA) requirements. Consideration of these early resulted in significant changes to design and operability of the plant (Laufer & Hoffman, 2000).

Fieldwork interviews for this thesis indicate that a proactive approach to government negotiations offers real benefits. By leveraging the infrastructure investment, the ALMA project not only won significant concessions, but also eased visa processes for foreign workers (ALMA, 2011). Through tight links with European Government heads, the SKA project has been relieved of substantial logistical costs of international meetings, and is soon to re-locate to new purpose built premises adjacent to the UK's Jodrell Bank facility.

Similarly, the Antarctic LIDAR project leader explains the benefits of early liaison with authorities:

> *"We submitted a comprehensive environmental assessment early which was accepted without restriction. This covered installation of the infrastructure and on-going operations. In 2005 we changed the configuration of the transmitter and reviewed our procedures in discussion with our aviation and communications sections. Since then we have not had any significant restrictions to our summer operations - we still have safety procedures in place, but pilots now fully accommodate our operations. All of our procedures have been reviewed by ARPANSA, and this process has not caused any delays" (interviewed 7 August, 2011)*

However, failure to fully understand regulatory compliance can be costly. For example, the Australian ASKAP radio telescope encountered unanticipated delays in achieving government approval for land use, requiring significant diplomacy and skilled effort from project personnel (CSIRO, 2007-2009). Blanchard (1990) urges early attention to regulatory approvals, and states that the cost of compliance with environmental and special interest groups needs must be factored into project cost estimates.

A 2007 report of major astronomy project surveys warns readers of changing political agendas, agency priorities, budget pressures, as well as unanticipated disasters, and scientific results. It recommends to: *"start with a more realistic sense of agency budgetary and policy environments...so that [project] surveys can be more resilient"* (Fellows & Alexander, 2010, p. 3). The world beyond the project is neither benign nor complacent, and early stage investment into securing a legally compliant, socially acceptable, and affordable project deployment plan pays dividends.

3.3.4.6. Mission assurance

While conducting field investigations for this thesis, I identified a particular characteristic of certain project managers; an unwavering sense of purpose in making mission success the highest priority at all levels of the project (ALMA, 2007; ASKAP, 2009; ITER, 2009; SYNCH, 2009). The adoption of this 'mission assurance' mindset is captured compellingly within aerospace industry reports (e.g. NASA, 2000) which encourages institutional line management to become more engaged in the execution of the project and be held accountable for mission success.

So important is this viewed at NASA, it now promotes and maintains specific safety and mission assurance offices with their functionality embedded in key project management literature. For example, the NASA Space Flight Program and Project Management Handbook (NASA, 2010b, p. 95) describes the focus of mission assurance to monitor the:

> *"established design criteria and standardized control design practices to ensure that the design is capable of:*
>
> - *Functioning properly during the required mission lifetime*
> - *Minimizing or eliminating potential sources of human-induced failures*

- *Permitting ease of assembly, test, fault isolation, repair, servicing, and maintenance without compromising safety, reliability, quality, and performance*
- *Allowing for access requirements that might arise during assembly, test, and prelaunch checkout, and*
- *Utilizing such analytical techniques as Design Trade-off Analyses, Failure Modes Effect and Criticality Analyses (FMECA), Parts Stress Analyses, Probabilistic Risk Assessment (PRA), and Worst Case Analyses"*

An expert panel inquiry of budget problems of the James Webb Space Telescope underlines this approach by including the recommendation (among many) to restructure the JWST project office to emphasise mission assurance. Its focus should be lowest cost to complete, launch readiness, and science requirements at the implementation phase, coupled with assigning project accountability to the centre management (JPL, 2010).

The implementation of a mission assurance function (part auditor, part advisor, part 'devil's advocate') means placing this vital resource outside of mainstream project delivery, yet close enough to have ready participation in critical testing, meetings, and reviews, and with access to project management. The role is principally one of questioning and checking that activities, deviations and changes, particularly at project interfaces, pose no unrecoverable threat to execution and performance.

Created at project start-up, the mission assurance function is best placed to conduct a project audit after the definition stage but before execution begins. Graham & Englund (1997, p. 192) describe this as: *"like a group of expert consultants...review the plans and proposals before the project team begins...and provide feedback on the technical and managerial feasibility of the plans...using their knowledge and experience to foresee problems."* NASA links early examination of the mission architecture to technical success, claiming that: *"in early stages of concept development it is not uncommon for teams to develop architectures which have elements that do not work well together. The criticality of this mistake is dependent on...technical, schedule, and cost margins"* (Saunders et al., 2003, p. 363).

When questioned, many of the interviewees for this study claimed that external panels fulfilled the niche of mission assurance while conducting design reviews and other early activities, but the temporary nature of these panels is never equivalent to a project-bound person or group. Moreover, rather than be created as part of the project execution and deployment team, there needs to be a distinct mission assurance role assigned at the project inception, and developed as a central (overhead) function necessary for driving project success.

3.3.5 Brief qualitative assessment

Having drawn out the more subtle, though highly influential, attitudinal environmental and launch conditions shown to be important for project success, it is useful to examine how these nine factors are addressed in practice.

For this, I selected three large radio-astronomy projects from the fieldwork studies detailed in Table 1-1. Although being similar in terms of being remotely located giant radio telescopes with large and complex information technology (IT) requirements, they are discriminated primarily by project budget, infrastructure size, and execution stage (see Fig. 3-11).

Identifier	Budget	Infrastructure	Location	Stage
Atacama Large Millimetre Array (ALMA)	US$1.4 billion	50 dish high-frequency radio telescope array, plus command and processing centre	Andes Mountains, Chile	First stage commissioning
Australian SKA Pathfinder (ASKAP)	A$140 million	36 dish mid-frequency radio telescope array and data processing centre	Inland from Geraldton, West Australia	Construction of antennas and infrastructure
The Square Kilometre Array (SKA)	€1,500 million	250/3000 dish low & mid frequency radio telescope, with control and data processing	Southern Africa or Australasia (to be confirmed)	Transition from concept stage to Phase 1 pre-construction

Fig. 3-11. Key Project Data – ALMA, ASKAP, and the SKA

In preparation for the comparative assessment, I examined the data collected during on-site investigations, as described in the approach and methodology for this thesis. The data were sorted to expose relevant examples of situations or events that fell within the special resilience factor categories identified in this section. Against each factor, I describe a challenge that faced each of the three cases, and the method and extent of the response from each project. Table 3-2 shows this work tabulated to enable ready comparison and contrasting of challenges and responses between the case projects, and reveal commonalities.

A summary review of the data in Table 3-2 presents useful insights. Cost, schedule and performance optimism was universal, and each project introduced constraints to meet budgets. Little effort was evident to learn from analogous high-tech projects. All three cases struggled at some point to deal with project ambiguities and uncertainties, though responses showed these challenges are surmountable. Some disconnect was apparent between lofty science goals and practical execution, later bridged through individual project initiatives. Both reporting and decision-making processes, and project information control, were competently managed, but with room for maturation to industry standards. Risk and contingency factors were handled only moderately well, exposing the ASKAP and SKA projects especially to the effects of unforeseen disasters. While the important external project landscape was managed well in all cases, the potential advantages of a formal mission assurance program have yet to be exploited.

Table 3-2. Comparative assessment of three case studies against resilience factors

Factor	Project	ALMA (Chile)	ASKAP (Australia)	SKA (UK based)
Realism	***Challenge***	• Expectations of a networked 64 dish array in original (2001) budget. Bottom up costing revealed significant project costs overlooked	• Underestimates of cost and resources to develop receptor (PAF) technologies • Possible descope impact due to budget trade-offs. Stakeholder expectation issues	• Underestimates of cost, time and resources to meet software and computing requirements • Potential for severe and negative impact on the project
	Response	• Re-baselining exercise in 2005 triggered call for additional funding • Descope to 50 dishes pre-construction • Project now proceeding	• Consultation with industry regarding volume production costs • Revised plan / funding proposal developed to show viability with alternate project pathway	• Use existing code wherever possible • Top-down 'cost-cap' budget 'as a design constraint' approach to development • Use first order parametric estimating models for software estimating
Lessons Learned	***Challenge***	• Domain knowledge considered held within the partners (NSF, ESO, NAOJ) through specific capabilities. However weakness emerged for industrial integration capabilities	• Domain system engineering knowledge held tacitly by individuals. • No formal systems to codify, archive, or transfer lessons learned	• Domain system engineering knowledge held tacitly by individuals. No formal systems to codify, archive, or transfer lessons learned. The level of coordination and hence collaboration is impacted
	Response	• Level of stakeholder investment meant major decisions not optimised • Therefore all decisions still not ideal or based on researched experience	• Currently no formal lessons learned mechanism evident	• Some effort made to consult developers and operators of like-projects, however highly sporadic, and communications of findings largely ineffective
Complexity, Ambiguity, and uncertainty	***Challenge***	• Deep technical domain knowledge for major system components and software, but project interfaces less defined and complex	• Push for technology break-throughs, especially in PAF's, computing, and 'green 'energy • These are complex, inter-related problems with unclear solutions	• Unfolding science goals and 'proof of concept' TRLs causing ambiguity • Complex Exascale computing capabilities do not yet exist, and may be unaffordable
	Response	• Large investment in system engineering resources to continually resolve interface issues • Project leadership instilled culture of 'relay-race' rather than 'marathon'	• Highly intensive and frequent technical and planning meetings held • There is some sense-making emerging, but peripety has yet to occur	• A more modest Phase1 SKA design released • Science ambitions scaled to computer power budget (flops and watts) • 'Moore's Law' uncertainty remains • Match contingency to complexity

Factor	Project	ALMA (Chile)	ASKAP (Australia)	SKA (UK based)
Mission & Goals	***Challenge***	• Science high-level goals considered fixed objective, with clear vision of project success. However re-baselining meant compromise	• The broad project goal is clear; however some divergence is apparent between long term and short term objectives	• Development of a mega-project mission within an international collaboration and funding framework • Scope creep
	Response	• Re-scoping of project largely maintains achievement of science objectives through adjusted operations	• A group is assigned to bring certainty to the long term purpose of ASKAP • Overcoming shorter term technical barriers is the present mission	• The SKA now has stated science goals against a top-down budget, a Design Reference Mission, and a Phase1 pre-construction Project Execution Plan
Reporting and Decision Structure	***Challenge***	• Need for strong and clear project reporting and execution structure, in face of 50/50 ownership • Decision structure and process must be consistent and workable	• ASKAP resides within a well defined project management structure. Reporting at the Integrated Project team (IPT) level is less consistent, though competent	• Reporting and decision-making structures are complex and variable, typifying the science community decision-making behaviour • Participation in committees and at decision meetings is inconsistent
	Response	• ALMA project structure well defined and implemented at work-site level • More prone to compromise and decision-delay at higher management levels • Third partner added (NAOJ) • Major decisions need lengthy discussion at Joint Alma Office (JAO) level	• Fine tuning the project structure to reflect the project team site location is in process. • Project reporting is enhanced through migration and automation of reporting processes to DAPTIV© platform	• Efforts to lift effectiveness and integration of meetings and decisions mostly unsuccessful • Task Forces work effectively • The planned move to a project office structure will 'normalise' reporting and decision-making to industrial model
Information Control	***Challenge***	• Project information control extremely important to maintain project control, and effective procurement systems	• Possible mismatch between ASKAP execution, industry, and large institutional framework • IP requires specialist management	• SKA design and cost data yet to be brought under a formal control system, and there is no formal PMIS in place.
	Response	• JAO maintains strict controls on project technical data, procurement data, system engineering documents and Standards, and PR material • Major meetings administered centrally • Some reluctance by NAOJ to announce problems early	• ASKAP project information is under dispersed control. IPT leaders maintain technical data control • Industry consortium established • IP is periodically identified through active scan and appropriately managed	• Appointment of a Systems Engineer under a Project Manager is starting to create information discipline • The planned move to a project office structure offers opportunity to professionalise communications management

Factor	Project	ALMA (Chile)	ASKAP (Australia)	SKA (UK based)
Risk & Contingency	***Challenge***	• Need for full identification and tracking of project risk, despite mixed contingency and risk culture within the major project owners	• Propensity to focus on tactical risks, and downplay need for contingency, despite evidence of significant likely cost-growth	• Propensity to focus on tactical risks, and downplay need for contingency reserves, despite past experience in mega-science
	Response	• American approach to risk adopted • Comprehensive risk register, risk 'burn' reports, and contingency established and tracked - 15.8%, later reduced to 9.2% • Task forces readily established (e.g. antennas specification problem)	• Little overt acknowledgement of, or pre-planning for, unknown risks • Recent moves to address project and corporate risk and contingency in new business plan	• Recent costing strategy foreshadows a contingency component • Growing awareness of importance to acknowledge *unknown* risks within the professional team, yet specific cash reserves remain unclear in costings
External Environment Aspects	***Challenge***	• Construction and operation of a mega-science facility in the Chilean Andes • The location is harsh and remote • Need for skilled and unskilled workers during construction phase	• ASKAP will be situated in remote Australia. There are indigenous people sensitivities, some environmental fragility, and competition from mining companies. Electrical quietness requires legislation	• Deployment of a large infrastructure project in sensitive geographic location requires lengthy and careful planning in conjunction with approval authorities • Requirement for a 'neutral' HQ site
	Response	• Substantial planning and site negotiation with Government at early stages • Landowner on ALMA Board • Specific 'Astronomy Site' legislation enacted • Tax-free 'diplomat' status for foreign project personnel. Project has sales tax-free status	• Substantial effort and cost is being applied to ensure compliance (in spirit and in fact) with land use policies • Radio-quietness is under legislation development • Negotiations underway with mining interests	• Some team awareness of project environmental aspects - mostly funding scenarios and site host issues. These are handled by relevant Domain groups, and overseen by the SKA Project Executive • Host and HQ site investigations are underway
Mission Assurance (MA)	***Challenge***	• Requirement for project 'watchdog' role to ensure vigilance and prompt response against threats to mission goals	• Implementation of project 'watchdog' role to ensure vigilance and prompt response against threats to mission goals.	• Implementation of project 'watchdog' role to ensure vigilance and prompt response against threats to mission goals.
	Response	• ALMA Advisory Committee charged with taking longer term project perspective, to identify potential dangers to project delivery • No specific in-project role identified for NASA- style Mission Assurance	• The establishment of a 'mission assurance' (MA) function is unfamiliar to Australian based science projects • There is no role assigned in ASKAP for a specific mission assurance function	• The establishment of a MA function is unfamiliar to European science projects • Current budget restrictions preclude establishment of a formal MA function • Internal and external engineering reviews (e.g. PDRs), fulfil part of the role

3.3.6 Conclusions and discussion

This study of special resilience factors illustrates that for most high-tech projects, both attitudinal and launch conditioning factors remain a challenge, no less so for large and complex IT projects. The nine factors are:

Attitudinal

- realistic, fact based
- a lessons-learned culture
- ambiguity-tolerant

Launch Conditioning

- mission and success clearly defined
- clear decision structures
- strong information control
- risk preparedness
- external environmental awareness
- mission assurance implemented.

Schedule and cost optimism especially is a well known phenomenon, yet it continues to be neglected by high-tech project management. The issue results partly from failure to forecast project costs accurately and partly through competitive funding environments where underestimates in time and/or cost have traditionally been tacitly accepted or even encouraged. Anecdotally, current global economic conditions indicate reducing tolerance to this approach in the face of stricter funding priorities (Matson, 2010). Use of lessons-learned has been historically weak, and remains patchy. High-tech mega-projects especially should formally plan for at least a degree of up-front research to inform the major challenges and decisions ahead. Early ambiguity in projects can frustrate project groups used to a more industrial model, yet are overcome through trust building – itself dependent on effective and frequent project team communication.

In regard to launch conditions, the benefits of defining the project mission and success definitions early are strongly evident, as are clear and consistent structures for reporting and decision-making. I advance the concept of a Project Information Office (PIO) with a remit covering not only information, documents and data, but also the broader responsibility for convening conferences, meetings, teleconferences, and managing/recording their 'traffic' flows. As such, the PIO would be the central coordinator of project community information needs, including project templates, branding, IP, and single point management media interfaces.

Risk management in high-tech projects is typically dealt with programmatically and often views projects as a deterministic process, but this approach fails to fully consider unknown unknowns. To address this epistemic uncertainty in high-tech projects, a two-pronged approach is suggested: (i) estimating and establishing an identified contingency reserve, ideally integrated to dynamic risk 'burn', and (ii) the early appointment of one or more 'proto' task forces panels kept in dormant readiness to offer expert advice against unanticipated events.

The execution of large infrastructure projects carries compliance obligations involving national authorities. Even with State blessing, these external negotiations are rarely simple, and need careful and dedicated stewardship at (or before) project start-up. Internally, the formation of a mission assurance function working alongside project management, supporting the project teams and reporting at Director level improves success through enabling peripety (Engwall & Westling, 2001). Integrated at the conceptual phase, the mission assurance function brings experiential capability and intellectual rigour to project definition. Finally, taking time to gain a full understanding of project complexity is essential to shape project structure and management approach. The present study advocates a robust strategic method through project mapping and development of multiple approaches, before committing resources to a focused strategy.

Management of the conceptualisation and planning phases has a pivotal effect on the ultimate success of projects. For international high-tech projects especially, the alignment of key activities with key players is crucial. It is people, with their talents, attitudes and experience, who ultimately deliver the initiatives set out in this study and sponsors should strive to hire the best staff available (Katsanevas et al., 2009). This underpinning aspect of projects is advanced by Cook-Davies (2002, p. 189) as: *"people perform every process, and it is the people who ultimately determine the adequacy"*.

3.4 Planning and baselines, project lifecycles, budgets and schedules

Finally in this chapter, I look briefly at the programmatical aspects of projects and relate these to pre-cursors of high-tech project success. Certainly the commonly held view of the project manager's job – to bring the project in on-time, on-budget, and meeting specified performance – is founded on the assertion that the project goals are supported by detailed advanced planning (Dvir, et al., 2003).

3.4.1 Project planning

In their analysis of the relationship between project planning and project success in R&D projects, Dvir et al. (2003, p. 94) confirm that, despite the claim of too much planning curtailing creativity: *"there is no argument that at least a minimum level of planning is required. In fact, planning is considered a central element of modern project management"*. They concur with Jugdev and Müller (2005) in pointing to the rather mechanistic advice in the PMBOK Guide that informs project managers that although planning does not guarantee project success, a lack of planning will probably assure project failure.

Planning itself implies the defining of goals and functional specifications, and unsurprisingly, Dvir et al.'s work reveals a strong positive relationship between planning, requirements, and end-user satisfaction. Kerzner (1998) posits that in some projects (e.g. 'new and emerging technologies'); it may not be possible to have a full definition of the project scope prior to commencement. As a result, the project may require planning 'from the middle out', requiring heavy involvement from the customer/user and a very flexible and adaptable approach to refining requirements. Verzuh (2003) develops this idea, pointing out the limitations of the planning horizon – the distance you can actually see into the future.

Project planning in all but the simplest systems will incur the creation of a 'baseline' schedule to capture the project plan at commencement, and enable subsequent tracking. Elenbaas (2000) warns against the notion that a useful baseline can be generated within project management tools alone, arguing that this vital activity must involve deep understanding and commitment from key project stakeholders, ideally involving a walk-through by the project manager. His reasoning is that the project baseline, and the detailed schedules/plans that it supports, are a bundled set of dynamics incorporating stakeholder assumptions and constraints, and form the project 'touch-stone' on which success depends so much. Interestingly, the GMT project elected to contract out the development of the project baseline. While this indicates a readiness to engage professional expertise within the project management process, time will tell if the required deep understanding is apparent (GMT, 2010).

This is not to say that baselines must never change. In his Portable MBA for Project Management, Verzuh (2003) raises that likelihood that tasks and deliverables will be left out of the plan. E.g. the way we will do the work will change; the estimates for cost, schedule, and resources will be wrong; and one or more stakeholders will demand variations to the project scope. Verzuh (2003) suggests permitting changes for the very early project reporting periods, then freeze the baseline for the remainder of the project.

3.4.2 Project lifecycles and phasing

Early mapping of the high-tech project lifecycle offers both task clarity and temporal horizons that underpin the schedule. Typically, Phase 1 describes concept generation based on an evaluation of alternative ways to achieve the project mission. Phase 2 is where the project definition takes place and proto-plans are formed, ready to take forward. Phase 3 covers project realisation through detailed planning and design, implementation, and execution (Winch, 1996). Further phases may be introduced to span commissioning/handover, utilisation (operations and maintenance), and ultimately close down and disposal. Khang and Moe (2008) go further in recommending application of a result-based framework capturing different sets of success factors against each phase allowing improved analysis and next-phase preparation.

The foregoing suggests a serial process with limited opportunity to condense the overall project length (Jugdev and Müller, 2005). However possibilities exist to reduce elapsed time through overlapping of project phases, although such concurrency can lead to significant cost growth. Winch (1996) discusses the concept of independent work packages that can proceed in parallel (essentially organised mini-projects) to accelerate progress, and offers examples such as rapid prototyping that is becoming an art in itself. Work Packages are commonly mapped onto a project work breakdown structure (WBS), and Verzuh (2003) shows how this is used to reduce risk – in one case by choosing a prototyping approach to develop a product in response to uncertain user requirements. Archibald (2003) refers to this overlapping as ‘fast-tracking’ in engineering projects, and ‘concurrency’ in military/aerospace projects, while noting the need for strong project management. He also warns readers of the mounting cost of lost time recovery for each successive project phase, and shows how a typical increase in personnel for high-tech projects leads to an ominous exponential growth in costs.

Archibald (2004, p. 6) looks specifically at high-tech projects and identifies two types of life-cycle models – adaptive and predictive. The latter, favouring optimisation over adaptability is directly relevant to this thesis, with the model descriptions found in all of the examples and casework in the present study and supporting their success:

- **Waterfall** (traditional, or top-down): linear ordering of the phases, which can be strictly sequential or overlapping to some extent; no phase is normally repeated (e.g. OPAL).
- **Prototyping:** functional requirements and physical design specifications are generated simultaneously (e.g. LOFAR).
- **Rapid Application Development (RAD)**: based on an evolving prototype that is not thrown away (e.g. ASKAP).
- **Incremental Build:** decomposition of a large development effort into a succession of smaller components (e.g. TOPSAT).
- **Spiral:** repetition of the same set of life-cycle phases such as plan, develop, build, and evaluate until development is complete (e.g. LOFAR).

3.4.3 Project budgets and cost estimations

The project budget is the cornerstone of the project plan, encompassing (a) the original estimates, (b) the almost inevitable growth as the project is conceptualised, (c) the expenditure of funds as execution proceeds, and (d) reconciliation at project close.

Announcing early estimates of high-tech mega-project costs is fraught with danger. Grün (2004, p. 249) recounts that the: "*significance of those first, early estimates of time and cost, especially when they are used for the authorisation of funds [are taken as the] standard of reference in all subsequent discussion. It is no use saying later that it was only an estimate*". This view is borne out by managers from several of my case studies who expressed regret that early estimates had appeared in reports to funding agencies (ASKAP, 2007; ALMA, 2007).

Countering this is the momentum effect. Once started, iconic national high-tech mega-projects have only rarely been terminated completely. A notable example being the Jodrell Bank radio telescope where overruns were only revealed after large amounts were already invested, and to stop it would bring severe loss of face to all involved. The telescope's creator, Sir Bernard Lovell is quoted thus: "*the sheer momentum and massiveness of the* *project saved it from stoppage and disruption"* (Howard, 2004, p. 51). Nevertheless, tougher global economic times indicate an increase in the likelihood of project cancellation in face of cost blowouts (e.g. NASA's *JWST*, and *Constellation* programs).

High-tech project budgets are under constant strain as expenses grow and managers are compelled to justify the increases to funding agencies. This 'amoebic-like' growth of industrial project costs is examined by Eden et al. (2005), who attempted to better understand the surprising nature of overruns, some well beyond what might be anticipated. Their first conclusion was that uncertainty is inexpertly understood or acknowledged, with one multi-million dollar aerospace project coming in at 58% above budget; the inherent uncertainty level later being calculated (from the estimating notes) as between +70% and -40%. Other key drivers of cost escalation include engineering changes (sometimes 'given away' by the project contractor); customer/user demands in terms of extra tests, information, and meetings; the futility of trying to bring an errant project under control reactively by increasing the labour force (Brooks law); and starting activities out of sequence.

The tactic of attempting to constrain project spend through budget reductions in early years is shown to be futile, as a review of NASA's (now terminated) Constellation program shows (see Fig. 3-12). Not only does this cause budget blow-outs in the out-years, it also raises risk.

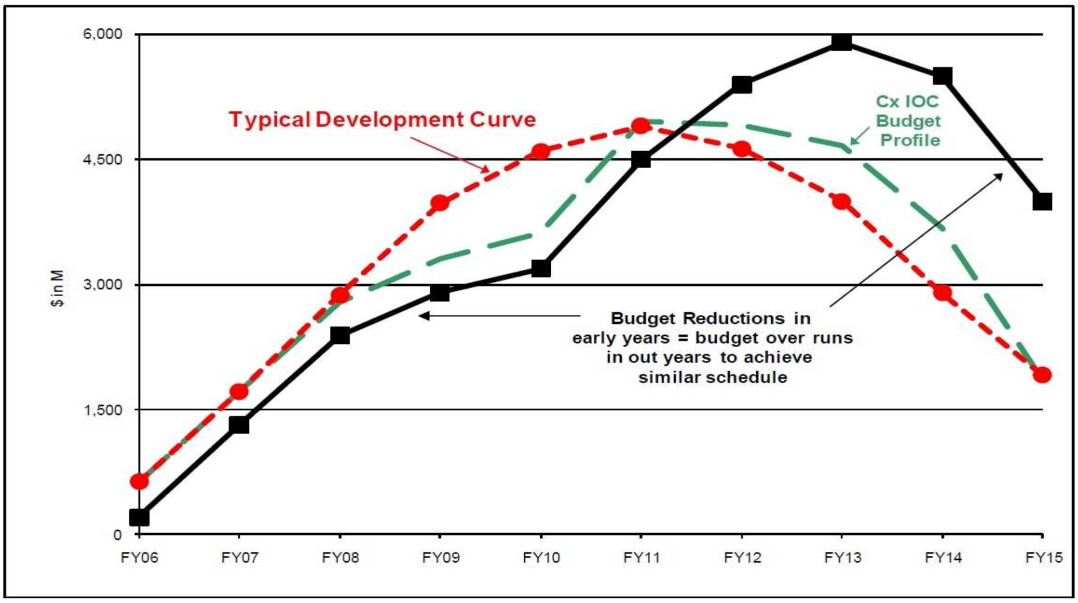


Fig. 3-12. The effect of budget reductions on NASA's Constellation program spend profile (Rhatigan, 2011 p. 11).

The US National Ignition Facility (NIF) project attributed its cost estimation errors to lack of a meaningful model offering a basis for comparison. Estimates for the conventional aspects of the NIF were accurate, but the 'first-of-a-kind' parts of the facility were grossly underestimated. Scott Samuelson, then Project Field Director quips: *"on these highly complex...projects, you make your best estimate...then double it. Don't plan on spending the extra...until you find out what you didn't know"* (NASA, 2011b, p. 56).

Even with modern tools, techniques and lessons-learned from like-projects, cost estimation is a very difficult activity indeed. The International Centre for Complex Project Management states: *"There is a huge amount [of proof] that even the best estimation techniques will only be accurate within a 25% cone of uncertainty, even when detailed requirements have been agreed."* (Cavanagh, 2009, p. 3). Notes from the Gemini telescope lessons-learned workshop (NRC, 1999) demonstrate general insufficient attention to constraining design goals to meet budgets, and poor estimating overall. At the Keck observatory especially, the early effects of science drivers on cost resulted in optimistic estimates. Cerpa and Verna (2009), in a study of IT projects, found poor cost estimates in 81% of the 70 failed projects, blaming deficient requirements as the cause. When interviewed regarding a recent study of global IT projects (ABC, 2011), Prof. Flyvbjerg found the average cost blowout to be 200%, with examples stretching to several thousand %. Rendleman & Faulconer (2011) report an average cost-growth of 33% in NASA space and earth science missions. A Major Projects Association seminar on management of design and engineering concluded that: *"unrealistic budgets for engineering design continue to haunt major projects [and] realistic estimates go with a mature understanding of the allocation and management of contingency"* (MPA, 2007, p. 1).

The US Space Science Support Office (Saunders et al., 2003) conducted research into predicting cost success on high-tech projects, concluding that good results are only possible with proper analysis skills and tools. They offer a graphical representation of cost analysis hierarchy (see Fig. 3-13), and urge for close attention to level 2 for 'real-world' checking.

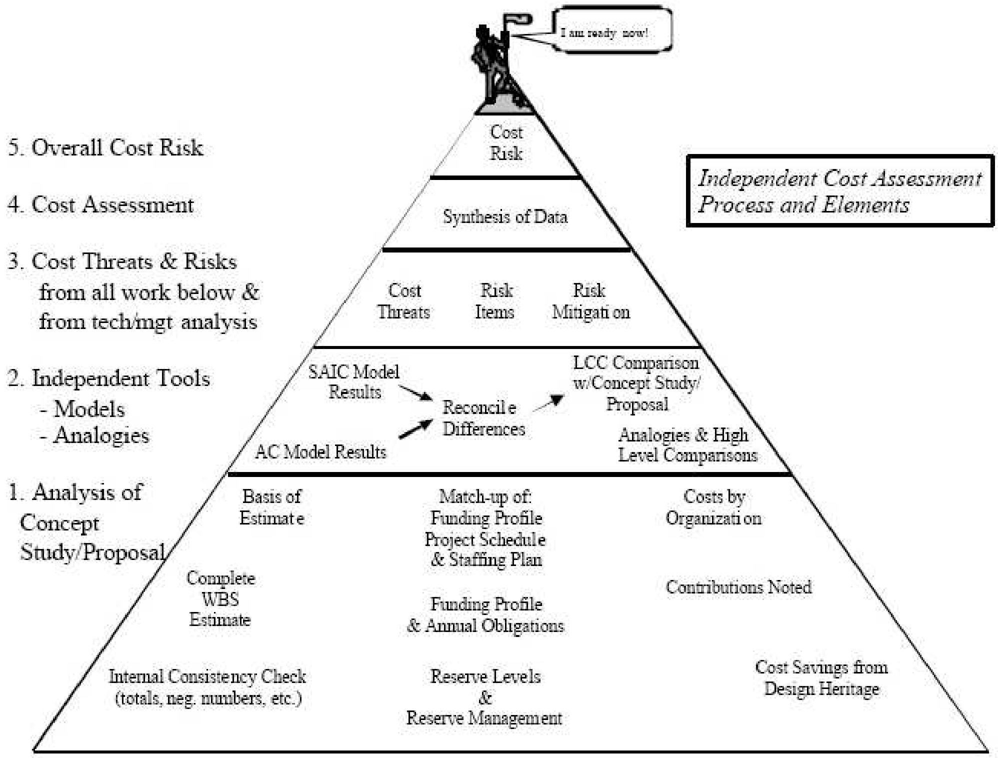


Fig. 3-13. Cost analysis hierarchy (Saunders et al., 2003, p. 369)

The US Government Department of Energy joins NASA in recently issuing a practical Cost Estimation Guide, offering their staff a 12-step, best-practices manual (DOE, 2011) endorsed by industry participants from aerospace, automotive, energy, and the Navy. However, they note that the Government Accountability Office (GAO) reports that while these good cost estimation characteristics have been known and published for decades, many US agencies have yet to apply them successfully in projects due to lack of inherent skills.

Cost estimates cannot be effectively executed alone. Investigations at the ALMA (2007) project provide an example of the highly interactive nature of the task. The raw data from goods and services cost enquiries must be supplemented by regular consultation with schedule planners, project management, risk plans, and checkers, as portrayed in Fig. 3-14. Moreover, project estimators need to be on guard against enterism[32], inevitably leading to overruns (ICCPM, 2011).

[32] Enterism – the practice of setting an unrealistically low budget to win a tender, then increasing the price later once the buyer is committed, or establishing the cost at a politically acceptable level.

Fig. 3-14. The interactive nature of effective high-tech project cost estimation

Cost estimation techniques vary according to the purpose and accuracy required. Widely accepted cost estimation classifications are published by the Association for Advancement of Cost Engineering International (AACEI), and comprise five classes as shown in Fig. 3-15. For each class (or broad purpose), a level of project definition is prescribed, and a selection of appropriate costing techniques listed, ranging from best judgement through to definitive. A detailed study of cost estimation techniques and their advantages and disadvantages vis-a-vis various types of high-tech projects is outside the scope of this thesis. However the importance of correct selection and the impact in terms of project risk and success are emphasised.

Cost Estimate Classification	Primary Characteristics	
	Level of Definition (% of Complete Definition)	Cost Estimating Description (Techniques)
Class 5, Concept Screening	0% to 2%	Stochastic, most parametric, judgment (parametric, specific analogy, expert opinion, trend analysis)
Class 4, Study or Feasibility	1% to 15%	Various, more parametric (parametric, specific analogy, expert opinion, trend analysis)
Class 3, Preliminary, Budget Authorization	10% to 40%	Various, including combinations (detailed, unit-cost, or activity-based; parametric; specific analogy; expert opinion; trend analysis)
Class 2, Control or Bid/Tender	30% to 70%	Various, more definitive (detailed, unit-cost, or activity-based; expert opinion; learning curve)
Class 1, Check Estimate or Bid/Tender	50% to 100%	Deterministic, most definitive (detailed, unit-cost, or activity-based; expert opinion; learning curve)

Fig. 3-15. The AACEI cost estimate classification table (DOE, 2011, p. 14)

A response to cost estimation risk is project cost contingency, where an amount is set-aside against a possible shortfall in the cost estimate. Fieldwork for this thesis concurs with Baccarini's (2005) survey; that a percentage figure derived from past experience is the most common method of determining the contingency amount (if applied at all). Baccarini (2006) revisits this topic, exposing serious flaws with the percentage method and offers 11 further approaches. In particular, he advances regression analysis as a robust and defendable (yet under-researched) method for predicting the final cost of building engineering projects.

3.4.4 Project scheduling

As per the American mode, NASA leaves little to chance concerning schedule monitoring, with their Space Flight Program and Program Management Handbook (NASA, 2010b) insisting on accurate time phasing of work accomplished through an Integrated Master Schedule (IMS). This provides a single integrated source of schedule data based on tasks/milestones, task durations, interdependencies, project constraints, for in-house and subcontract effort. NASA recognises the insufficiency of analysis of schedule variability in the early project stages, noting few viable models. For this reason, NASA schedulers are required to have a technical background or at least an understanding the technical principles just as the project manager needs to understand the basic science behind the project.

Project management performance during execution is principally driven through the project schedule, combined with the somewhat intangible project ‘sense of urgency’.[33] The creation and controlled dissemination of the project schedule underpins a project pace that is shown to lift project performance.

Other things being equal, a higher-urgency project is expected to progress faster due to more attention received, and shorter turn-around time for project requests and other administrative tasks (Cao & Hoffman, 2010). A sense of urgency was listed third in a table of issues for project management success by Attarzadeh (2008). Highly related to limited time, money, and other resources, this author recommends regular status checks, meetings, and project-wide reminders to maintain pace. Howell et al. (2010) were more guarded in their comments, arguing that the driving effect of urgency can itself increase uncertainty by limiting the resource (e.g. time) available for comprehension and by decisions made on more limited information. Nevertheless, managers under time pressure are shown to be more actively involved, and this probably counters any increase in unexpected project behaviour.

Schedule slippage is directly linked to project cost increases, most obviously via the ‘marching army’ fixed costs, and are probably amplified in high-tech projects (e.g. the

[33] Examined further in section 5.1.3.8

JWST) through higher costs generated by senior technical staff and sophisticated machinery (Siegel, 2011). Costs for the Mars Science Laboratory are forecast to grow by $400 million, simply due to a two-year slippage (Rendleman J D, Faulconer, 2011).

The importance of tracking project schedules is borne out by Andrew Klekociuk's experience with the Antarctic LIDAR (LIDAR, 2004) where he related to me: *"early slippage should have indicated how long things were going to take. We should have built a robust scheduling system early"*. Similarly, Dean Morris from the Australian Synchrotron explained in interview (SYNCH, 2009) *"delays at the start (e.g. recruitment) were never made up. It was poorly planned. FX transactions and procurement had to be learned and much time wasted on complex contractual legal clauses that were never enacted, for example liquidated damages"*.

3.5 Chapter Summary

In this chapter, I have examined four pre-cursor areas key to high-tech project success. First, at project inception, the operating entity (including structure, location, and management) must be chosen very carefully, and the framework for collaborative partnerships established for both funding of, and contributing to, the project.

Second, the arrangements for sourcing and acquiring the project assets need determining, taking due account of the international environment. Some non-intuitive features of contractual arrangements are listed to show approach and application. Nine key strategies for procurement success are advanced.

Third, project resilience is addressed, revealing three attitudinal factors, and six conditioning factors shown to be important in building robustness into high-tech projects. These are tested through a qualitative survey of three of the case studies, and shown to be relevant.

Last, several of the more programmatical processes are briefly covered, including planning, project lifecycles and phasing, cost and budget estimates, and scheduling. These four areas, supported by compelling evidence from field research, are shown to be crucial as pre-cursors to success in large science/engineering projects. In the next chapter, I introduce a meta-study of mega-project success factors, and apply scientific analysis to reveal a ranked series of high-tech project success drivers.

Chapter 4 – Detection of predictive success drivers

4.1 Introduction

This section is central to this thesis and concentrates only on the material presented in the author's paper 'Key success drivers – meta study findings applicable to large high-technology projects'[34] (reproduced in Appendix K).

In it I draw on case study work and research from the previous four decades, plus contemporary mega-project experience to ask: what are the key strategic areas that show strong correlation to project success? Data are examined to discover success factors and success criteria for large engineering and science projects, and I compare these with general mega-projects. Findings are presented that contribute new insights for life-cycle project management, most applicable at the planning, formation and approval stages, and show comparative importance of top ranking high-tech project success drivers.

Much has been written regarding project performance, and the literature is rich in empirical studies of tens, and sometimes hundreds, of projects in an effort to distil factors governing their success or failure. Case study work, involving report analyses, interviews and questionnaires offer much insight through evidential data complemented by qualitative judgement (Grün, 2004). Other studies have derived conclusions through statistical analyses and although meaningful, require more interpretation by the practising project manager.

Many studies stem from a perception that large, publically funded projects, often launched in a fanfare of optimism, frequently overrun in terms of cost and time and occasionally become *fiascos* (Grün, 2004). While many notable mega-projects[35] are delivered 'on time, on budget', large projects - especially those underpinned by, or delivering, IT or new technology - are very demanding of management capability, resources, and systems engineering, and too often fail in one or more performance criteria (Merrow, 1988; Morris & Hough, 1986; Hartman & Ashrafi, 2004; MoD, 2009; Neumann, 2009).

[34] This chapter is a slightly modified version of the author's peer reviewed paper titled: Crosby, P. (In-print). (2012). Key success drivers – meta study findings applicable to large high-technology projects, *International Journal of Information Technology Project Management*, *3*(2). See Appendix K.

[35] Defined in section 2.3

4.2 Research approach

In this chapter I mainly draw from peer reviewed journal publications, supplemented by published reports and case study extracts from academic authors. Data were sought from a purposely broad range of studies from the Western world covering the past 35 years, containing diverse project characteristics in terms of purpose, budget, location, engineering innovativeness, and sponsor. The only selection made was to include a representative sample (one third) of high-tech projects with some systems engineering component identified. These sources were initially selected from literature searches using the keywords *'project success'*, *'mega-project'*, *'critical success factor'*, *'lessons learned'* and *'project learning'*. From this search, 29 general studies were selected for examination encompassing 2,820 projects (cases), as well as two success factor summaries drawn from other papers. A sub-set of 20 studies (928 cases) were classed as high-tech. From each study, the presented success factors (derived from questionnaires, statistical analyses, or both) were grouped into common headings and recorded by frequency. For example, phrases such as "clear project mission", "defined objectives", "stated project targets" and "documented program goals" were grouped as a single key concept. This process resulted in the most common findings being captured under 18 distinct headings. Table 4-1 shows the full study list.

Table 4-1. List of studies showing number of individual cases

Lead Author (date)	Nature of Study / Data Source	QuaN or QuaL	General Cases	High-tech Cases
Akkermans (2002)[1]	*General research*	*L*	*n/a**	✓
Anbari (2008)	*Post project reviews*	*L*	*n/a*	✓
Belassi (1996)	*Mixed projects*	*L*	*91*	
Blackburn (1994)	*Iridium satellite systems project*	*L*	*1*	✓
Clarke (1999)	*Various projects*	*L*	*n/a*	
Cooke-Davies (2002a)	*Variable projects*	*L*	*136*	
CSIRO (1998)	*Big science projects*	*L*	*9*	✓
De Wit (1988)	*UK & US projects*	*L*	*8*	✓
Dvir (1998)	*Qualified by P type*	*N*	*110*	✓

Dvir (2003)	*Defence projects*	*N*	*110*	✓
Ferratt (2006)	*ERP Projects*	*N*	*70*	✓
Grün (2004)	*Few major projects plus other information*	*L*	*4*	
Hartman (2004)	*Mixed projects*	*L*	*5*	
Honour (2004)	*Broad range of technology projects*	*N*	*42*	✓
Hyvari (2006)	*Mixed projects*	*N*	*100*	✓
Katsanevas (2009)	*Survey of physics project managers*	*L*	*n/a*	✓
Kerzner (1987)[2]	*General research*	*L*	*n/a*	
Kleinman (2008)	*Astronomy Survey project*	*L*	*1*	✓
Merrow (1988)	*Large civilian projects*	*L*	*52*	
Milosevic (2005)	*Project Managers*	*N*	*55*	✓
Morris (1986)	*Civil and aerospace projects*	*L*	*8*	✓
Muller (2007)	*General large projects*	*N*	*959*	
Murphy (1974)	*Various projects*	*N*	*646*	
Ninin (1997)	*CERN projects*	*L*	*4*	✓
Pinto (1989)	*R&D Projects*	*N*	*159*	✓
Procaccino (2002)	*IT professionals*	*N*	*21*	✓
Rubenstein (1976)	*Mixed study, some R & D*	*L*	*103*	✓
Turner (2004)	*Various projects*	*L*	*n/a*	
Verner (2005)	*Software projects*	*N*	*122*	✓
Weck (2006)	*Project practitioners*	*L*	*5*	✓
Winch (1996)	*Review of several 'classic' projects*	*L*	*n/a*	
	Total Cases		**2820**	**928**

1. *Extracted from Ferratt (2002)*
2. *Extracted from Lim (1999)*

**n/a = No. of cases not stated*
L/N = Qualitative /Quantitative Study

In the course of research for this thesis, I conducted wide ranging formal interviews with project management representatives and teams.[36] Discussion concerning success factors formed part of these interviews and the opportunity was taken to refine and validate the 18 common headings for grouping the success factors drawn from this study. The method involved note-taking (or recording) of each interview, and verbal verification of the interviewee's meaning of phrases used. Identical, or similar, meanings were manually correlated. The interviewees were not asked to rank the factors, just agree or disagree with the classifications, resulting in minor changes to the common heading terminology only.

Having grouped the success factors, and their frequency of occurrence drawn from the meta-study of the publications, calculation techniques from the Analytical Hierarchy Process (AHP) developed by Saaty (Coyle, 2004) were applied in the form of pair-wise comparisons to reveal a ranked set of success drivers, followed by statistical consistency tests to check the confidence level of the results. This work is described in detail in Appendix F. No attempt was made to pursue the analysis through weighted criteria to a single choice, since clearly all 18 resulting success drivers are contributors to success, and are highly interrelated.

The output from this analysis is shown in Table 4-2, which presents the derived project success drivers ranked by relative importance for all projects, and high-tech cases.

Table 4-2. Success drivers ranked by relative importance

#	Success Driver	All Projects Ranking	High-tech Ranking
A	*Project management (PM) control & execution systems in place, with robust policies, planning, procedures, document control, audit, etc*	*23.72*	*23.87*
B	*Clear project definition, requirements, goals, objectives, scope, and project mission; sound business case*	*23.72*	*19.53*
C	*Mature project communication, information systems; effective public relations management*	*11.34*	*11.18*
D	*(Top) management (or sponsor) support with sustained commitment, appropriately engaged*	*7.85*	*8.96*

[36] See section 1.3.2

E	*Project baseline, estimates accuracy, project phasing, effective project performance (reviews) and measurement*	*7.85*	*8.96*
F	*Leadership skills, PM experience & stability; motivating & socially capable PM*	*5.24*	*5.79*
G	*Agreed realistic customer / user expectations; frequent customer contact*	*3.17*	*3.37*
H	*PM/Organisational understanding & competence in project management*	*3.17*	*3.37*
I	*Adequate resourcing of the project*	*2.31*	*2.37*
J	*Aligned perceptions of project goals & success - management and team; sense of urgency instilled*	*2.31*	*2.37*
K	*Effective stakeholder engagement / partnership (e.g. client, contractors, etc)*	*2.31*	*2.37*
L	*Organisational responsibilities assigned to right-sized capable team*	*1.68*	*1.64*
M	*Mature, effective project management change control process; effective deviations handling & configuration control*	*1.68*	*1.64*
N	*Understanding & continuous management of risk; visibility of risk register*	*0.91*	*1.13*
O	*Project Manager & PM systems matched to project complexity, and culturally aligned*	*0.91*	*1.13*
P	*Effective means of learning from experience and continuous improvement environment*	*0.66*	*0.78*
Q	*Full understanding, and early engagement, of host government environment and institutional requirements*	*0.66*	*0.78*
R	*Right-sized systems engineering; managing and procuring in right sized project 'chunks'*	*0.51*	*0.78*

4.3 Key findings and conclusions

The ranked project success drivers in Table 4-2 reveal some valuable general conclusions for the project practitioner.

First, a relatively small (though not trivial) number of key project topics and indicators are demonstrated to impact significantly on the chances of success. Most significantly, implementation of excellent project control systems and processes, and a clearly defined project mission are shown to be twice as important as the next ranked driver. These considerations are important throughout the project but it is clearly necessary to test the intent, robustness, and understanding of these factors at the conceptual/approval stage.

Second, the rankings show the importance of 'softer' indicators such as social capability and expectations management that may not have been previously obvious. Selecting and appointing the right project management team are clearly vital, taking account of factors such as motivation, cultural sensitivity, and instilling the right amount of urgency. Moreover, recent studies highlight the need (some following negative events) to invest in effective project information control, both internally and externally.

Third, some factors that may be intuitively expected to rank highly e.g. risk management and system engineering process (as opposed to the application of systems design as part of goal setting etc.), appear low in the table, ranked at N & R respectively. At face value, this indicates that while important, these may not be the make-or-break factors that alone determine project success or failure. For risk especially, this was counter-intuitive to contemporary experience and is worthy of further enquiry to separate the management science approach (the probabilistic future) described as *decisioneering* (Miller & Lessard, 2000), and the more applied managerial approach (the uncertain future) that continually matches risks with strategies. The topic of risk is revisited later.

Lastly, it will be noticed that, following the analysis, both general and high-tech columns rank the success drivers in the same order, albeit with differing importance values. The variations, although minor, reflect the character of high-tech projects (often involving R&D) where definitions and scope are often less clear, making top level support and baseline information more necessary. Similarly, management of risk, complexity and systems engineering process require slightly more emphasis. Overall though, high-tech projects clearly rely on the same key success drivers as most other projects.

The combined analysis offers more insight for high-tech project practitioners than contained in the 'headline' rankings alone. To extract the key subtleties revealed through scientific analysis and the ‘lived experience’, a closer examination of the top ranking drivers follows.

4.3.1 Project management system

The extent of a formal project control environment is largely a decision taken by the project management, in light of organisational policies and practice, type/size of project, and to some extent, project leadership style. Observations by the author revealed the application of single-machine/small network systems (e.g. MS Project), various tailored project management systems (in some instances designed to align with published ISO Standard type quality systems), and large corporate management information systems (MIS) such as PRIMEVERA, DAPTIV, MRP, and SAP. Findings from this meta-study show that, although the project control environment must be well matched to the task in terms of complexity, culture, and maintenance, though no one system or product stood out. The key point is that a system of some type must be in place.

The importance of standardisation in projects is highlighted by Milosevic & Patanakul (2005, p. 189) in their survey of project managers who collectively concluded that: *“having standardized PM tools helps with project success: more punctual schedules, more satisfied customers, better cost-effectiveness, and higher-quality accomplishments.”* An empirical analysis of the relationship between project planning and project success by Dvir et al., (2003, p. 95) found that: *“A minimum level of planning tools and procedure use is also important but what kind of tools is of no importance.”* A very frank report from the Gemini telescope Lessons Learned Workshop (NRC, 1999) contains at least five quotations from team members lamenting the lack of, or lateness, of effective project management control.

Atkinson et al., (2006, p. 691) support project tools but with a caution: *“tools and techniques…are very useful in the right place. However they [can bring] a focus on operations…with consequent lack of attention to strategic issues”*. Erno-Kjolhede (2000, p. 31) also qualifies in remarks about project management theory applied to research projects when writing *“project management tools for scheduling and planning are helpful in research projects – but also potentially misleading. Thus they should be used as flexible* *tools that are continuously adjusted to fit current project reality. They should not be regarded as a blueprint for the research project"*. An OECD report endorses proven, standardised tools to support large science infrastructures, though it points out that some partner countries may already have approved management tools and procedures, and their use may be mandatory (OECD, 2010).

Ninin & Vanden Eynden (1997, p. 4) investigated the application of project based management for high-tech activities at CERN, referencing a 1997 inquiry showing that 100% of staff involved supported the concept. They conclude that: *"project-based management has been experienced recently for several controls projects and has proven its success from the human, organisational and managerial points of view."*

4.3.2. Project mission, definition and goal

Pinto & Slevin (1989) in their compelling report containing 10 critical project success factors posit that the project mission, while apparently obvious, is *the* most important factor across all project phases and argue that if forgotten or unclear, the project will likely fail. Clearly the early stakeholders must not only know and agree on the purpose of the project, but also ensure that it is defined in the form of a documented and socialised scope containing technical objectives and goals, supported if appropriate by a business case.

Hartman & Ashrafi (2004) in their paper on SMART project planning recommend the establishment and agreement of success criteria at the outset, claiming this to be the single most important contributor to project success. Similarly, in 'Taming Giant Projects' Grün (2004) argues that goal formulation is one of four success factors that (inter alia) influences the causes of [project] failure.

A Royal Academy of Engineering report addressing complex IT projects asserts: *"Prior to commencing there should be a clear definition of the benefits to be derived from the project [without which] a project is destined to fail before it has begun."* (RAE, 2004, p. 21). However, not all large high-tech projects are able to have their mission, requirements, scope and goals precisely defined, especially in the early stages. In looking back over 30 years of project management, Winch (1996) discusses the difficulty of looking over the cognitive horizon, and how the political, economic and regulatory environment may result in project trade-offs. He nevertheless advises early resolution as far better than proceeding with unresolved aims.

4.3.3 Project communication

Competent information management throughout the project was found to be crucial (Clarke, 1999) to effective execution in two principal domains. The first area concerns communication with parties external to the project team, for example; users/customers, advisory committees, arms-length sponsors, political masters, suppliers, and the general public. Casework consistently reports the dangers of unofficial pathways for project information which may be interpreted (at best) incorrectly or (at worst) cause upset, or even financial or commercial strife, through premature announcements. The solution lies in the establishment of a project communications position early, and implement of firm policies for information approval and distribution, especially in relation to problems, procurement, or discoveries.

The second area concerns internal communications, with examples of commonly reported deficiencies represented pertinently by the Mars Climate Orbiter Investigation Board (NASA, 2000). Their report investigated factors leading to the loss of NASA's $125 million spacecraft: *"as a result of a mistake that would shame a first-year physics student – failing to convert imperial units to metric"* (O'Hare, 2009, p. 123). Under the general finding of inadequate communications between project elements during its development and operations phases, the Board lists specific inadequacies as contributing causes of software programming errors leading to mission failure:

- inadequate communications between project elements led to a lack of cross discipline knowledge among team members;
- a lack of early and constant involvement of all project elements throughout the project life cycle (e.g. inadequate communications between the development and operations teams);
- project management did not develop an environment of open communications within the operations team; and
- inadequate communication between the project system elements and the technical line divisions at the partnering research institution.

The weaknesses in the above example offer good lessons and reflect typical project interfaces at which communications breakdowns inhibit or prevent project success.

4.3.4. Top level support and commitment

Appearing as the fourth most important in high-tech project success, this driver is relevant to most business endeavours. Pinto & Slevin (1989) echo other writers when they identify the responsibility of top management to support and resource a project once authority for expenditure has been approved, and also mention top management's ability to either help or hinder a project. Indeed, there is some evidence pointing to the negative effects of too much management, citing 'interference' and 'meddling'.[37] Procaccino et al. (2002) adds that removal of a project sponsor has more detrimental effect on success than starting without one.

Despite the dangers of interference, casework research demonstrates the powerful benefit of committed and concerned senior level interest in a project's execution, and of a readiness to act supportively when needed. This is validated through the often referenced Apollo project studied by Seamans and Ordway (1977) who table as one of their lessons from Apollo: *"In the final analysis, the presence or absence of [top level] support is the single, most crucial element that spells success or failure"*. I conclude that top level commitment is vital for success, but note there is an important distinction between 'support' and 'interference'.

4.3.5. Project baseline, phasing, and performance monitoring

The purpose and importance of a project baseline is threefold: (a) as a basis for cost and schedule estimation for project approval, (b) to establish a performance measurement reference, and (c) to establish appropriate expectations of project management and team prior to project initiation. Carried out in the context of project scope and budget, the baseline supports the project launch decision and the inevitable trade-off decisions by project management during the project. Surprisingly, a documented baseline such as this is frequently missing from projects (Shenhar & Wideman, 1996).

Cost and schedule estimation is held as part science, part art, and is notorious for poor assumptions and inaccuracies, especially in IT projects where optimism bias can drive severe underestimations. Project estimators must take into consideration project based, and external,

[37] See section 3.3.4.2

events on an historical probabilistic basis, and allow for the calculated contingency that Butts and Linton’s casework (2000) show is so often understated.

Breaking large projects into phases and sub-projects, and the defining of work packages, is reported by Clarke (1999) as one of the most important tasks in new or development projects. Her study cites benefits including greater ownership by project teams; spread of responsibilities and accountability across a greater number of people; and easier delegation, objective monitoring, communication, problem identification and change management. This idea is developed further by de Wit (1988) in calling for specific objectives for different project phases, such that project success can be more usefully monitored and determined on phase performance.

The benefits of periodic project reporting is a common finding in studies of project success as Turner (2004) found when defining reporting as a critical condition of project success, and its absence as a route to failure. Kerzner (1998) similarly lists ‘uniform status/monitoring reporting’ as a critical success factor, especially in the growth stage of projects. Reporting systems should be internally consistent and ‘fit for purpose’ in that they should contain only sufficient, clearly presented data (supporting the modern ‘dashboard’ approach), avoid duplication and, where possible, be automated.

4.3.6. Project leadership and management

It is of course people who deliver projects, not processes and systems. Without competent, intelligent, and dedicated teams and individuals it is difficult to imagine any project finishing successfully. However, having the talent is not enough, and projects require both leadership (of people) and management (of processes and systems); these two attributes may not always reside in the same individual (Crosby, 2006).

Muller & Turner’s (2007) large study of project managers and their influence on success, points out positive correlations between project success and older, more experienced managers, and also warns against assigning managers to projects below their capabilities. Project managers should be appointed early, lead the project through to the commissioning stage, and ideally work in their own culture. No performance difference was detected between male and female managers.

Individual leadership qualities and their effect on projects are less tangible. Thompson (in Ashby & Miles, 2002) sets out three basic skills as predictors for success – capacity (knowledge and basic intellect, or innate ability), authenticity (the genuine article), and motivation (eloquently coined as: 'influence many, control few'). In a project with a history of problems, a weariness of change and lack of commitment, Clarke (1999) found that an absence of these qualities contributed to a general lack of motivation in people, especially to be a part of project changes. Clarke cites management example as one of the best ways to raise confidence and awareness of what can be achieved. As awareness increases of what is happening in their organisation, people become more involved and committed, and as a consequence, better motivated.

In the high-tech area smaller teams may work more effectively than in general projects, as Moody & Dodgson (2006) argue in their study of a complex aerospace project. They describe a single small, committed team with overlapping and complementary skills, made up of a proportionately large number of systems engineers with specialist knowledge across blurred project phases. This flexibility of implementation phases - which they suggest can only be done with a small team that can be across everything – is presented as a key to success.

Recruitment and nurturing of individuals cannot be ignored, as Rubenstein et al., (1976) show in their studies on influencing innovation success. Fieldwork indicated that certain people had played (often informal) roles in successful project initiation, progress, and outcomes.

Project managers and leaders have plenty of responsibilities and their selection can be pivotal to project success. However many high-tech research projects are cross-institutionalised and the project manager has only very little formal authority over project participants who are essentially peers, and who may only have a part-time commitment to the project. Erno-Kjolhede (2000) examines what 'power' to lead remains in such circumstances. He concludes that whilst accountability, commitment, information, influence, network control, and personal powers are attainable, formal authority must give way to persuasion and negotiation flair. He further argues that in high-tech projects, this is not necessarily a drawback. This approach to effective leadership and project success is more associated with knowledge, commitment, team-building, vision, and treating people as peers than it is with authority, subordination and issuing orders.

Gratton & Erickson’s study (2007) of 55 collaborative teams isolated eight human resource (HR) practices leading to project success, highlighting the benefits of capitalising on the trust residing in skilfully managed ‘heritage’ teams. Their research indicates that when 20% - 40% of the team members are already connected through past associations, strong collaboration was evident at the start.

There are indications from the research that project manager profile, especially more subtle traits, has a significant effect on project outcomes. Indications are that high-tech projects present special challenges worthy of psychological and psychometric investigation, and are suggestive of further research.

4.3.7. Other drivers

Following the most consistently highest ranked project success drivers, there are other strategic project dimensions in which early attention can materially influence success. Some of these areas, e.g. project manager competence, client/user expectations, and adequate resourcing, are well documented elsewhere. Other drivers have more subtle aspects reflecting specific research and are discussed below.

Urgency - Taking into account the caution concerning the potential harmful effects of urgency from Morris & Hough’s (1986) thorough study into precursors of success, the weight of evidence from more recent casework is that time pressure is a crucial variable for project success or, at least for avoiding project disasters. In this vein Grün (2004, introduction) alerts us to the: *“inherent silent power of time”*. Pinto & Slevin (1989) also emphasise urgency as having important implications for success in R&D projects, encouraging the project manager to instil a sense of pace into the team, on the basis that urgent projects demonstrate a greater ability to secure resources than projects viewed as routine, or even dull. However, it is possible to go too far, as the NASA investigation into project management of the failed Mars Climate Orbiter (NASA, 2000) showed. At the time, a ‘faster, better, cheaper’ (FBC) strategy pervaded NASA’s space projects, however the tipping point where increasing scope met downward driven schedules and costs was unforeseen, to the extent that unmanaged project risk was dramatically increased, ultimately inducing failure. A specialist report into the FBC approach from that time concluded that a major cultural shift was required to maintain the viability of FBC the approach (Spear, 2000). It should be noted that the Mars Pathfinder was an FBC success story from that era (NASA, 2011b).

Client/Supplier Involvement - Customers (often described as ‘users’ for high-tech facilities) can have a profound influence on project outcomes, as described in Procaccino’s study (2002) showing that success is directly related to the level of customer confidence in the project management and development team. Grün (2004) addresses the same point, describing it as the ‘worst case’ when no permanent users are nominated to be involved in the planning phase, resulting in the operation and maintenance phases being ‘left to chance’. In studies of R&D projects (Pinto & Mantel, 1990) and IT projects (Taimour, 2005), client participation is clearly identified as a leading success indicator.

Supplier engagement through the procurement process is similarly important, beginning with the industry engagement strategy (Schill, 1979) and implementation of a project contracting policy (Morris & Hough, 1986; MPA, 2009). In high-tech mega-projects involving R&D, pre-contractual relationships are both common and essential, and can pose a problem known as ‘lock-out’ which could mean exclusion of precisely those organisations that have specific relevant knowledge or skills from the early stages of a project (Hall & Kahn, 2006). Such situations require expert management to avoid impediments to successful project delivery.

Change Control - Findings from this study elevate the subject of change management from a project tool to a strategic success driver ranked (M) just above risk in Table 4-2. Both the literature casework and study fieldwork demonstrate that handling of deviations found through testing, failures, or inspection must not only be tackled systematically, but also be properly managed through corrective and preventive processes linked to configuration control systems. When discussing design changes in crewed space programs (where the impact can be potentially counted in lives) at NASA’s 2010 Project Challenge conference, one speaker expressed the view that ‘there’s no such thing as a small change’. Robust change management not only avoids repetitive errors: it is a foundation for continuous improvement through problem tracking and recording via a lessons-learned system and is thus a vital component of the project management system.

Risk - The topic of risk management has become ubiquitous in our society and the world of project management. This is reflected in contemporary PM literature and studies that offer modern approaches that attempt to match growing project complexity (Flyvbjerg et al., 2003; Harris, 2009). An example is the recently released Standards Australia draft handbook (Standards Australia, 2011) that revisits the relationship between risk management principles, framework, and process, and offers 19 techniques for risk assessment, including the common cause/likelihood matrix approach.

It is standard practice for projects of all kinds to create or adopt a risk management plan, evaluate project risk(s) by applying some form of score matrix, and establish a risk register to document the results. NASA's System Engineering Handbook (NASA, 2007a) points to the limitations of risk assessment methods underpinned by scoring matrices, listing these (p. 145) as:

- *"Interaction between risks is not considered. Each risk is mapped onto the matrix individually.*
- *Inability to deal with aggregate risks (i.e., total risk).*
- *Inability to represent uncertainties. A risk is assumed to exist within one likelihood range and consequence range, both of which are assumed to be known.*
- *Fixed trade-off between likelihood and consequence.*
- *Using the typical 'likelihood-consequences' matrix, the significance of different levels of likelihood and consequence are fixed and unresponsive to the context of the program."*

Nonetheless, fieldwork interviews reveal that this process at least helps identify and categorise risk (albeit often subjectively), as well as encourage risk mitigation techniques and/or controls (including the shifting of risk along the value chain). In the better examples, (e.g. the ALMA project) effort is made to plot the risk in terms of phases and value, thereby enabling risk retirement (or 'burn') to be tracked, although risk in projects is never reduced to zero (Thomson et al., 2001). Nonetheless, studies show that this pays off, as in the work by Voetsch et al., (2005) who concluded that 53% of the respondents who reported their projects conduct risk reviews "*Almost Always*" report completing projects on time. Voetsch et al., (2005, p. 6) adds: *"there is a statistically significant relationship between… the presence of a project risk management process…and reported project success rate of an organisation."*

Given these strong correlations, why does risk management rank relatively low among key success drivers? Fieldwork evidence suggests two reasons. First, whilst project practitioners agree that risk identification and management is a requirement, too often it is seen as 'busy work', pulled together largely to fulfil project funding or audits, and rarely consulted as a tool-at-hand to assist monitoring the project's exposure to failure (RAE, 2004). The second reason is simply that risk management is seen as part of the project fabric, something that the project manager practises subconsciously in daily decision-making, and does not report as an explicit success factor. Both explanations indicate a lack of serious and active risk assessment, at least partly explained by Butts & Linton (2009, p. 47) in their insightful report concerning project estimation failures in NASA:

> *"Often it is not what we know will get us. It isn't even what we don't know that bodes trouble. It is what we don't know that we don't know that hoses (sic) things up. This is a cognitive blind spot created by the fundamental nature of knowledge that has not yet been encountered."*

It is therefore the very nature of risk that, despite the difficulty in identification and quantification, it should drive project proponents and managers to more diligently assess significant threats, their potential impact, contingency, and mitigation.

External environment - Projects are not always self-contained: big high-tech projects in particular can require large physical spaces for development or deployment, involve regulatory standards, require public funding and/or political support, stakeholder engagement, and may rely on social approval before proceeding. Belasi & Tukel (1996), when grouping factors for project success, identified this external framework of political, economic, and social factors, including marketplace forces. They point out the potential for early project termination should such factors be judged too risky or influential. Other factors, addressed by the RAND study of 52 mega-projects (Merrow, 1988) stress the potential conflicts between projects and institutional problems associated with environmental regulations, health and safety rules, labour practices and procurement controls. Fieldwork showed none of this has since diminished.

System Engineering - Finally, the concept of system engineering (SE) and its value, especially to complex projects, is often raised at the development stage of high-tech projects. Prevalent in defence, and large engineering projects, the aim of SE is essentially to apply influence at the design phase to enable easier and faster integration and test, ensure interface compatibility, and reduce risk, time and cost. SE is a discipline in itself, and where the approach is applicable, it is fundamental to project lifecycle management.

Swart and Meiring (2003) examined the application of SE to the SALT telescope, affirming its application to such high-tech projects, and describing schedule and technical benefits, and the potential to influence cost profoundly, as Fig. 4-1 shows.

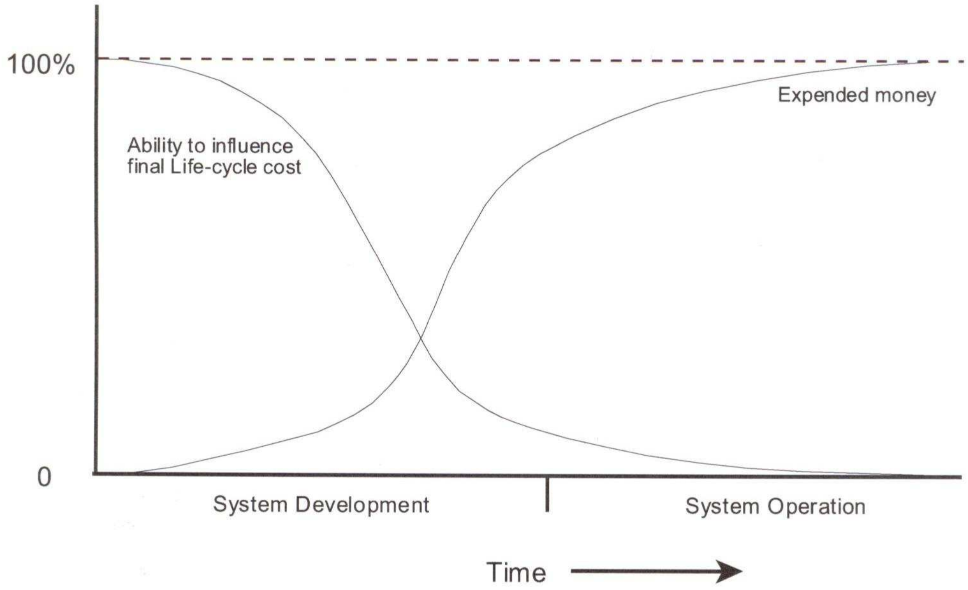


Fig. 4-1. System engineering ability to influence cost (Swart & Meiring, 2003 p. 169)

A detailed study (Honour, 2004) of 42 projects and SE practice shows consistent correlations between investment in SE and project success (especially regarding over-runs, cost and effective risk retirement) as well as subjective rises in output quality. However a one-size fits all approach to SE is not indicated and care is needed to avoid over-driving the project with SE. Honour's work (2004) determined that in terms of person-effort, the optimum is 15-20%, a figure he found corroborated in prior works by NASA and by Kludze (2004), and confirmed by the UK VISTA £35 million infra-red telescope project. Similarly, when describing the large and complex Gemini telescope project, then Engineering Leader Dick Kurz believes that: *"it takes… professional SE to really carry it off"* enabling the project to stay on budget and close to schedule (Michaud, 2009, p. 34). Fig. 4-2 shows the distinct areas covered by systems engineering and by project control, and the tasks requiring management by both functions.

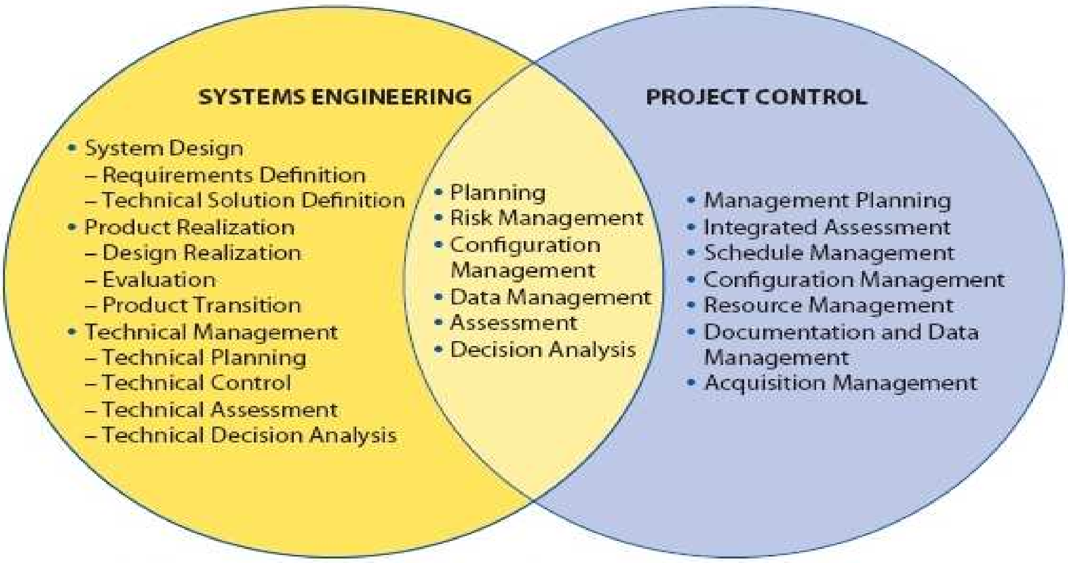


Fig. 4-2. The interface/overlap between system engineering and project control (NASA, 2007a p. 4)

4.4 Implications for management

Once the key success drivers are derived and ranked, attention can turn to exploiting the knowledge across the project life-cycle. The detailed processes for establishing the project organisation, environment, and toolset, are outside the scope of this thesis, however, assigning the identified success drivers from Table 4-2 to the project stages and strategies shown below ensures that the key concepts may be embedded at a productive point.

Conceptual Planning - This is the time for clarifying the project definition, scope and goals, and if required, the business case [B]. Sponsor commitment must be in place, and client/user expectations agreed [D, G].

Post Concept Approval - At this point strategies are developed for dealing with operations in the host environment [Q], key resources are identified and secured [I] (including management [O]) and a detailed risk review undertaken [N].

Project Approval - Strategies are implemented for project policies [A], systems engineering, site acquisition, procurement [Q], information management (including outreach and Public Relations) [C], and staffing.

Project Commencement - Planning, execution, and review systems, operating procedures, and document controls [A] are now instigated. Project baselines and phases are defined [E]. Change management, continuous improvement [P], and configuration control [M] are established. Strategic relationships are commenced with key suppliers [R].

Project team governance is asserted early through the project manager's approach to leadership, motivation, and social competence [F]. Especially important at this stage is the assignment of accountabilities [L], aligning staff perceptions of goals and success, and instilling a sense of project momentum [J].

Post-Project Reviews and Lessons Learned – Given clear evidence that, despite the collected experience from general and high-tech projects, failures continue to happen, the question begs – why do we fail to learn from them? Current practices evaluated by the author indicate an understandable focus on achieving the project deliverables, with many time-poor practitioners unwilling or unable to find and digest the experience of one or more cases relevant to their own project. Lovallo and Kahneman (2003, p. 8) investigate cognitive behaviour in projects and conclude that: *"the natural way [managers] think about a complex project is to...bring to bear all one knows about it, paying special attention to its unique or unusual features. The thought of going out and gathering statistics about related cases seldom enters a planner's mind"*.

The formal conduct of a post-project review involving at least the core execution team is essential and could be viewed as a post-project success driver. In at least one major high-tech organisation (NASA) the costly failure to learn from past mistakes has been addressed through an Agency-wide 'lessons-learned' case study initiative. The topics of project reviews and lessons-learned are further explored in section 5.3 of this thesis.

4.5 Chapter Summary

This chapter has presented a broad and deep meta-study of success factors in both general, and high-tech, projects reported in the literature. Applying peer judgement derived during wider research for this thesis, the most frequently reported success factors were grouped into 18 common headings, and subject to frequency analysis.

Application of the Analytical Hierarchy Process (pair-wise analysis) shows that project management control and execution systems, and a clear project definition and goal set, are by far the most important drivers of project success. Mature information management systems rank third in importance, followed by 15 other significantly important factors shown to feature markedly in improved project outcomes.

The next chapter builds on the preceding investigations of pre-cursor success factors and meta-study derived success drivers by investigating remaining key considerations of high-tech mega-project success.

Chapter 5 – Project execution – other key considerations

5.1 Project manager characteristics and techniques for success[38]

5.1.1 Introduction

The head of the management team of any large high-tech project will naturally be selected for his or her demonstrated skills and experience in leading such enterprises. This section of the thesis looks beyond the overt qualities of high-tech mega-project managers, and seeks to reveal the less obvious characteristics, traits, and initiatives that lead to project success. I examine these characteristics through examples drawn from the literature, and evidence from recent and current cases of large, complex projects. I expose the personal and professional attributes, skills and exemplar initiatives that are ingredients in project success.

The management of big, high-tech projects has been repeatedly investigated but is not well understood (Cook-Davies, 2010), especially in terms of the personal characteristics and applied techniques of the project manager. While general competency standards (e.g. the PMBOK® Guide) exist, and some high-tech organisations have implemented their own codes (e.g. the NASA's Systems Engineering Competency Framework, [NASA, 2009b]), these very much focus on application of vocational skills.

Early research into managerial characteristics leading to success or failure relied on trait theory (inherent personal qualities). Only later was training potential recognised as underpinning a situational or contingency theory of management (Müller & Turner, 2010). The 1980s popularised the visionary approach (vision and missions statements etc.) focusing on organisational change, followed by embracement of the soft leadership factors of the emotional intelligence school and more recently the development of the competence school (Müller & Turner, 2010). Traditional management theory places greater authority at higher organisation levels on the premise that senior managers know more, can make better decisions, and adopt command and control responsibility (Nicholas, 2004). However in complex, high-tech organisations it is valid to challenge this point, since system complexity, coupled with reliance on subordinate specialists, means that managers – especially at top leadership levels - are unlikely to know everything needed for complex decision-making.

[38] This section is drawn from the author's peer reviewed paper titled: Crosby, P. In print. (2012). Characteristics and techniques of successful high-technology project managers, *International Journal of Project Organisation and Management, 4*(2). See Appendix K.

Contemporary high-tech project managers are typically required to work in a number of dimensions including project leadership, research supervision, technical realisation (sometimes amid a daunting range of deliverables), financial accountability, planning and schedule responsibilities, project communications, and the challenging art of people management. For those whose forte is essentially project execution, the project formulation period especially can present bewildering problems requiring quite different skills and characteristics (Sykes, 1990). Adding to the challenge are the complexity and seemingly intractable nature of mega-projects. Even where authors have devised success 'roadmaps', the number of pathways and inter-relationships can be daunting (Murphy et al. 1974; Grün, 2004).

While recruitment processes are typically diligent when considering experience, background, and training of candidate project managers, I attempt to identify more subtle and deeper level characteristics of project managers that might be of practical use for improved selection of candidates for future projects.

5.1.2 Data, and research method

My research for this part of the thesis includes accounts relating to large high-tech projects, and published from the mid 1970s to the present. This period offers rich experience from peer reviewed research papers, relevant case studies, and articles from the professional management domain. Research also canvassed the popular bodies of knowledge (e.g. the PMBOK® Guide, as well as published accounts of specific big science and engineering projects. An important initiative from the literature was the UK research activity called Rethinking Project Management (Maylor, 2006). Of particular note from this work was the need for increased recognition of human issues, the social nature of projects, and resulting challenges for management.

Despite the breadth of work around the topic, there remains a knowledge gap relating to specific characteristics of managers with high-tech project success. To help bridge the gap by the use of contemporary field data, I conducted a series of investigations at several large scientific facilities in Europe, Chile, South Africa, and Australia (See Table 1-1). One aspect to this fieldwork was to probe commonalities and application of traits and techniques with a focus on the effects of managerial approaches and behaviours.

Field notes made from formal and informal interviews, general observations from experience in the workplace, and expert group meetings all supplemented the research. The combined methodologies of literature research validated through fieldwork, though by its nature incomplete, enabled the extraction of several recurring themes, each presented as detailed findings under sections 5.1.3 and 5.1.4 below, and summarised in section 5.1.6.

5.1.3 Project manager characteristics leading to success

Processes to recruit, interview and appoint the necessary outstanding individual to manage a scientific and/or engineering project are generally adept at attracting candidates with the required qualifications, project management exposure, and general experience. This study posits that the successful management of high-tech mega-projects especially, as distinct from large projects (Sykes, 1990), is a particular and highly challenging task, requiring a special portfolio of attributes beyond those commonly identified at interview. These attributes or traits are presented in this section as pre-cursors of high-tech project success, and are set out below.

5.1.3.1 The uncertain nature of mega-projects

A commonality between definitions of a project is that of a broadly definable task, and therefore necessarily a *temporary* endeavour. Mega-projects surviving the often precarious ‘approval for expenditure’ stage and lasting up to a decade or more may strike hurdles, or even get truncated, before reaching an operational phase. Those who run such projects have to know when to change course, when to proceed or pause, and above all, when to stop (Sykes, 1990). Thomas & Mengel (2008) suggest complex projects present ambivalence and ambiguity of the not-yet-known, with emerging situations that crucially shape meaning, interpretation, and social significance. When describing project shapers, Smith & Winter (2010) add to this the scanning of project boundaries for unwelcome ‘messengers’, and alert us to peripety; the arrival of events that reframe understanding of all that has gone before. Moreover, in developing the concept of *ProjectCraft*, Smith (2007) warns readers of social uncertainties in the form of unknown agendas, and emergent and divergent strategies. Interviews on this topic within the case studies (AAD, 2009; ITER, 2009; ALMA, 2007) confirm a fundamental attribute of the successful project manager – the ability to deal with uncertainty, and the personal career impacts, within an enterprise of undefined duration.

5.1.3.2 Personal authenticity

When asked about characteristics that underpin the respect and loyalty accorded to project managers, a common response across most project teams personally interviewed can be summarised as "authenticity' (AAD, 2009; ITER, 2009; CERN, 2009; Samuel, 2009; Kendra & Taplin, 2004). Phrases such as: *"he's done this before and draws on that experience*", "*a dogged, quiet achiever*", and "*he leaves the flag-flying to others and just helps us get on with it*", provide useful insight to attributes that are anecdotally linked to successful project execution.

In Verzuh, 2003, p. 27-30, Graham and Englund conclude that: *"Any lapses by upper managers in the authenticity and integrity of their dealing…are likely to have a severe impact on the achievement of project goals.*" They go on to say: *"It is a recurring theme in our experience…that authenticity and integrity link the head and the heart, the words and the action; they separate belief from disbelief, and often make the difference between success and failure"*. When discussing leadership, Thompson similarly identifies authenticity (the 'genuine article') among the three basic skills as predictors for success (in Ashby & Miles, 2002).

The broad appreciation for the success associated with project managers who demonstrate authenticity and genuine talent should not be confused with, or offset by, charismatic charm, despite its reported benefits within transformational leadership. Morris and Hough's (1986, p. 219) seminal study of project success and failure notes that: "*not all leaders are charismatic personalities...this in no way diminishes the significance of their leadership*". When considering charisma in his 5-year study of leadership, Collins (Ashby & Miles, 2002) found that truly successful managers tended to be modest, humble, and reserved, but enormously wilful personalities. Von Braun, the father of Western rocket technology, is described as not being an original scientist, or the discoverer of new physical laws, but he: *"always had this vision [and] enough foresight to exploit a chance of bringing it to fulfilment"* (Young et al., 1969, p. 23). Smith (2007, p. 83) adds: *"You become a leader not primarily because of your natural charisma, but because others believe you to be a leader"*.

Whilst a Major Projects Seminar (MPA, 2007) concluded that project manager domain knowledge increased the chances of success, the attribute of authenticity does not necessarily require deep knowledge of the project's science/engineering technologies and goals (Verner & Cerpa, 2005). Moreover, while technical ability does provide increased credibility in a high-tech environment, it should not be an overriding indicator of the effective project manager (Blanchard, 1990; Graham & Englund, 1997). In the case of Australia's nuclear research reactor, OPAL, the three project managers spanning the construction phase had no specific nuclear experience, but all were judged by team members as being competent technical project practitioners, and well matched to the task. Findings within a British Computer Society (2006, p. 22) report imply that domain knowledge may be more important in the IT realm, suggesting: *"IT project managers additionally require sufficient understanding of the technology...to identify potential difficulties arising...and to gain the respect of their team."*

5.1.3.3 Collaborative approach

A feature of modern giant scientific and engineering programs is their global involvement. Whereas projects such as CERN's Large Hadron Collider (LHC), and the coming Square Kilometre Array (SKA), physically span country borders, almost all high tech mega-projects are international collaborations regardless of their host location. To share know-how, risk and cost, resources may be pooled in the areas of research and development, project planning, and funding. However, as the preparatory SKA work has shown, this is not to say that there is always shared agreement of the goals of the collaborative partners.

The project manager, faced with the complexities of international collaborative working, requires a sound understanding of mechanisms for cross-cultural, multi-disciplinary groups – something only achieved by practical experience. The project manager is likely to be central to any high level strategic collaborations and competency is crucial for project success.

Collaborations with external parties also call for experience and skill. Goldratt (1997, p. 173) addresses this point in connection with project vendors saying: *"Persuading people to collaborate is always necessary. The time when you could dictate [to suppliers] is over. If you want people to think, to take initiative, you cannot dictate"*.

In a contemporary UK study (Samuel, 2009), the practical coordination of collaborations in mega-science is described as particularly difficult, with limitations imposed by time zones and travel budgets, this having implications for who is seen as the overall leader, and who is accountable and responsible for successfully delivering the project. Project directorates need to be very sure that the Project Manager can meet this key challenge.

5.1.3.4 Balancing leadership with management

Critical observation against modern theory shows that managers do not always transform into good leaders, or vice versa. Management is largely about coping with complexity and good managers bring order and consistency through processes, plans and structure, and by monitoring results. In contrast, leadership is concerned with directing change and aligning people by communicating an inspirational vision, and then helping them overcome hurdles (Crosby, 2006). To achieve success, both roles obviously require some capability of the other. Laufer and Hoffman (2000, p. xxi) write: "*most project management writings stress the managerial aspects of projects, failing to recognise the significance of leadership*", and conclude that project managers have to assume *both* leadership and managerial roles.

Müller & Turner's (2010) research into leadership competencies by industry type revealed strong correlations between successful high-tech managers, and critical thinking (intellectual quotient); team development (managerial quotient); and influence / motivation / conscientiousness (emotional quotient). Another report amplifies these traits, saying: *"leaders must apply intuition, emotional intelligence and empathy in building relationships and maintaining trust while dealing with uncertainty, risk and emergent ambiguous 'unknown unknowns' over protracted time-scales"* (ICCPM, 2011, p. 21).

The supervisory demands of high-tech mega-projects, characterised by creative people operating in environments of minimal formal structure and reporting relationships resonates well with the 'transformational leadership' (TL) style. First introduced by Burns and added to by Bass (Hötzel, 2004; Keller, 1992), TL describes a leadership approach that transforms followers into leaders, inspires extraordinary performance, and exemplifies coaching, mentoring and intellectual stimulation. Whereas transactional management reflects a cost-benefit exchange (plan, negotiate, and reward), transformational leaders articulate an attractive vision (excite, inspire, and support). (Stewart, 2006; Keegan et al. 2004).

The effectiveness of TL within the project world was investigated by Keller (1992), who formed the view that TL would appeal to well educated workers who desire challenges – traits that generally apply to R&D employees. However Keegan et al. (2004) conclude that, while project managers are not dissimilar to line managers in terms of TL behaviour, the positive effects may be less pronounced in the temporary project environment. Early results point to a weakening of effect due to: "*the multiple and temporary leader-follower relationships, shifting alliances, and overlapping social relationships* [seen in projects, meaning that] *project managers are unable to make the promises or exercise the same influence over career paths"* (Keegan et al. 2004, p. 615). However, the nature of complex, multi-disciplinary high-tech projects suggests that a TL approach should elicit increased performance levels and success, and further research may usefully examine new leadership theories and forms of organising project teams to fully realise these gains.

Whilst the literature is replete with examples of *leadership* qualities and project performance, there is little commentary concerning the characteristics of project *managers* relating to project success. Practical handbooks tend to skim over the topic, confining advice to the need for general management proficiency, adding characteristics such as knowledge of project management, performance accomplishment, and personal traits surrounding attitude, personality, team guidance, and driving project objectives while balancing constraints (PMBOK® Guide, 2008).

To round out the picture of practical application of leadership/managerial balance, we can look at real-world examples. A striking example came from my visit to the ITER project, where it was immediately clear that the new project manager[39] had taken a firm grasp of the challenge ahead, placed a small number of very capable people as his direct reports, and accelerated the awarding of civil works contracts. To paraphrase his remarks: *"I want scientists, engineers, and administrators to see those trucks moving and dust rising, we need to instil a feeling that this project is actually happening"* (ITER, 2009). The NASA Space Flight Program and Project Management Handbook (NASA, 2010b, p. 86), describes how: "*the Galileo PM had two management rules for working with his team: Do what I tell you, and don't let me do anything stupid—and he ensured his team understood that the second rule always took priority over the first."*

Case study interviews for this thesis (CSIRO, 2008; CERN, 2009; ASTRON, 2009; ITER, 2009) offer rich data revealing commonality of views concerning project manager traits as a combination of transformational leadership and management skills including:

- Qualified, and experienced, in complex technical projects
- Knowledgeable and functional in the popular project management applications (e.g. PRIMA VERA, MS Project)

[39] At the time of my visit, ITER (an experimental fusion power reactor) had recently come under much criticism for rising costs, delays and technical challenges. The former Project Director was relieved, in favour of an American led team that was clearly instilling a sense of pace through tangible site preparation. At the time of writing, the program remains in difficulties with completion now predicted to be 20 years late, and total cost to exceed € 15 billion, an increase of € 5 billion from the 2009 estimate.

- Obsessively mindful of the critical path, and always driving forward
- Effective delegator, but not afraid to 'get hands dirty' when needed
- Ready and able to do 'what it takes' to remove roadblocks
- Sets the example in terms of ethics, behaviour, and standards
- Maintains an intellectually demanding environment
- Maintains a systems engineering view, but is not stuck at that level
- Knows what to communicate, to whom, and when.

5.1.3.5 Persuading and negotiating

Interviewees from the field case studies underlined that, high-tech projects are characterised by design challenges including technology changes (e.g. ASKAP, 2009), contractual and construction delays and amendments (e.g. OPAL, 2009), commissioning problems (e.g. LHC, 2009), internal differences of opinion, and a host of external environmental challenges (Merrow, 1988; Eden et al. 2005). In the case of multinational science endeavours, it is not unusual for partner contributions to be 'in-kind' further complicating the authority hierarchy. More than one interviewee likened people management in high-tech projects to 'cat herding'.

A key skill then for the successful high-tech mega-project manager is the ability to foresee, mitigate, and manage these problems through skilled and sensitive persuasion and negotiation.

When reviewing large, dispersed collaborative projects Erno-Kjolhede (2000) concludes that whilst accountability, commitment, information management, influence and control have force, formal authority must give way to persuasion and negotiation flair. However he suggests that in research (high-tech) projects, this is not necessarily a drawback. Mega-project managers will require the confidence that comes with experience and maturity to strategically influence outcomes, and understand the advantages of transformational management. In a practical sense, there comes a time for each of the high-tech mega-projects considered by this thesis where R&D and technology develop must give way to construction, fundamentally changing the nature of the project execution. As one LOFAR team leader put it to me: *"At some point, we need to kick out the scientists"* (LOFAR, 2009).

Project Management Institute (PMI) documentation describes several project execution scenarios where the project managers' negotiation skills must be adept (PMBOK® Guide, 2008). These are borne out by fieldwork cases and include the highly demanding task of managing stakeholder expectations in terms of likelihood of project acceptance, proactively anticipating concerns, and resolving identified issues. To quote the Guide: "*Managing expectations helps to increase the probability of project success by ensuring that the stakeholders understand the project benefits and risks*" (PMBOK® Guide, 2008, p. 262).

Mega-project procurement, commonly assigned to a specialist department, will likely have some accountability to the project manager, especially when involving any major, strategic, or critical path acquisitions. Such activities draw on persuasion and negotiating skills as a key characteristic for successful contract execution and procurement logistics.

5.1.3.6 Trust, culture and diversity

Trust is a key ingredient (Sauer, 2008) in forming and maintaining collaborative social relationships, and several interviewees implied its importance unprompted. Samuel's research (2009, p. 28) draws on Politis (2003), Chowdhury (2005), and Ross (2006) when establishing that: "*trust is an important condition within any team since teamwork is dependent on knowledge sharing, and knowledge sharing is influenced by the degree of trust that exists between people".* Samuel continues: *"It is difficult to build trust...and whilst this is true of any team, the challenges imposed by geographical and cultural dispersion becomes particularly important for managing global teams."*

The challenge to build trust within global multi-cultural projects necessarily tests the capability of the project manager in dimensions rarely discussed at the project outset. Kendra & Taplin (2004) address the subject of project success within different cultural frameworks and identify the need to recognise the differing values and the task of developing shared value sets to underpin the building of strong project management. Riordan (2001) echoes this view for scientific and engineering cultures within mega-science projects while Aronson et al. (2010), in their study of project sprit and success, suggest that the project manager has responsibility for demonstrating and sharing a set of values which nurture the unique culture of high-tech successful projects. In discussing knowledge transfer barriers, Disterer (2001, p. 4) asserts that:

> *"Trust results in common expectations of reliability, consistency, and plausibility. Trust reduces the fear that others will act opportunistically.*

Likewise…management must act as peers to give an example in knowledge sharing".

Perhaps when the stakes are highest, issues of trust and harmonisation of diversity become most valued, yet conversely most testing. Following the Apollo program, NASA commissioned a 'lessons for management' report to identify key success characteristics that arose from this most complex technical endeavour (Seamans & Ordway, 1977, p. 294). In relation to dealing with diversity, the report found:

"NASA was dealing…with all sorts of people from all kinds of disciplines. Many of them were not used to working together, much less in the exposed environment characteristic of the Apollo program, In addition to engineers, technicians, and construction workers, [we had] theoretical scientists, legislators from Congress, lawyers, businessmen – a whole gamut of individuals. NASA's goals, problems, failings, had to be explained to all, in a language they could understand. [We] had to encourage all to work in an open, time-constrained, team-oriented, and stressful environment that was new and puzzling to many."

Again from the space engineering sector, Thomas Coughlin (Leader – NEAR asteroid orbiter project) ties trust to the successful delivery of a spacecraft within 27 months and US$4 million under budget. He explains the one-off launch window meant: *"I had to let all the people involved, including me, do their job, and only their job. This involved a lot of trust".* (Laufer & Hoffman, 2000, p. 193).

Finally, Graham & Englund (1997), when identifying environments for successful projects, are clear on the need for unprecedented levels of trust and openness, and caution that managers may have difficulties when coming from a less trusting organisation. Certainly, team leader candidates at large European projects (CERN, 2009; ITER, 2009) are questioned closely regarding their skills in nurturing diverse, cohesive teams.

5.1.3.7 Personal profile

While contemporary recruitment practices in science and engineering are clear regarding non-discrimination by way of age, gender, or ethnic background, it is useful to look at what the literature and current experience says about profiles and delivery of project success. Müller & Turner's (2007) large empirical study of project managers and the influence of their profiles (e.g. age range, experience, gender, nationality) on success, point out many useful implications when matching project managers to roles.

First, in terms of the importance of project success factors, the study reported that having experience with more complex and challenging projects increases the awareness of success factors generally, and that project managers should not be assigned to projects below their management capabilities. Contrary to Crawford and Cooke-Davies (1999), whose findings show no significant variation in terms of core success factors, some nationalistic variation was detected by Müller & Turner (2007). In their work, European project managers rated success factors as averagely important, significantly lower than other parts of the world (although peaking in middle age). No differences appeared in performance based on gender.

Müller & Turner looked further at differences by nationality. They point to Wang and Huang's (2006) work showing that project success may be determined differently than in the mainstream project management literature. Contrary to an emphasis on time, cost, and quality, Chinese project managers emphasise relationships as the main criterion for overall success. Research cited on the Indian IT industry (Agarwal & Rathod (2006) identified functionality within scope as the foremost success criteria. Overall, project managers with greater experience emphasise the importance and influence of team satisfaction on success.

There are also differences in rating of success criteria, and performance against them by age, reflecting a growing of confidence with experience. Older project managers assign higher importance to teambuilding, and research in the military acquisition environment (Gadeken, 1995) strongly links competencies to experience. Müller and Turner (2007) found this well supported by Lee-Kelley & Leong, Loong (2003), and Dolfi, & Andrews (2006), each finding a significant correlation between project manager experience and project success.

Second, project managers that are capable and responsible for the wider project life cycle (not just planning, execution and close-out) tend to be more successful. Project managers should therefore be assigned at the earliest stages and ideally lead their project up to the commissioning stage (supported by Murphy et al. 1974).

Third, Müller and Turner (2007) found that project managers working in their own culture tend to be more successful than expatriates, implying improved outcomes from local site candidates, mentored (if needed) by a more senior manager who may come from abroad.

Gadeken (1986, p. 41) surveyed the profiles and career progression of 1300 engineers and scientists and found: *"that manager-engineers exhibit the same preference for leadership roles that [other] managers do, but do not possess the same level of social poise nor enjoyment of human interaction"*. Gadeken's (p. 44) advice that: *"engineers and scientists need more interpersonal development to improve both their selection opportunity and success"* remains a valid pointer for today's recruiters.

Whitty (2010) sees the project manager acting a role through adopting a persona that is largely about looking the part, in order to play the part. His broad research characterised project managers as fulfilling emotive needs through dressing and behaving in 'expected' ways, yet finding individuals feeling anxious and tense, yet excited in their jobs.

Finally, an intrinsic quality of the mega-project manager is the intellectual maturity and discipline to manage beyond: *"the rational, objective, and universal representations of 'the project' with a phronetic analysis of the ambiguous, fragmented and political reality of project situations"* (Cicmil et al. 2006, p. 679). For high-tech IT projects, Souer & Reich (2008) couple these qualities with the need to exhibit emotional intelligence that reflects deep personal identification with project goals. The foregoing notions imply a 'super-manager' with vast experience, and delivering success in the face of great uncertainty, while expertly tackling the challenges of the wider economic, geo-political, diplomacy, and social aspects of the project (Blanchard, 1990). The present study found it is precisely this rare mix of intelligent gravitas, technical awareness, social proficiency, and political confidence that sets outstanding mega-project managers apart.

5.1.3.8 A sense of mission and urgency

Ultimately a key characteristic of mega-project managers is the enthusiasm and determination to keep driving the project forward, and to effectively communicate this 'sense of mission' throughout the team (Graham & Englund, 1997; ITER, 2009). Mega high-tech enterprises have voracious appetites for funds, even during quiescent periods, and maintaining progress is crucial, especially when unplanned deviations occur.

Managers might well consider the analytic approach from Goldratt's (1997) *Theory of Constraints* (TOC) that contends that any manageable system is limited in achieving its goals by constraints acting on the critical path. The TOC process seeks to identify the constraint and restructure the project execution around it, using five focusing steps.

NASA manager, Jerry Madden (Laufer & Hoffman, 2000) argues that a critical characteristic for project managers is the application of judgement to position stress levels between lethargy and team fatigue. The skill to juggle resources, quickly re-plan, and restore the critical pathway requires a special, multi-dimensional intellect and the ability to maintain a balance between unproductive stress and pressure, and motivating urgency. George Morrow, NASA's Director of Flight Projects concurs with Madden, adding: *"If we managed the early phase of projects with the same sense of urgency as systems integration and test, we'd be a lot more efficient in the overall life cycle"* (NASA, 2009a, p. 33).

Grün concurs while tackling a different aspect. He argues that in order to achieve success, the project manager must be prepared to limit goals so as to counterbalance the tendency to expand the technical scope of mega-projects. Such forces are often hard to oppose in high-tech projects and: "*therefore it is essential to have, or to create time pressure for the project."* (Grün, 2004, p. 31). Specifically in the software project area, a sense of urgency was strongly linked to regular project checks, and listed third in Attarzadeh and Ow's list (2008) of IT project success factors.

When looking to create positive, and diminish negative, determinants of success, extensive research by Murphy et al. (1974) asserts that the project manager should develop commitment and a sense of participation and mission among project team members from the outset. Seamans & Ordway (1977, p. 275) recount from their Apollo project study that: *'To marshal our resources and order our course is a task of the greatest delicacy which must be accomplished under the most relentless urgency'*. It is likely that the pace-setter in this case stemmed from the Presidential announcement of a lunar-landing within a decade, itself driven by fear of the Russians winning the race to the moon; nonetheless it shows the influence of executive level decree (Young et al., 1969)

Finally, my fieldwork interviews from the present study revealed a tangible sense of proprietorship at the ranks of senior management, and this was cited among many project teams as important in driving the project mission in terms of direction and maintaining pace. (CSIRO, 2009; CSIRO, 2008; CERN, 2009; ANSTO, 2009, TOPSAT, 2010). Peter Swenson, ITER's project manager stated in interview: *"I got [concrete delivery] trucks rolling to show the project was moving and to show a sense of urgency. I wasn't popular by putting the scientists on time recording [but it emphasised] the way to go forward"* (ITER, 2009). Ms. Loots, MeerKAT's Risk Manager, told me: "*We need to keep tension in the project execution system"* (MeerKAT, 2009).

5.1.4 Managing project initiatives and environment

5.1.4.1. Project structures and teams

The effectiveness of a project to achieve its goals is dependent on the shape and functionality of the project structure and operating environment (Graham & Englund, 1997). Miller and Lessard (2000) go further, arguing that institutional arrangements and strategic systems are greater determinants of success of large engineering projects than project engineering and management.

Management structures, and especially the relationship between management and stakeholders in large high-tech projects, commonly generate tensions for the project. As one recent European study (Katsanevas et al. 2009, p. 56) found:

> *"the existing successful projects demonstrate that a certain degree of structure and management is not only necessary, but can also support the success of the science project itself. The balancing between enough regulation or structure and too much has to be done in a way satisfying both the researchers and the funding agencies".*

Collaborations can also present demands on project structures, especially in the case of equal partners. The initial 50:50 division of the ALMA radio telescope project between European and American partners (ESO and NRAO respectively), each having a project manager operating under a joint Board, naturally slows down and complicates any decision making. (ALMA, 2007).

The Australian OPAL nuclear project commenced without a formal project manager, favouring instead a Management Board drawn from other parts of the ANSTO organisation. However this was soon found ineffective and a 'traditional' project manager role was then established, successfully taking the project through to completion. Once established, the manager/team relationship clearly worked, with a former project officer stating to me: *"These were people like I've never met before; they never took a sick day"* (OPAL, 2009).

Experience from the successful AUGER project, operated under the auspices of Fermilab, show that even in loose structures, some rules are needed, and responsibilities need to be clear. A noted feature of AUGER's success was the project manager's proclination to frequently visit the many partners, facilitate exchange of information, and address problems promptly and visibly (Katsanevas et al. 2009).

The ability to effectively manage team-based structures applies equally in the commercial environment. In a report on the success of the 343MW Huntstown CCGT power station in Ireland (Garnett & Hatfield, undated p. 5) the authors conclude:

> *"Open teamwork [between contractors and staff] proved to be a definite benefit to the project. With the complexity of construction, there will be no shortage of [failures and mistakes] to overcome without having an institutional adversarial blood stream running through the project".*

Samuel's study (2009) concurs with the present study's fieldwork and with commentary from the AUGER project, that in mega-science/engineering teams (and academic groups particularly) the need for team building activities was considered to be inappropriate and largely unnecessary. Each of these sources reason that association with a project having a grand science ambition is sufficient basis for a robust common passion.

In the high-tech area smaller teams may work more effectively as Moody & Dodgson (2006) argue in their study of a complex aerospace project. They describe a single small, committed team with overlapping and complementary skills, made up of a proportionately large number of systems engineers with specialist knowledge across blurred project phases. This flexibility of implementation phases - which they suggest can only be done with a small team that can be across everything – is presented as a key to success.

A study by Gratton et al. (2007) of 55 collaborative teams isolated eight HR practices leading to project success, highlighting the benefits of capitalising on the trust residing in skilfully managed 'heritage' teams. Their research indicates that when 20-40% of the team members have past associations, strong collaboration was evident at the start. The success rate of 'heritage' teams points to an interesting area of future research.

Casework interviews confirmed that team confidence and experience is an important precursor to success. R. Ekers, former Director of the Australian Compact Array, stated: *"We knew we had the best team on the planet at the time to do this...a small number of 'top notch' systems thinkers... with a median age around 40"* (CSIRO, 2008).

The present study found that setting up a standard project management structure within the organisation should not absolve the project manager and/or Directorate from reviewing its effectiveness, and instigating change where necessary. Germany's XFEL x-ray laser project commenced under a thorough, well documented governance structure, yet was later compelled to recommend a taskforce review to deal with the orthogonal nature of external entities (DESY, 2009). Projects managers need to be ready to embrace such change.

In summary, when selecting potential managers for scientific and engineering projects, Directorates should not overlook the matching of characteristics to the operating environment and structure. A manager may appear to have failed at one assignment, yet could perform well at another with different organisational and team conditions. Organisational structure, control, systems, and processes are not on their own sufficient for successful innovation, and there is overwhelming evidence that the right individual is a necessary condition for project success (Rubenstein et al., 1976).

5.1.4.2 Managing task forces

Despite considerable planning, risk assessment and capable management, it would be most unusual for a major scientific and engineering project to proceed to conclusion without a significant problem appearing. Occasionally, something approaching a 'wicked problem' may emerge that defeats normal problem-solving approaches (Partridge, 1981). One study found that, on average, projects met five unexpected events during execution, and some had twelve (Miller & Lessard, 2000). The handling of problems that threaten the critical path is a key test of capability for the project manager, and any recruitment process should carefully review the candidate's approach, experience and performance in relation to major problem solving.

The recognition of the need for immediate assistance, convening of specialist personnel (physically or virtually), managing the process to solve the issue, and transferring the outcomes to the project team(s) are all vital functions, requiring leadership, mature judgement and coordination skills of project managers. Each of the case studies for this thesis employed the task force (or' Tiger Team') concept, an ad-hoc group operating heuristically to deal with a crisis, critical deviation or roadblock (Pavlak, 2004b).

To further explore this aspect, I conducted a mini-survey of eight experienced leaders of large scientific and engineering projects (see list in Table 1-2). Each respondent was asked to comment using narrative against questions designed to elicit better understanding of the operative nature of task forces, and the challenges they pose for high-tech project managers. The three 'open' questions posed were:

a) Overall, how well do you think task forces are effective in achieving their stated goal? (i.e. how likely are you, or were you, to set up or join a task force to solve a problem?)

b) What conditions do you consider necessary for task forces to be successful?

c) What kind of problems are best suited to be solved by a task force?

The conclusions of the research focus group are shown below, gathered under three aspects:

Membership & Support - The ideal task force team size is between six and ten members. Other than support staff, all members should be professional scientists/engineers offering a fair representation of skill and opinion. As in other project groups, it helps if members know each other and can bond quickly. A mixed gender membership from the same or close generation is suggested. An expense budget should be set, and if secretarial support is required, this function should be managed only by the leader.

Authority & Scope - The task force must be given a clear mandate in the form of a task statement and deadline. The problem to solve must be clearly scoped, and any terms of reference should be brief and non-restrictive, other than having task depth and boundaries defined. Often, the task force itself will not be given authority to make actual decisions, however any authority awarded must match the responsibility/accountability required.

Success factors for task forces

- Task forces operate best when tackling (a) emergent program level challenges to enable an effective technical way forward, and (b) addressing deficient organizational practices to improve the program.
- There is a will amongst stakeholders for a situation to be un-stalled, or solved.
- A deadline or other imperative exists.
- The task force members are able to ‘roll their sleeves up’, leave their egos at the door, and become totally objective. ‘A ‘burn’ on the problem by a small group can often break the impasse.’
- The group is co-located, appropriately isolated, and really taken ‘offline’. The group is given management and organisational support, and is relieved of other duties and distractions.
- Frequent meetings and reports to the project manager or sponsor are used to keep on track.

- The format of the outcome is defined, and the ‘end conditions’ built-in so that closure is effective.
- The results must be capable of being actioned/implemented.
- The task force leader must have technical expertise and a systems perspective, be experienced in the domain, and have the ability to synthesise the outcomes. The team leader needs to be smart, objective, build confidence and trust, and be a respected ‘dictator’.

The survey indicated that, while some delay normally occurs in assembling the members, task forces were effective in quickly tackling ‘showstopper’ events. They bring focus to wide-ranging discussions (e.g. technology options), simplifying complex problems, and are useful to reset the existing pathway to an outcome. Using scenario analysis, task forces can explore unfolding circumstances in emergency planning, or as part of strategic planning (Standards Australia, 2011). As such, the timely assembly and deployment of a task force in response to project stress offers a useful interview topic for candidate managers.

5.1.4.3 Project information management

It is one thing to create or shape a project structure, and another to make this effective through communications and information management. High-tech projects have an inherent need to convey large amounts of complicated information across a range of domains and levels both inside and outside the organisation.

My fieldwork for this study revealed two important areas beyond functional document control processes that draw on the characteristics of the project manager – that of managing information exchange (the delivery dimension), and managing information dissemination (the content dimension).

Technical data, designs, system descriptions, and other evolving documents normally require iterations within and outside the project and need careful consideration by management in terms of their distribution, especially among collaborative groups. The project manager must display firmness in approving circulation lists and meeting participants, yet be ready to modify according to circumstances. Case interviews verified that the project manager is unable to be involved in every information exchange; therefore clear protocols must be implemented that reflect the project needs and management style, as well as the expectations of stakeholders (CSIRO, 2008; ANSTO, 2009; SYNCH, 2009). Moreover, science and engineering projects tend to generate valuable intellectual property (IP), and project management must establish and demonstrate standards in compliance with IP policies.

Managers also declare their character through the quantity, quality, and detail of the information they disseminate, and to whom. This especially applies to reports, meeting outcomes, and funding matters where the attributes of judgement and discretion must be keenest. I found agreement among the case study interviewees that project managers releasing information through messages to sub-groups and teams (especially from headquarters to sites); need to strike an appropriate tone of leadership rather than officialdom. Trust issues were evident here also, and the experienced project manager is expected to display care concerning delicate and confidential matters.

In a study using success factors to improve project management, Clarke (1999) identified communication throughout the project as critical, in particular its influence on the acceptance of change. Her research strongly links effective communication with interpersonal skills.

Lastly, Clarke (1999) emphasises the importance of communicating within the final stages in a project as opportunities to convey achievement and project learning. She also proposes that one of the best ways to motivate people and make them more confident of what can be achieved is through more effective communication. A practical example is NASA’s annual Project Management Challenge that includes a formal awards ceremony where group and individual achievement is recognised through motivating project story information.

5.1.4.4 Adopting mission assurance

A particular characteristic of project managers drawn from fieldwork combines leadership with the traits of being ‘resolute’ and ‘fastidious’, and is displayed as an unwavering sense of purpose in making mission success the highest priority at all levels of the project.

This single-minded (though not tunnel-vision) approach becomes very apparent during deeper investigations of project system management, where integration of technical domains often reveals both technical and philosophical inconsistencies at the interfaces. The resolution of these tensions can easily lead to outcomes that can potentially compromise the sustainability of the project, and it is imperative that the project manager applies fortitude and leadership to maintain project focus, and as highlighted in the fieldwork, is supported by the Project Directorate in doing so (ITER, 2009; CERN, 2009; CSIRO, 2009).

The adoption of a mission assurance approach is captured most compellingly within NASA reports. Following a review of NASA's 'Faster, Better, Cheaper' (FBC) approach to space missions in light of a growing failure rate (Spear, 2000), certain flaws began to emerge concerning cost cap challenges, taking shortcuts under pressure, and risk conflicts for project managers However the recommendations largely missed the root cause. Meanwhile NASA's Mars Climate Orbiter Mishap Investigation Board (MIB) independently concluded that: *"[FBC] has failed to instil sufficient rigor in risk management throughout the mission cycle"* (NASA 2000, p. 6), and recommended the implementation of a new paradigm, termed Mission Success First. The MIB went further to describe how the Mission Assurance function should operate within projects, its rigorous oversight of testing and verification, and most importantly, interfacing with project management in driving mission success criteria.

In NASA's model (NASA, 2000), mission assurance requires that institutional line management become more engaged in the execution of the project, and be held accountable for mission success. This means project managers asking the right questions at meetings and reviews, getting the right people to those reviews to fearlessly uncover mission critical issues early in the program, and pursuing their resolution. Given the obvious tensions arising between mission assurance and project deliverables, these are clearly key responsibilities requiring valiant project management.

The legacy of past methodologies applied to high-tech/long lifetime projects can remain to challenge contemporary project managers, as in the case of FBC and the Space Shuttle navigation units (Goodman, 2002), and NASA's Genesis spacecraft program (NASA, 2005). Project managers joining existing science and engineering enterprises need to be capable and ready to build latent risk into their mission assurance programs.

5.1.4.5 Managing project complexity

Scientific and engineering mega-projects are typically characterised by multiple components, multiple functions, and requiring the involvement of multiple organisations (Milosevic & Patanakul, 2005; Grün, 2004). They are information rich (Thomas & Mog, 1997), and cannot be designed or communicated by a single expert (Moody & Dodgson, 2006). The management of complicated (intricate, of many parts), and complex (interwoven, interdependent), projects demands exceptional skills, described succinctly by Shenhar & Dvir (2007, p. 115):

"Managing successful [complex] projects is a serious challenge. Not only must project leaders cope with poor communication among managers, designers, and customers, but also they are strongly dependent on a complex web of external suppliers, complicated procurement systems, and lengthy, detailed contracts … and other collaborators."

Cavanagh (2009, p. 4) captures both the range and essence of what complex project management demands of the project manager as:

"vision and motivation; empathy; attention to relationship building, in order that trust may be mutually awarded and maintained through difficult periods; the ability to take a holistic view; consummate communications skills; practical application of experientially-derived wisdom; and perhaps most of all, courage – the courage to be able to speak the truth (and hear it!), and to take good risk".

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In dealing with project performance in large engineering projects, Miller & Lessard (2000, p. 19) note that: *"Their technical difficulties do not condemn them to failure; far more troublesome, however, are the difficulties arising from their complexity, irreversibility, and dynamic instability."* Such complexity and dynamism lead to unpredictability with new risks emerging correspondingly with project length.

Commenting on the success of the Gemini telescope project, Dick Kurz tells how the job of building such a complex scientific instrument required a new kind of partnership, incorporating multiple countries and expert project management. *"[It was recognized] that a project of this magnitude takes…professional management and professional system engineering to really carry it off*" (Michaud, 2009, p. 34).

In a recurring theme in this study, mega-project complexity is not restricted to technical design, interfacing, and execution; it extends to innovation outcomes (Dodgson et al., 2008), structural, social, and exogenous factors that will severely test the less experienced manager. Schein (1965) highlights the interplay between individuals, teams, and management that can work positively and negatively in a context of personal ambitions, confluences and conflicts, and project goals (in Levine, 2002). Cooke-Davies and Teague (2009, p. 7) elegantly summarise the aptitude required of project managers when they write:

"delivering a complex project is not so much…knowing what to do and designing a system and processes to do it, as a matter of skillfully navigating the tides, storms, and cross-currents of human beings, with all their desires, motivations, quirks, and behaviours, while constructively engaging with them to achieve desirable outcomes"

5.1.5 The usefulness of practice guides

Since the 1970s, project management institutions have formed around the world, offering their membership the benefits (inter alia) of shared information and professional certification, based on published 'Bodies of Knowledge' (BoKs) largely developed through practice rather than research. The attractiveness of formal recognition is indicated by Project Management Institute (PMI) data showing that in 2006 almost 86% of its 210,000 members were certified as Project Management Professionals (PMP). (Morris et al., 2006). Other BoKs are offered by the UK's Association of Project Management (APM), the International Project Management Association (IPMA) whose Competency Baseline is an amalgam of European BoKs, and the Engineering Advancement Association of Japan (ENAA).

The role and effectiveness of the BoKs was deeply researched by the UK Rethinking Project Management group in 2006, who found that while clearly useful, there are flaws in their development. Project front-end management in particular, with its human, structural, and external issues so influential on project outcome, is cited as being especially deficient in BoKs (Morris et al., 2006). This general view is echoed in a recent Position Paper from the International Centre for Complex Project Management (Cavanagh 2009, p. 2) which states:

"we have a bagful of well-developed methods and tools, and a reasonably comprehensive project management body of knowledge. Ironically, these things…aren't enough, and relying on them alone won't work".

Nevertheless, while project management certification against the BoKs principles alone does not guarantee good project management execution, a track record of well run projects plus certification is a very strong indicator of a high performing project manager (Müller & Turner, 2007).

The PMI is strongest in terms of spread and influence, and their guide (PMBOK® Guide, 2008) is the most widely recognised and accepted Book of Knowledge (Crawford, 2000), being self promoted (p. 4) as: *"a foundational project management reference for its professional development programs and certifications."* Although not purporting to go beyond the status of practice handbook, it is useful to review the PMBOK in terms of alignment with the ideas presented in this study, and test for any epistemic value supporting the practical application of the research outcomes; refer to Table 5-1.

Table 5-1. Alignment between the concepts in this study, and the PMBOK® Guide

Characteristic/Attribute/Skill	**PMBOK® Guide 2008**	**Alignment**
Authenticity	Generally implied only in sections 1.6, 2, 4.3, and 9.3	Weak
Collaborative Approach	Touched on in Section 9 and Appendix G	Weak
Leadership and Management Capability	References in sections 1.6, 2, 9, with 'soft skills' addressed in Appendix G	Moderate
Persuasion and Negotiation	Referenced in sections 9, 10, 12 and Appendix G	Strong
Trust and Diversity	References in section 9 and Appendix G	Moderate
Personal Profile	Not addressed	Weak
Sense of mission and urgency	Urgency only addressed in terms of risk in section 11	Moderate
Project structures	Referenced in section 2, 4, and 9	Strong
Task Forces	Implied references in sections 5, and 10	Weak
Information Management	Referenced throughout	Strong
Mission Assurance	Implied in section 8, 11 in terms of quality and risk only	Weak
Project Complexity	Scattered mentions in various sections	Weak

The conclusions indicate, perhaps unsurprisingly, that the PMBOK® is intended much more as a practicing project manager's handbook than a project personnel assessment or development tool. Whilst 'good practice' is captured in terms of knowledge, processes, tools, and techniques, the publication is less informative concerning the more subtle (e.g. interpersonal) characteristics required of project managers that can significantly impact on project success, and currently falls short of being strategically useful in this regard. Nevertheless, the latest (4^{th}) update begins to address some of the characteristics dealt with in this paper, largely listing these in a new appendix (PMBOK® Guide, Appendix G – Interpersonal Skills). This is suggestive of recent acknowledgement of the importance of these types of factors and offers potential for future expansion.

Archibald (2003) looks at the formalised BoKs, and while he acknowledges their usefulness in relation to processes, acknowledges the 'extreme difficulty' in developing these practice guides to meet the global challenge. He is, however, more confident that contemporary project maturity models[40] offer a reliable benchmark for integrated project management principles and practices, and a useful platform for evaluation of organisational competence. An assessment of project maturity models by Ibbs and Kwak (2000, p. 42) similarly endorses their use as a: "*legitimate and sustainable reference point from which to begin making process improvements*". The best known, SEI's Capability Maturity Model Integration (CMMI) provides organisations with the essential elements for effective process improvement, and identifies where the greatest payoff exists.

5.1.6 Summary and conclusions

This section set out to look beyond the standard set of skills and qualities attributable to managers of high-tech mega-projects, and sought to add new knowledge by exploring the less obvious key characteristics of project managers that lead to project success.

Data were sourced from the published literature spanning the last 30 years, together with extensive fieldwork from nine mega-science facilities, and the personal experiences of a selected group in relation to task forces. The data were examined using a grounded theory approach, gathering supporting arguments, and drawing compelling and practical inferences.

The limitations of the methodology are acknowledged, and adding a temporal dimension with numerical analysis to show management trends would likely yield further conclusions. The study also reveals an incomplete understanding of the application of transformational

[40] Maturity models claim to improve organizational performance by identifying organizational strengths and weaknesses and providing benchmarking information. Current examples include CMMI, OPM3, P3M3, PRINCE, BPMM, and Kerzner's project management maturity model. There is no standard related to these models.

management in high-tech projects, and the relationship between charisma and success, and further research is warranted.

Whilst a definitive set of personal qualities is idealistic, the research shows that eight personal characteristics, traits, or skills are strongly indicated as subtle, though significant, factors in driving success within scientific and engineering mega-projects. These are:

- The ability to deal with the temporary and uncertain nature of mega-projects;
- Having and demonstrating personal authenticity;
- Applying skill in the management of collaborations;
- Having an appropriate balance of management and leadership talent;
- Motivating strategic influence through persuasion, encouragement, and negotiation;
- Building trust in a diverse cultural environment;
- Having a personal profile well matched to the project; and
- Driving a clear sense of project urgency.

These factors are interrelated and careful consideration is required in the selection of someone with the right mix of traits (Nicholas, 2004). A further five factors were shown to be positively related to project success in the context of creating, managing successful project structures. These are:

- Establishment of an appropriate project and team structure;
- Deployment of effective project task forces;
- Effective information management;
- Application of a mission assurance approach; and
- Competent management of complexity.

The success drivers described could usefully supplement the discussion agenda at the project manager interview stage by exploring the candidate’s approach and experience in these subtle, yet vital, pre-cursors of mega-project success. Ultimately, the project management must be chosen on the basis of competency, and a range of project management skills (European Commission, 2010).

5.2 Authentic intent in high-tech projects

Despite the real difficulties associated with approval, cost estimation, funding, and execution of high-tech mega-projects, it is comforting to imagine that the overall mission is genuine and that the protagonists are open and truthful in their intent to successfully deliver a project against stated goals. The fieldwork and case literature examined in the course of the present research revealed no obviously fraudulent projects; however they do exist, and when revealed, make assessment of success largely futile. For this reason I include a brief discussion of the phenomenon.

This section does not consider situations of fraudulent project reports, fake data, or false discoveries. I also exclude from the discussion the view of philosopher Karl Popper (1902-94), that science actually advances by falsification (the ability to be refuted), which he claims is believed by many scientists. (Corredoira & Perelmen, 2008; Farndon, 2009; Cave, 2011).

First we may ask: why fund high-tech mega-projects at all? Given the general track record of success, it would seem both logical and prudent to confine funding to those projects that demonstrate fact-based confidence in meeting project targets. However this would mean only low risk projects would get funded, and as both commerce and governments know, without risk, challenge and stretch-goals, a nation does not progress. What of the more esoteric disciplines (e.g. astronomy) that have no readily identifiable benefit to the general tax-payer? Howard, in his PhD thesis (2004, p. 247), investigates the legitimacy of astronomy and asks: "*what arguments, strategies, tactics and rhetoric do astronomy advocates use to persuade funding agencies to part with large sums of money?*" He answers that: "*Astronomy successfully...justifies itself...to successfully procure resources from society because: first, it has popular support; second, it has an educational role; third, because modern societies are 'scientific' in that they value science for its own sake*". Howard is remiss in not adding the quantifiable benefits of direct contractual involvement by industry, and the indirect value of technology 'spin-offs's (e.g. Crosby, 2008a). One could argue that slipped programs, ballooned budgets, and the debatable societal benefits of big science edge towards deceptive practice; however no fraudulent intent was detected in any of the fieldwork cases examined in the course of the present study.

There is little in the literature on the topic, though Charles Smith has considered the subject in some depth in his book, Making Sense of Project Realities (Smith, 2007). He pulls no punches when describing projects of dubious purpose as fraudulent. His definition includes efforts from those well-meaning, honest groups of people found in academia, private research departments, and publicly funded institutions that inadvertently (and perhaps naively) see no deceit in misstating or omitting crucial information to project stakeholders. However he excludes projects which are plainly incompetent, or created out of stupidity or ignorance, thereby absolving incompetent managers. Kruger and Dunning (1999, abstract) are less generous, describing such individuals as: *"suffer[ing] a dual burden: Not only do these people reach erroneous conclusions and make unfortunate choices, but their incompetence robs them of the metacognitive ability to realise it"*. The US senator Tom Coburn (2011) writes about abuse of NSF monies in trivial research, and gross mismanagement of science funding. He voices serious concerns over contracting irregularities and malpractices with the loss of millions of dollars with dubious outputs. One example revealed $169 million contingency money drawn in advance because no barriers existed to prevent it. Coburn reasons that every dollar lost to mismanagement, fraud, inefficiency, and duplication impacts scientific advances directly by cutting into the budgets for astronomy, biology, chemistry, earth sciences, and physics.

Smith (2007) re-tells the factual story of a university project that received Research Council funding based on industry collaboration. Instead of offering to close the project when the industry partners withdrew, the work proceeded, with the University group delivering a theoretical (though related) outcome instead of the promised tool. Remarkably, the Council had no problem with this result, conveying the distinct impression that they considered University targets met, and early termination may well have jeopardised prospects of future funding. Clearly this case fits Smith's description of a fraudulent project - the victim being the tax-payer as shown in Fig. 5-1. However he offers the benefit of the doubt that there really was an original shared intent to complete the collaborative effort.

Kirilyuk's contribution (in Corredoira & Perelman, 2008, p. 139) to an alternative publication on how physics and astronomy actually gets done, considers nanotechnology, a field he believes to be founded on intellectual fraud, unrealisable promises, and 'publicity-driven trickery'. He states that: *"the practical reason for that bizarre giga-fraud so easily accepted by the most prestigious institutions is the rapid shrinking of the...prosperous field of solid-state physics whose adherents have found "nanotechnology" as an efficient replacement [driver] for their disappearing financial support."*

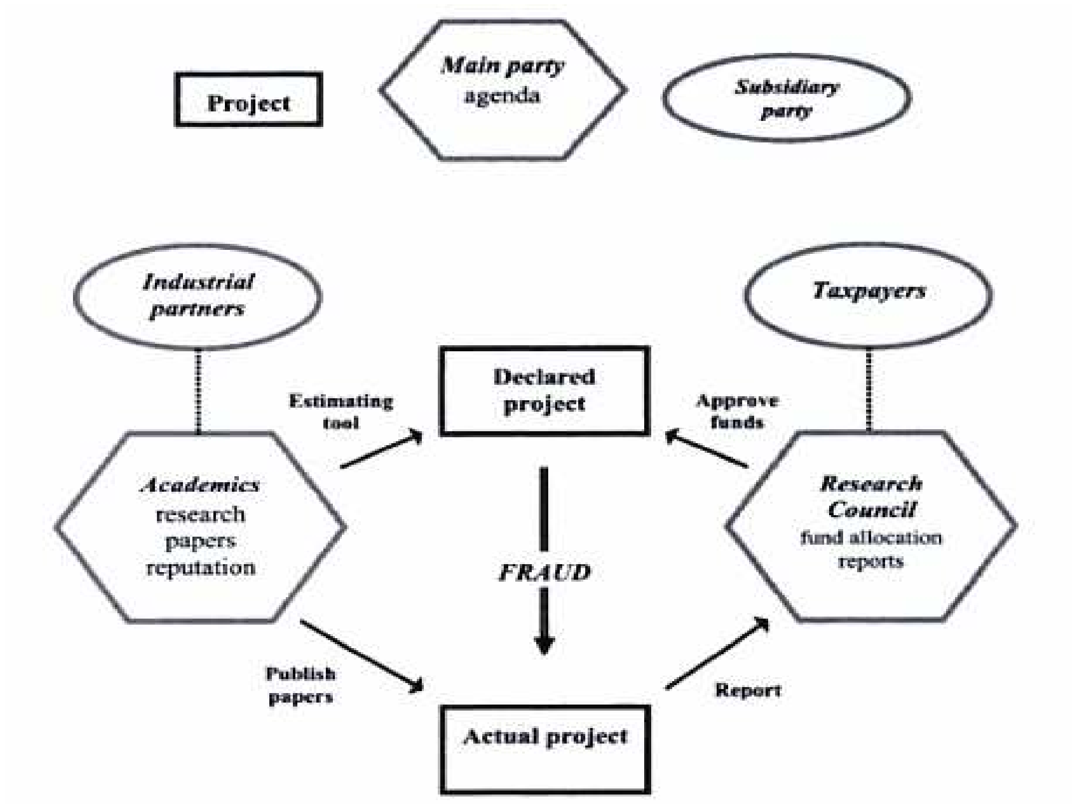

Fig. 5-1. Social interactions – a fraudulent research project (Smith, 2007 p. 63)

Institutional high-tech mega-projects essentially become shams when they fail to deliver all or part of the promised outcomes, including unacceptable delays or cost increases, performance variations, or dubious (or missing) contributions from collaborators. While high-tech research is far from certain in nature and vulnerable to change as the project unfolds, the sometimes unrecognised danger is that if external stakeholders believe that funds have been falsely allocated or agreed goals have not been met, they are likely to feel misled, or even defrauded.

Even NASA's iconic Apollo moon landing program is not without criticism, and a retrospective study by Young et al. (1969) concludes that, despite the principal goal being achieved, the much trumpeted spin-offs to science, industry and the economy are at best, hard to prove. Moreover, Young et al. (1969 p. 91) point to a '*truly staggering series of falsifications*' concerning programmatical aspects of Apollo's development.

Cold Fusion is a widely documented case where researchers convinced funders to underwrite massive project costs despite questionable results. The field originated with reports of an experiment by Martin Fleischmann, then one of the world's leading electrochemists, and Stanley Pons, in March of 1989. In 1992, Fleischmann and Pons moved to a French laboratory under a grant from Toyota, but this was closed in 1998 after spending £12 million. Between 1992 and 1997, Japan's Ministry of International Trade and Industry also spent a further US$20 million in researching cold fusion before announcing the end of the program in 1997. In the 1990s, India stopped its research in cold fusion because of the lack of consensus among mainstream scientists and the US denunciation of it. Experimentation continues today in spite of rejection by mainstream science (Condensed from Wikipedia, 2011).

Group-think can override common-sense in these matters, and I turn again to Smith who describes a multi-billion pound defence project offered to a reputable contractor at 30% under the firm’s original bid, only after tender ‘rules’ forced the emergence of another bid. Despite the implausibility of the competitive offer, the company’s Directors were compelled to beat the cheaper offer, and urged senior managers to find a way to deliver the requirements. Privately, people shook their heads and said it couldn’t be done, yet the reporter tells Smith: *“What surprised me most was the alacrity with which this [challenge] was taken up”*. Project failure was inevitable (Smith, 2007, p. 59).

Protracted government or commercial projects involving large numbers of people and great expenditure may be characterised as ‘boondoggles’ where, having realized that the project has essentially failed, the participants do not bring this to the attention of the top management or funders. Such projects continue "going through the motions" while salaries continue to be paid. Sometimes senior management are complicit in this deceit; being reluctant to accept the reality of a long-failed project. Sometimes the product or service may eventually be delivered, but never work well enough to recoup its development costs. One example of a ‘boondoggle’ was the RCA "SelectaVision" video disk system project, hatched in the 1960s and continued for 20 years despite cheaper and better technologies. The wasted $750 million is considered a factor in RCA’s bankruptcy in 1988.

Institutional science/engineering projects that have diverted from the expected path, and big defence projects that have required ‘rescue’ funding, are a cost to the tax-payer. However as the budget for typical high-tech projects grows into the multi-millions or larger, customers are not above seeking legal remedies for their loss. An example is the case between BSkyB and EDS (now part of Hewlett-Packard) concerning fraudulent misrepresentation and contract breaches surrounding an IT project. In a landmark decision, EDS’s failure to properly analyse project timescales (often traditionally considered a minor programmatical detail in R & D projects) was found to be beyond carelessness and was dishonest. Moreover, EDS could not rely on caps in the supply contract to limit liability. The lesson suggested by

Bond Pearce Solicitors is for project estimators to be extremely careful to ensure that representations made in the tendering/funding application process are genuine, especially in relation to cost and timescales. The EDS case is important as it establishes a precedent for fraudulent misrepresentation in IT projects, allowing the funder to claim unlimited damages, in this case £700 million. Such exposure must begin featuring more prominently in risk assessments (Bond Pearce, 2010).

What drives intelligent, rational, and often politically adept people to deliberately misstate information or ignore agreed plans and goals? In the commercial world there are certainly economic pressures to win contracts that lead to offers more aligned with customers' notional expectations than reality, and these can backfire (e.g. Boeing’s late delivery of the *Dreamliner* aircraft to India, with consequential US$500 million compensation). The world of institutional high-tech mega-projects is more complicated. First, applications to funders need to be compelling, with positive outcomes predicted for core science/engineering goals and socio-economic impacts (see COST, 2009). These proposals may be ‘tweaked’ with features that optimise approval chances, but non-science benefits are soon internally de-prioritised after project commencement. Second, national and regional funding schemes (e.g. European FP7 Programme) operate within defined periods, value bands, and priority areas. Clearly, any funding application that is heavily manipulated to reflect funder’s stated conditions, are by nature counterfeit. Lastly, projects created essentially to recruit or retain technical staff without a robust purpose, must be considered phony.

There is one other category of high-tech institutional project that may appear fraudulent or bogus at best, but actually has genuine strategic undertones. Unfettered research (sometimes labelled ‘curiosity-driven’ or ‘blue-sky’) describes projects where the investigator is permitted to choose the problem without having to justify the relevance to his or her employer. Odlyzko (1995) examined the decline of unfettered research, concluding that such arrangements are beneficial despite their apparent dubious nature, citing electronic cryptography as a successful example. Nonetheless, non-tied research funding is becoming more limited in both commerce and universities, forcing choices between fields. Odlyzko (1995, p. 17) cautions: *“Scientists have been notoriously bad in deciding on priorities between subjects [and] while scientists usually feel that knowledge is good by itself, the public is unlikely to support the large scale research enterprise we have without utilitarian justification.* Campanario and Martin find (in Corredoira & Perelmans, 2008) that proponents of unorthodox project ideas find increasing difficulty in obtaining funding. In times of financial constraints, the shareholder or public underwriter may take some convincing to see ‘blue-sky’ research as a genuine endeavour worthy of serious funding without clear success definitions.

How might we rationalise our attitude to large high-tech projects that appear dubious and may be fraudulent, but could also herald the next big technological breakthrough? Smith (2007) reminds us of the risks and unknowns in high-tech R & D, and counsels us to accept a measure of honest optimism in the form of confidence to achieve lofty project objectives. Moreover we need to examine not the mechanistic aspects of projects for fraudulent purpose, but the surrounding management where the vested interests and political interplays occur. Finally, Smith intimates that the real world is not black and white but all shades of grey, and that many projects later recognised as a great success have likely contained some element of fraud at their inception. Kirilyuk calls for systematic change by remarking: *“only decisive, qualitatively big transition to the unreduced analysis of real, multivalued system dynamics can put an end to exponentially growing expenditures for successively failing, practically fraudulent giga-projects”* (in Corredoira & Perelmans, 2008, p. 140).

In summary, I conclude that institutional large scale high-tech projects are highly susceptible to deceitful behaviour. Misstated forecasts at the approval stage, dubious diversions of effort, conveniently forgotten baselines, and deviations in terms of budget, schedule, and goals are possible, in ways unlikely to be overlooked in their commercial equivalents. However to describe this as fraud is misleading. The very environment that shapes and nurtures science/engineering programs tacitly permits such deviations from approved plans or outputs, often without any perceived consequences. This is epitomised by the SKADS project (SKADS, 2005), an international effort focusing on the development of new telescope receptor technology. Consensus among many of the SKA stakeholder representatives is that most of the planned deliverables will not be completed, and a good fraction of the €28.5 million budget (of which €10.5 million was EC funded) was expended needlessly.

Given the above, the relevance of authentic intent in high-tech mega-project success is reduced to the question - how can a project that has been deliberately or naively diverted from its initial (and approved) aims, measure or claim success? I assert that the answer lies in the fundamental notions framing the project’s critical success factors (CSF) described in section 2.4.3. Put simply, unless a full and proper review process takes place to redefine the CSFs in response to any material change in circumstances, the project can only be judged against the extant metrics. To claim success without deceit, a ‘shifting of the goalposts’ must be supported by an agreed change of game rules.

5.3 Project review and close out

Project reviews are key events in the project lifecycle (Cooke-Davies, 2002b). Whether highly invasive, or a light appraisal, each offers an opportunity (through fresh eyes) to check and adjust the project's trajectory for success. In this section I examine the efficacy of project reviews, close-out and lessons learned activities, and their influence on project success.

Any project, purely by definition, is a temporary endeavour with an end-date. This might imply a winding down of effort and gradual dispersal of resources. Interviews with personnel from closed projects within this study's fieldwork indicated this was certainly not the case, and that the approaching termination date presents special challenges in terms of agreed milestone achievement, performance reconciliation, and tensions concerning future assignments for project personnel. Archibald (2003, p. 356) agrees, saying: *"closing out a [high-tech] project is more easily said than done. The project manager has the job of literally putting ...the project team out of business. This is a very demanding assignment."*

5.3.1 Project review

Projects examined for this study essentially followed a traditional execution path, marking progress through periodic sequential reviews, often labelled as 'stage-gates' or equivalent term (See Fig. 5-2). These types of reviews typically mark the passage of a project through life-cycle phases, often coinciding with further investment decisions and possibly becoming GO/NO-GO points - especially for industrial mega-projects. Projects containing an R&D element (e.g. those making up the casework for this thesis) typically planned for and conducted a Concept of Design Review (CoDR), a Preliminary Design Review (PDR), a Critical Design Review (CDR), and some form of Pre-Construction (or Baseline) Review in advance of construction and operational reviews.

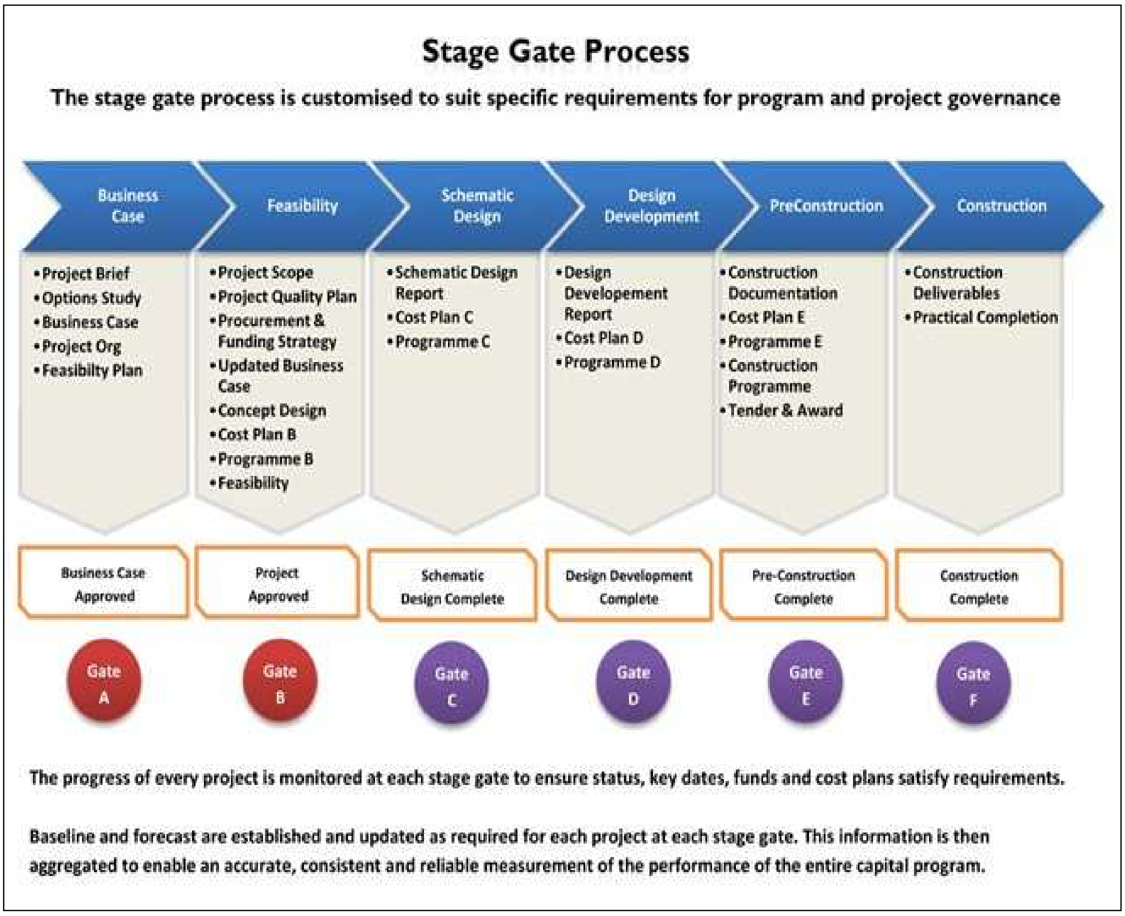

Fig. 5-2. Major project execution phases aligned with approval/completion 'Gates' (Capex-Pro, 2011)

Both the literature and the case studies consider each review as a serious exercise, often conducted by a mixed panel of peer reviewers and independent specialists. The importance of effective review is underlined by the identification of inadequate review function as a root cause in the loss of NASA's CONTOUR mission in 2002 (NASA, 2003).

The review panel's core task is to evaluate the project against the stated aims and key success criteria (Harris, 2009), involving a critical examination of previous achievement, identification of strengths and improvement areas (Archibald, 2003), and an examination of the viability and risk profile of forward plans. The large-scale timing relationship between high-tech project phases and supporting reviews is shown in Fig. 5-3. In this (de-identified) example from NASA, the various design reviews are mapped to project phases and their associated plans.

Reviews as a whole contribute to effective life-cycle management (Smith, 2007; Anbari, 2008), as shown in the major re-baselining review of the US National Ignition Facility (NIF).

In tightening the project scope, NIF management polished the project-completion criteria very carefully and incorporated all changes in the project execution plan where they remained unchanged (NASA, 2011b).

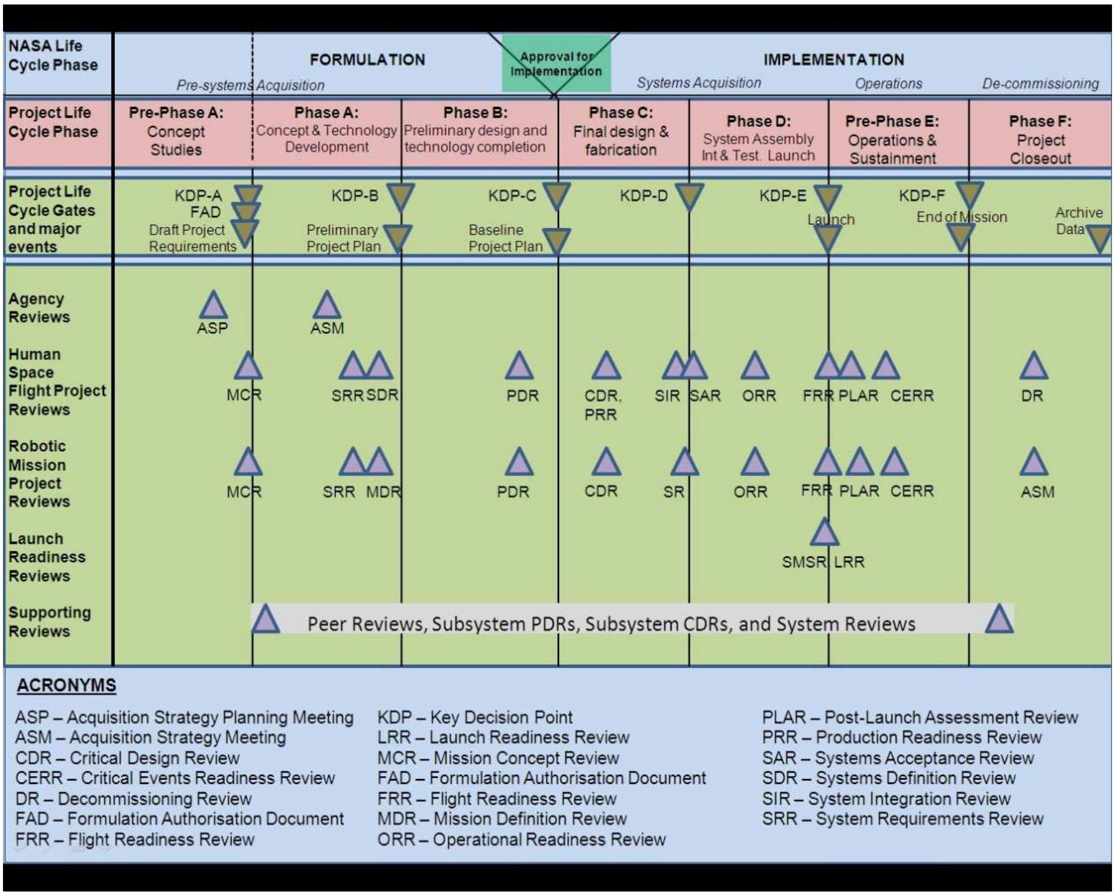

Fig. 5-3. The life cycle phases adopted by NASA showing supporting reviews (adapted from NASA, 2007b Ch5 p. 2)

Project reviews typically operate at two levels. At the lower end, an in-house Review Board will carefully scrutinise progress and performance, and make decisions regarding next steps. At the higher end a panel of experts often serves as an independent Review Board to examine technical progress, review the design, critique the execution strategy, and offer advice and recommendations regarding problems and risk (Shenhar & Dvir, 2007). The frequency of review in high-tech enterprises naturally varies. Williams (2008) mentions intervals of three months for the Ericsson Company, whereas SmithKline refer to 'a regular...project review process based on milestones.' BAE SYSTEMS Lifecycle Management Framework (LMF) material shows regular reviews to be central in technical project execution, and although driven strongly by lifecycle phases, are inferred to be at least quarterly in practice (BAE, 2009). Similarly, the time taken for each review varies considerably, lasting anywhere from a few days, to around six weeks in the case of NASA's Mars Pathfinder project, which had more than 100 peer reviews (NASA, 2011b) and employed the services of 25 consultants and seasoned NASA/JPL managers (Nicholas, 2004). The Mars Pathfinder rover review program included six incremental delivery demonstrations, emphasising the seriousness of the project review investment.

Fieldwork for this thesis indicates that project reviews can be a tense time (SKA, 2010, LHC, 2009, LOFAR, 2009). The exposure of a large, complex, and multi-stakeholder (and sometimes highly emotive) enterprise to external assessment requires careful planning, and gathering of accurate and pertinent information. Following my appointment in 2006 as the co-ordinator of the Project Review Board (PRB) at the (then) CSIRO-ATNF, I developed a 'dashboard' style of project report in order to improve the efficiency of the review process, and the effectiveness of the group's deliberations. Though not new to industry, the PowerPoint based design (Fig. 5-4) with dual 'traffic light' style assessment represented something of a leap of faith for a scientific institute review panel used to a substantial (though inconsistent) range of project reports and data. The dashboard tool also shifted responsibility for project data compilation (especially financial data) to the project leader/manager, as well as requiring a self-assessment prior to the PRB's judgement. The introduction of the dashboard sparked much debate until the efficacy was demonstrated at subsequent Division-wide project reviews, and formally adopted as the preferred tool by the PRB Chair.[41]

Following the implementation of DAPTIV© program management software to CASS in 2010, more elaborate dashboard-type reports became available, largely auto-populated with data extracted from other enterprise tools such as SAP, and Redmine. Despite criticisms regarding the security weaknesses of DAPTIV's 'cloud' hosting, and imperfect interfaces with other PM applications, the sheer ability to generate fast, comprehensive, and informative reports obviously shows the way forward for effective project reporting. An example of a DAPTIV report is shown in Appendix G).

[41] The dashboard tool remained in use at ATNF PRBs until superseded by semi-automatically generated project reports that became available following the introduction of the DAPTIV© application.

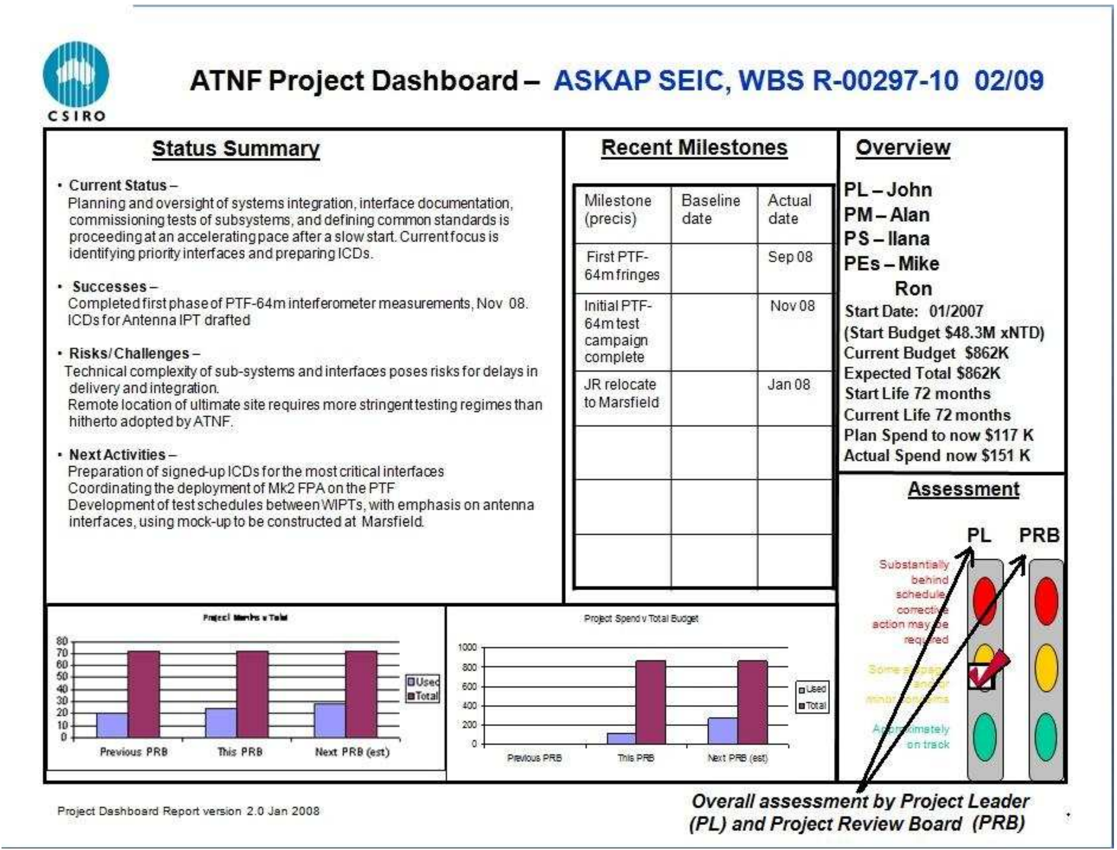

Fig. 5-4. Example of a single-page dashboard style project review report developed by the author

While the overtly stated reasoning for progress reviews is to provide a project-independent view on progress, tracking, and trajectory of cost, schedule and practical execution, there is always the underlying spectre of budget cuts, completion pressure, and a decision point for continuing (Nicholas, 2004). Like any investigation or audit scenario, the success of the project review (in terms of beneficial outcomes to all stakeholders) lies in the planning (the 'charge' to the panel), an agreed response, and to some extent in the attitude of the parties, especially the project representative(s). NASA's Project Management Handbook offers sound advice for high-tech project leaders, including a quote from the (un-named) WISE Project Manager at the Jet Propulsion Laboratory (JPL):

> *"I desire tough review board members who really know their areas of expertise. I want people who work hard at reviews, ask a lot of questions, and write a lot of RFAs (Requests for Action). Reviews allow the project to tap high-quality people with a lot of experience. In a sense it's free labor (sic). These are good people to glean information from. Many look at reviews as a burden. I do not. We answer every RFA.*

There are no rejects or RFAs tagged as advisory. Every RFA is worked to the point where the initiator concurs with the closure" (NASA, 2010b, p. 108).

Serving on a review panel is not trivial work, or without its obligations and personal challenges. There is an expectation that members will take sufficient time to read the project material, review guidelines, and take time (often on a voluntary basis) from busy schedules to attend the event. One commentator's view (Fisher, 2010, p. 6) of project reviews in the field of large astronomy intimated:

> *"[They] usually involve a lot of reports and presentation preparation and travel. There is definite value in these reviews, but any scientist...will recognise how inefficient the process is and may dread being assigned to...these review committees. An additional danger of excessive reliance on the review 'process' is that it can lull a project into a false sense of security. We cannot review the answer to a question that we are not clever enough to ask. Modern radio telescopes are sufficiently close to the state of the art that we should at all times admit the possibility of a surprise."*

The output of project reviews is invariably a detailed report, sometimes employing an advanced preliminary account summarising the main issues. Anecdotal feedback from casework for this thesis indicates that the review findings are most pertinent when delivered promptly, and in a form that can be readily responded to (ASKAP, 2009, VISTA, 2009, LHC, 2009). To achieve this, attention must be given to formulating an action plan (possibly as a separable appendix to the review report), that clearly states each issue, and the objectives for resolving it. Project Management can then discuss each issue; determine the course of action, who is responsible, and a proposed date for close-out. Representatives from the project, and the review panel, then sign agreement to the action plan, with copies circulated to functional managers. A suggested template is provided at Appendix H.

The action treatment will vary according to the issue, and some matters will require both immediate handling, and a longer term response. The casework for this thesis shows that institutional high-tech projects typically do not generally exhibit a sense of urgency or obligation around matters of addressing review findings, although in fairness, the assessment reports sighted were not well crafted to elicit responses within a specific timeframe. For example, the SPDO's response to the SKA project's CoDR (narrative form) report took one year, whereas an industrial high-tech equivalent would likely be much more time focused.[42] NASA traditionally uses a Problem Failure Report as a generic instrument to record, pursue, and track issues. In the case of the Mars Pathfinder craft, the NASA project team collectively responded to over 800 of these – this not considered an unusual number (Nicholas, 2004).

5.3.2 Post project reviews

Post-project reviews (or 'post-mortems') represent the final phase of project execution (other than a lessons-learned and knowledge transference phase discussed in section 5.3.3). Indeed, the standard project management texts (e.g. the PMBOK, IPMA Competence Baseline, PRINCE2, APM, etc.) each highlight the importance of a final review. One would therefore imagine that a project 'post-mortem' for high-tech mega-projects is an automatic step; a welcome activity for the central project players to gather and reflect on both their achievements and opportunities to improve (Caupin, et al., 2006). Unfortunately, research shows this is not always the case.

Harris (2009, p. 97), when looking at the role of (under-used) risk data during project reviews, concludes that: *"around 26% of large project organisations may still have no formal project review process, and those who do may have limited managerial involvement."* Cerpa and Verna's (2009) paper investigates IT project failure factors; the authors remarking (p. 130) that: *"few project post-mortems are conducted, and little understanding is gained from the results of past projects"*. Von Zedtwitz's survey finds that only 20% of R&D projects receive a post-project assessment (Anbari, 2008). Verna and Evanco's (2005) collaborative survey of software development projects adds hard data to this view, finding that 33% of 42 projects had post-mortem reviews, and that such reviews were significantly associated with 'good requirements and managing risks'. Another survey of 92 IT organisations found that: *"more than one fifth did no post-mortems whatsoever*", the authors mentioning a *"grim suspicion that the projects not subjected to post-mortem analysis are the very ones we could learn most from"* (Collier et al., 1996, p. 66).

Williams (2008, p. 252) in his investigation of high-tech projects, comments that 80% of all R & D projects did not conduct a review at completion and of those that did, most did not follow a process. Nonetheless, his work found sufficient encouragement to report:

[42] For example the BAE SYSTEMS Lifecycle Management Framework requires the design review output to be in the form of a [Review] Certificate, with any conditions to be addressed within 60 days.

"As firms increasingly become more innovative and project-based, many are recognising the need to capture the learning from individual projects, and make it available throughout the organisation...learning is particularly important and relevant in new projects where they are at the state-of-the-art level of technology."

Cooke-Davies (2002b) finds that pressure to close the project, low priority, and other distractions present barriers to proper project close out, however there is little extant research as to why post-mortems may not be held. Interviews during casework for this study suggest that the atmosphere surrounding high-tech projects which are approaching termination is simply not conducive to a formal review activity. Anbari et al. (2008) mention possible embarrassment to project staff, and prospective damage to professional relationships. Research in Australia involving ranking of importance of project management practices relating to project close out showed 'capturing lessons-learned' as a poor third activity after 'monitoring and controlling', and 'planning and closing' activities (Crawford & Cooke-Davies, 1999).

5.3.3 Post project review processes

The conduct of post-project reviews in the high-tech arena varies substantially according to organisational culture (e.g. institutional or commercial), size, geographic spread, and management maturity. Schindler and Eppler (2003) describe several methods ranging in formality from 'walk-throughs' during semi-formal team gatherings, document-based reviews, up to the Post-Project Appraisal (PPA) model adopted by British Petroleum - the latter being carried out by a specialised (independent) unit some two years after project close and taking six months to complete. Boeing takes a similarly extensive approach, as described in section 3.3.3.2. Archibald (2003) posits that the ideal timeframe to conduct the post-project review is between one and three months after project closure, allowing some perspective regarding the ultimate success of the venture, but not so much time for memories to fade or records to be lost.

Collier et al. (1996) offer a five-point process for post-mortem reviews, emphasising the data collection stages through personnel surveys prior to a 'project history day'. Their steps are:

- Project Survey (survey design, methodology for evaluating results)
- Collect objective information (metrics, tracking)
- Briefing meeting (key roles, key benefits, risks, looking beyond the data)

- Project history day (problem statement, participants, activities, results)
- Publish the results (the good, the bad, the ugly).

Anbari et al. (2008) put forward a process model for project post-mortems reflecting empirical studies from the literature. Their approach is prefaced with an introduction to various quality tools (Quality Function Deployment [QFD], Pareto Charts, cause and affect diagrams, etc.) which they suggest helps to prepare and control the review. However research for this thesis indicates that most institutional projects do not employ quality management specialists, and applying such tools ad-hoc will add little or no value. I assert that experienced managers of high-tech projects will have more than sufficient ability to organise an effective project review using the process model of the type outlined in Table 5-2, and which I developed and applied during the post project review conducted on the Dutch LOFAR radio-telescope project (see section 5.4).

Table 5-2. Summary of post-project review process for large, high-tech projects).

	Preparation	Output	Activity
Step 1- initiating the process	Identify the primary and secondary CSFs and other performance indicators (PI)[1] Consult any organisational guidance or procedures	Clear understanding of top level goals Understanding of approved processes and responsibilities	Capture CSF and project goals Obtain required approvals and resources.
Step 2 – planning process	Consult key project team members re: availability Prepare post-project review plan	Date, place, and participants agreed Draft plan for the review activity	Announce review date and location to all participants
Step 3 – assign responsibilities	Determine roles required, get agreement from people to accept	Roles and responsibilities assigned in the plan[2]	Assign activities as required Circulate plan with event programme
Step 4 – Conduct the review	Book venue, get materials ready Explain the programme	Facilitator prepared, with CSFs and PIs identified	Conduct review using appropriate approach for the organisation[3]

Step 5 – Conclude the review	End of workshop summarisation	Notes and materials collected	Drafting of post-project review report
Step 6 – Disseminate knowledge	Decide on audience for the 'lessons learned'	Finalisation of 'lessons-learned' workshop report	Disseminate as agreed
Step 7 – archive & add to knowledge base	Develop (or append) 'lessons-learned' to knowledge database	Archived material securely stored and accessible	Lessons learned readily retrieved by subject, and applied in subsequent projects

Notes

1. *Ideally the CSFs/KPIs are identified at an early stage of the project formation. Primary CSFs would normally relate to objectives around schedule, cost, and performance (plus others), whereas secondary CSFs might include funder expectations, quality, mitigation of risk, spin-off technologies, etc. PIs describe expectations that may be adjunct to the core deliverables (apprentices trained, tooling integrated, etc.)*

2. *For example: arrange the venue, prepare workshop materials, invite the personnel, circulate any pre-workshop material, provide refreshments, arrangements for booking and funding travel, accommodation and local transport.*

3. *Approach options include: (a) chronological – by project phase, (b) categorical – issues compiled by topic – programmatics, technology, finance, personnel, procurement, etc, (c) sequential – working through a logical project flow, or (d) by perceived or ranked importance. Whatever the approach, the main questions are: What was supposed to happen? What actually happened? Why were there changes/differences? How well did we handle things? What can we learn from this experience? (Adapted from Schindler & Eppler, 2003 p223).*

Project reviews are not the place to assign blame or punishment for errors, or criticise individuals or management (Nicholas, 2004), yet Cooke-Davies (2002b) appeals for honesty so that lessons are of real and lasting value. Nor should the focus only be on issues and problems; there is likely to be just as much to learn and hand on from project successes and positive achievement. Korowajczuk and Almeida, speaking in NASA's Year in Knowledge (NASA, 2010c), emphasise the positive 'hidden agenda' of post-project reviews being the opportunity to develop new employee skills through dissemination of knowledge and experience.

5.3.4 Post project review analysis

While project perturbations may be individually and usefully examined during the project 'post-mortem', the complexity of high-tech mega-projects is such that a serial examination technique may easily fail to link or demonstrate cause and effect. For example, schedule slips may result in serious over-spends causing project dynamics to run as positive feedback loops (or vicious circles); themselves driving spiralling costs. Harris (2009) promotes the use of cognitive mapping as a dynamic tool to visually represent causes and effects together with risks. Williams (2004) endorses and applies this concept using a complex high-tech electronic design project, immediately defining the problem as beyond the advice given in standard project management texts (e.g. the PMBOK® Guide) which he describes (p. 274) as: *"insufficient for complex projects where lessons are non-trivial."* He goes on to advocate project mapping techniques that show chains of causality. His research finds that the tracing of dynamic behaviour, particularly where feedback occurs, reveals patterns that are hard to predict intuitively (see example Fig. 5-5).

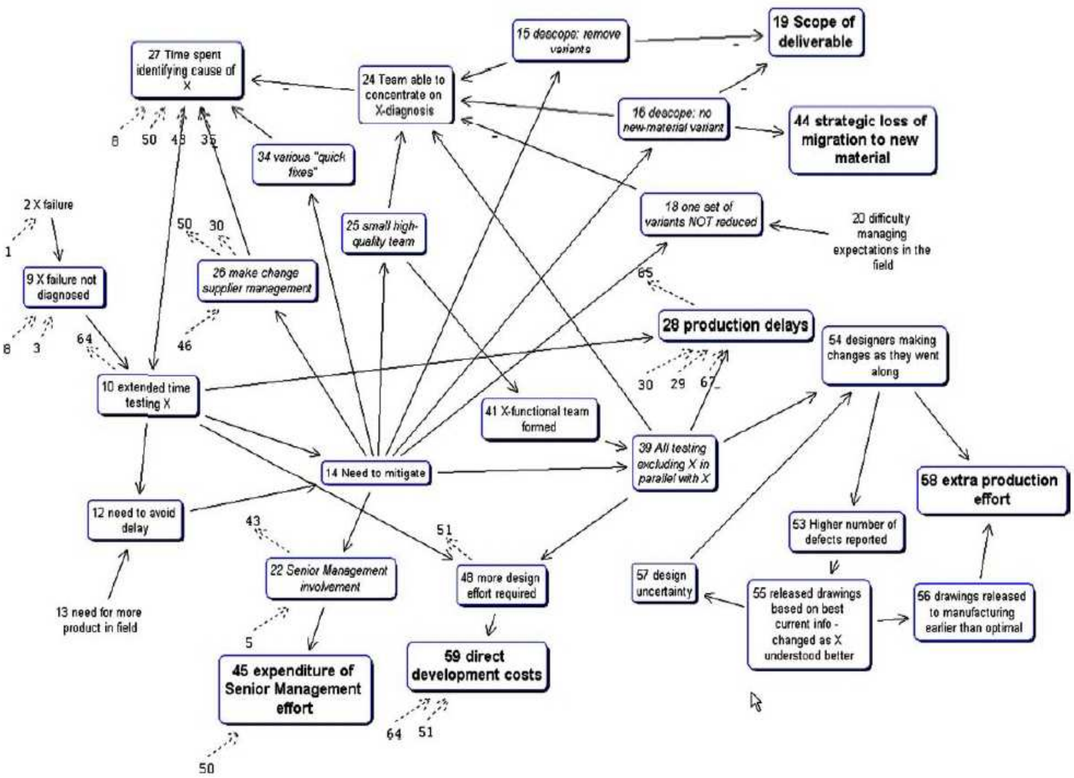

Fig. 5-5. Example of mapping of 'causes' from project review exercise (Williams, 2004 p. 276)

Mapping of chains of concepts during project reviews is shown to add clarity the causal analysis, and thus aid understanding, but the technique requires skill and experience for a meaningful interpretation.

From their investigation into how large industrial IT institutions learn from past projects, Schalken et al. (2006) promote the use of concept hierarchy trees as a tool to organise project factors which show influence on one or more identified success factors. Put simply, their method requires breaking up of individual or group remarks (from open questions in the review process) into single topics, thereby deriving a list of factors relating to project issues. These can then be discriminated by frequency of observation, and organised graphically on the ‘tree’ such that related topics appear on the same branch – a process known as comparative analysis (See Fig. 5-6).

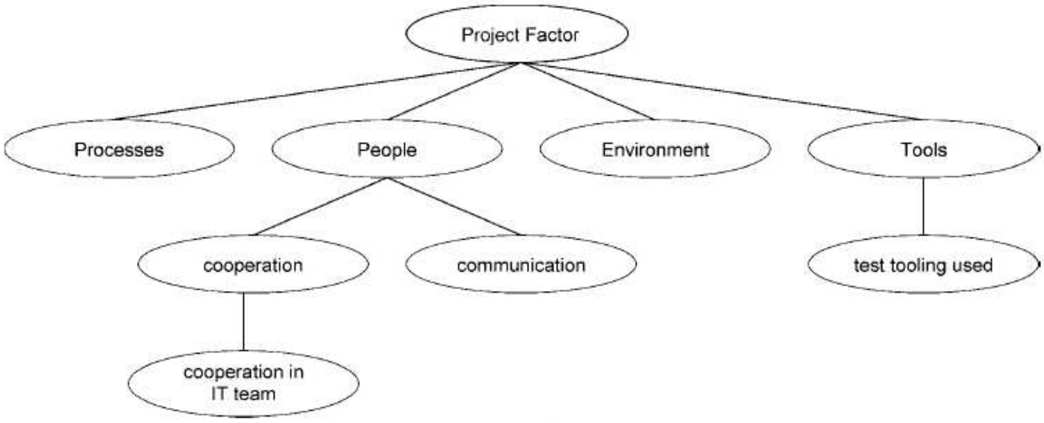

Fig. 5-6. Simplified example of concept hierarchy tree (Schalken et al., 2006 p. 40)

Schalken et al. go on to describe the interpretation of the project evaluation, importantly distinguishing between positive (e.g. aspects that were well executed) from negative criticisms. Statistical treatment follows for data reduction and analysis of correlations, leading to scientifically derived conclusions likely to apply to projects of similar scale and discipline, but generic enough to deliver broader organisational learning. The authors acknowledge some threats to the method’s validity, noting that such open-ended evaluation process can be a ‘double-edged sword’, being dependent on the quality of the subjective categorisation.

5.3.5 Lessons learned

The need for, and benefits of, learning from one project to the next is emphasised strongly in the literature, though most authors comment that few organisations manage this systematically to any depth, or in a useful format (Schindler & Eppler, 2003; Verner & Evanco, 2005; Atkinson, 2006; Williams, 2008; Anbari, 2008). An independent review of the ASKAP project found organisational knowledge systems and lessons learned 'severely lacking' (Schoening, 2009).

Williams (2008, p. 248) looks deeply into the subject, showing that 32% of organisations he surveyed have a specific department to drive process improvement through lessons learned, but adding: *"in practice, projects are often not reviewed at all, or if they are..., methods often do not give real understanding, let alone incorporating lessons into organisational processes."*. Both Anbari (2008) and Williams (2008) reference Kerzner's (2000) assertion that (p. 249): *"without lessons learned, a company can quickly revert from maturity to immaturity in project management. Knowledge is lost and past mistakes are repeated"*. IACCM[43] research found that large organisations rarely analyse their experience from collaborative or contractual transactions; for example to identify common factors leading to claims or disputes (ICCPM, 2011). However the crux of the matter is not simply in realising that projects hold lessons for future projects, but in taking practical steps to accumulate and disseminate the learning before it dissipates (British Computer Society, 2006). In other words, knowledge gained 'ad-hoc' will not naturally lead to retention of project insights; a condition dubbed by Schindler and Eppler (2003) as 'project amnesia'.

The accumulation of heterogeneous knowledge in project based organisations can be organic, as Salter et al. (2009) found in their study of the impact on innovation of intra, and extra-organisational links. Using casework within the Arup organisation to test theory, they found the wide and uneven nature of knowledge distribution a central challenge for organisations, only solved through intra-organisational ties shown to provide individuals with access to knowledge, and increased chances to combine information and help shape innovation.

Williams (2008) and Schalken (2006) look at project management Standards, methods, and maturity models (PMBOK® Guide, PRINCE2, OPM3, ISO 1006) but find little guidance on how learning from projects actually might operate (i.e. transference of tacit knowledge)

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[43] International Association for Contract & Commercial Management

beyond suggesting that reviews are important and that lessons should be documented. More recent publications discuss the importance of know-how (procedural or heuristic knowledge), and especially know-why (insights and experiences), favouring narratives and case studies rather than numerical data (Schindler & Eppler, 2003).

Processes for capturing lessons from projects range from individual journal entries for private learning and reflection through to formal post-mortem events, conducted openly, sometimes using trained facilitators. As described in section 5.3.3., these 'history days' offer the opportunity (if time and culture permit) to go beyond the simple recording of issues and their solutions and search for root causes. When practiced competently, the deeper findings are recorded as (micro) articles, reports, case studies and in databases. Collier et al., (1996) put forward a detailed process employing artefacts that guide the process through formal surveys, evaluation, and analysis.

Based on the experience of working with technical management Standards over ten years, I support the view that processes for extracting lessons from post-project reviews need to be formalised as auditable procedures. Put simply, I posit that if the process isn't conducted in organised manner, it won't get done. However casework, and the literature are inconclusive on the matter; Cooke-Davies (1996) arguing that there is insufficient evidence to support the universal documenting of such processes. Williams (2008) data shows just 62% of survey respondents as having a formal lessons capture procedure, but 12% admit to non-adherence. Crawford & Cooke-Davies (1999), and Williams (2008), note that people outside project management and technical staff are also important contributors to lessons-learned activities, as shown in Fig. 5-7.

Fig. 5-7. Showing the range of personnel involved in 'lessons learned' activities (Williams, 2008 p. 258)

Practical transfer of lessons-learned into knowledge repositories, or even personal experience 'banks', takes many forms. The case research for this thesis shows that the majority of organisations that undertake the activity do so through meetings or workshops (activities that Williams (2008) shows to be well correlated with increased perceptions of success). Less frequent activities include staff interviews, project audits, and documented histories/narratives. Individual presentations are evidence of personal learning, although ad-hoc in nature. The most mature organisations also use corporate training, searchable databases, and incorporation of lessons-learned through improvements to organisational procedures. Much less common is the procedural requirement to revisit lessons from previous projects as a prelude to new project planning.

The ability to readily retrieve the information is crucial and repackaging/consolidation of the data is normally required before reuse (Schalken et al., 2006). IT and web-based knowledge systems allow a more sophisticated approach, encouraging stories and possibly expert commentary, again fully searchable – a publically accessible example being NASA's Engineering Network (http://llis.nasa.gov/llis/search/home.jsp). The creation of narratives to effectively capture both problem and context is obviously more onerous than a simple database entry. Even so, Williams (2008) argues that narrative thinking is more suitable to the task than brief logico-scientific statements because of the complexity inherent with motive, causality, and emotion. Moreover, personal accounts offer added value because practice often occurs outside approved policies or procedures which may constrain shorter descriptions. Narratives also better depict subtle project transients and dynamics.

My fieldwork for this thesis discovered a range of activities within high-tech mega-projects concerning reviews, syntheses of the findings, and the capture of lessons. The various practices found in ten of the casework projects are summarised in Table 5-3. Informative comments are presented in the referenced footnotes. The results clearly point to lost opportunities for gathering project wisdom.

Table 5-3. A summary of post-project review and 'lessons-learned' activity by projects investigated in this thesis.

	Issues[44] noted and held personally	Issues noted and openly published	Issues reviewed by project group	Post-project 'history' or 'learning' session held	Systematic application of lessons to next project
ATCA (CSIRO)	No	Yes	Yes	No[45]	No[46]
ASKAP (CSIRO)	No	Yes	Yes	N/A	N/A
TOPSAT (RAL et al)	Yes	No	Yes	Yes	Yes
XFEL (DESY)	Yes	Yes	Yes	No	No
LHC (CERN)	No	No	Yes	No	Yes
ITER (ITER)	?	No	Yes	N/A	N/A
VISTA (STFC-ESO)	Yes	Yes	Yes	Yes	No
OPAL (ANSTO)	Yes	No	Yes	No	Yes
ALMA (ESO)	Yes[47]	Yes[48]	Yes	N/A	N/A
SYNCHROTRON	Yes	No	Yes	No	Yes

[44] Defined as: problems, errors, opportunities for improvements, or lessons learned captured in point or narrative form.

[45] "The open learning style culture came to an end at the end of the project. Partly because many key people moved on to other projects, or returned to their old division, partly replaced by a culture of success (or proclaimed success) with little enthusiasm for learning from mistakes, which meant admitting to them. I recall one meeting in which some mistakes were being openly discussed was considered bad form! An attempt many years after to hold a 'lessons- learned' workshop never happened." *(R. Ekers-ATCA).*

[46] "This depends on your definition of 'next project'. After the ATCA we had a period of more modest projects (e.g. Parkes 21cm multibeam) and these benefited greatly from lessons, either through personal knowledge of individuals or structures developed and kept because they were successful. However by the time of ASKAP little of this remained, and there was no attempt to recover this knowledge. In corporate CSIRO the situation was even worse with positive measures taken to erase the history of past lessons learned." *(R. Ekers-ATCA).*

[47] "This is generally the case. However, some situations are (substantially) complicated by the fact that ALMA is not a legal entity. It can therefore be a challenge to identify who owns some issues." *(T. Beasley-ALMA).*

[48] "In particular we have an openly available Top 10 issues register (currently listing about 30 issues!) that is regularly updated and openly discussed by the management team." *(L. Ball-ALMA).*

What constitutes a barrier to successful learning and transference of lessons? Both Williams (2008) and Harris (2009) present organisation culture as the major barrier, and major enabler of learning; the former author citing Scarbrough et al. (2004) who drill deeper to reveal factors such as project team autonomy, co-location, socialisation, specialisation, and links between sub-units. Other authors list individual authority level, power distance, uncertainty avoidance, and the (non) desire to learn, as being influential. Atkinson (2006) and Harris (2009) mention the temporary nature of projects as a challenge, while Anbari (2008) adds the practical barrier of project teams lacking awareness of knowledge codified within their organisations.

Factors from the literature, combined with case study research for this thesis, show that the project amnesia phenomenon can be related to the four elements suggested by Schindler and Eppler (2003) – time, motivation, discipline, and skills, as shown in Table 5-4.

Table 5-4. Elements that constitute barriers for effective post-project learning.

Time	Time pressure to complete project, team attention turning to new tasks/roles
Motivation	Insufficient incentive to learn from others. Previous project team not respected, consider that "my project is different". Team members not recognising personal benefit. Past knowledge not seen as valuable.
Discipline	Lack of formal process or procedure. Non-integration of experience recording in the project. Problems in coordinating post-mortem event, sometimes due to people departing.
Skills	Underestimation of effort, competencies, and understanding of project complexities. Ineffective editing/preparation/archiving of data for reuse. Lessons described too generically.

In the course of research for this thesis, the gathering and dissemination of lessons-learned was found to focus around the final project review stage. Received wisdom infers that it is the wrap-up and close-out stage of project execution that offers the best perspective and opportunity to examine and reflect on issues, perturbations, and improvements. However Schindler and Eppler (2003) argue for a more regular gathering and review of key experiences, on the grounds that events will be more current, can be recalled more easily, and frequent assessment reduces the effort and expense of a major review and archiving exercise at project termination. Whether one approach is better than the other offers an avenue of interesting further research.

Finally, what evidence of impact is there from post-mortems, and lessons-learned activities? Crawford and Cooke-Davies (1999) report a Working Party's assessment of the effectiveness of lessons-learned activities. This suggests that a 'fault-line' runs through the transference process (see Fig. 5-8) which materialises when the new project team (Team B) is unconvinced of the value of previous experience (Team A). This lack of incentive is shown to be strongly linked to a lack of project community within the organisation. Supporting data from the Working Party shows 'effectiveness scores' of over 70% at the lessons capture stage, deteriorating to 65%, 58%, and 25% for the succeeding steps.

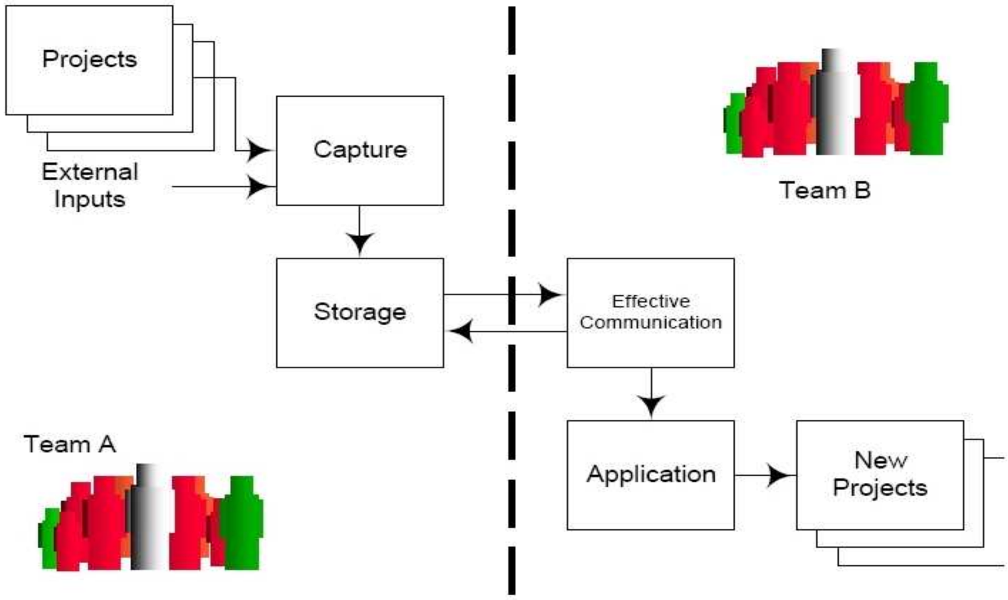

Fig. 5-8. Obstacles to systematic transference of 'lessons' between projects (Crawford et al., 1999 p. 5)

Survey work by Williams (2008) indicates that 88% of project managers assessed their own competency to have increased as a result of lessons learned activities, while 61% believed that project competency within their organisation had improved. Only 55% thought that projects are more successful. Around 48% of those surveyed agreed that lessons learned were transferred from individuals to teams, only 36% reported transference to related projects (a key weakness), and just over a fifth said lessons benefited the broader organisation. Moreover, 89% felt that 'learning networks/communities of practice' were important, but only 12% of organisations actually had these. Atkinson (2006) contends that, even where past performance data exists, managers fail to access it while planning new projects. It is reasonable therefore to deduce that proximity to the project under scrutiny, and competence of social interchange within the organisation, are factors proportional to successful cross-project learning, especially for tacit (rather than codified) knowledge. Further, the development of a learning culture is crucial to lifting the performance of high-tech mega-projects and their position when competing for funds.

Although the literature is rich concerning the usefulness of organisational and project learning gleaned from reviews, a cautionary view comes from Engwall and Westling (2001) related to their work on peripety (see section 3.3.4.3). These writers suggest caution before the adoption of late phase practices from successful projects into new projects. Their argument is that the processes targeted for possible application in other projects come from performance resulting after the peripety period, and may only confuse early stage project management. Nevertheless, the weight of evidence is that the task of capturing, organising, archiving, and transferring lessons-learned is crucial to effective project management maturity at both the individual and organisational level.

In this thesis I endorse the views of Schindler and Eppler (2003) who promote the integration of learning and knowledge management to a strategic priority, and suggest that there should always be dual aims: project success, and advancement of learning in the organisation. They strongly endorse this for high-tech project success by saying (p. 20): *"The risk of a knowledge loss at a project's end is a serious problem for organisations, especially in knowledge-intensive industries, such as...high-tech [sectors]"*.

5.4 The 'lessons learned' process – LOFAR example

As follow-on from my investigations of the LOFAR radio telescope at the Dutch ASTRON organisation in 2009 and 2011, agreement was reached with the Director of ASTRON that I would facilitate a LOFAR lessons learned workshop. This activity was seen foremost as an opportunity to gather insight into events that helped or hindered the project, as well as gain a broader view of how high-tech mega-projects can be managed better and with a greater probability of success. In other words, what can the lessons of LOFAR teach us for future large science/engineering projects?

A full report of the LOFAR lessons learned workshop (including the questionnaire, and detailed group responses) is shown in Appendix J. A summary appears below.

The planning and preparation of the workshop processes and draft documentation was carried out by me. The review and analysis processes described by Collier et al. (1996) and

Schalken et al. (2006) offered a basic framework, which I modified to match the LOFAR project environment, and compress the main activity into one intensive day. Logistical planning was undertaken by Dr. Albert-Jan Boonstra (ASTRON).[49] Detailed planning meetings were held at ASTRON on 28 January and 4 April 2011 with LOFAR's Project Director, Dr. Michiel van Haarlem. I devised and followed a detailed 7-step approach to the workshop planning. An invitation to participate, together with a workshop outline and program, was sent to the entire LOFAR project team. The workshop event was held near to ASTRON's headquarters at Dwingeloo, the Netherlands, on 5 April 2001.

A total of 26 LOFAR staff attended the workshop from all levels/departments of the LOFAR project, including Prof. Mike Garrett, ASTRON's Director. Each participant was allocated to one of the following five 'break-out' groups: Astronomy; Hardware; Software; Observatory; and Management and Finance.

5.4.1 Workshop Methodology

A simplified diagram of the workshop activity flow is shown in Fig. 5-9.

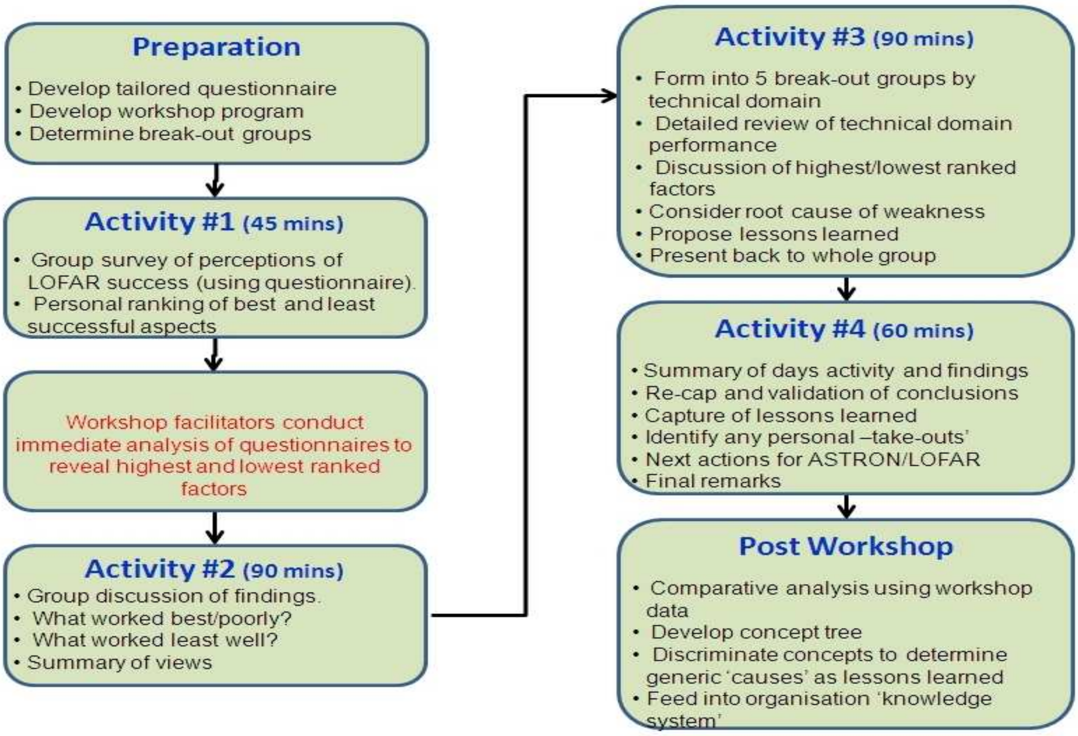

Fig. 5-9. Simplified diagram of the workshop activity flow

[49] Names used with approval, and under an ethics clearance.

Prior to the workshop, I developed a questionnaire designed to stimulate consideration of LOFAR's successes and challenges. The first 18 topic headings were drawn from the research into mega-project success drivers which are the subject of the meta-study forming chapter four of this thesis. These were carefully adapted for the workshop so as to encourage broad consideration of the related issues, (i.e. not 'pigeon-hole' ideas), and better match the LOFAR project. Planning discussions stimulated the addition of topic 19 – *'LOFAR's technical successes or challenges'*, since it was anticipated that the participants would welcome the opportunity to comment. A further undefined box (topic 20) was added to capture any remaining factors that anyone felt strongly influenced project success, or constituted a major challenge to LOFAR. It was agreed that the questionnaires would be anonymous.

The workshop program was devised around four main activities. In activity #1, the 26 participants were issued with the workshop questionnaire and asked to independently identify LOFAR's <u>three strongest</u> and <u>three weakest</u> success factors, according to their view and experience. In activity #2, the group discussed these highest and lowest rated performance factors and tendered examples of project events for added insight.

In activity #3, LOFAR's technical domain performance was examined against the key factors confirmed in activity #2. For this session, the five break-out groups were convened, using pre-defined staff lists to ensure appropriate demographic spread. For each group, a co-ordinator/scribe was assigned and given the added brief of ensuring that all members contributed actively, though without dominating the view. Dr. Boonstra and I circulated the groups, acting as facilitators. Working in their technical domain break-out groups, each team was asked to focus on the highest and lowest ranking factors, consider root causes, develop lessons-learned, and present these back to the entire workshop group.

Lastly in activity #4, the group recapped the key findings of the workshop (Table 5-5), and discussed ways to best capture lessons-learned in ASTRON projects. The participants were given an opportunity to describe to the group any personal lessons that they will take forward to new projects.

Table 5-5. A summary of key findings from the LOFAR workshop

Strongest success factors	Weakest success factors
Technical challenges	Collaborations, cultures, standards, obligations
Top level commitment and support	Resources – human, financial, physical
Socio-political environment, early engagement. Physical, infrastructure,	Project management systems (PMS) and controls, discipline, tools, document
Procurement & contractor management	Project communications and information management
Group Ambivalence	
Project management (all levels) competency, leadership	

5.4.2 Post workshop analysis

By applying the comparative analysis technique (post-workshop) LOFAR's specific weaknesses were traced to more strategically useful (in the organisational sense) 'cause' areas as shown in Fig. 5-10.

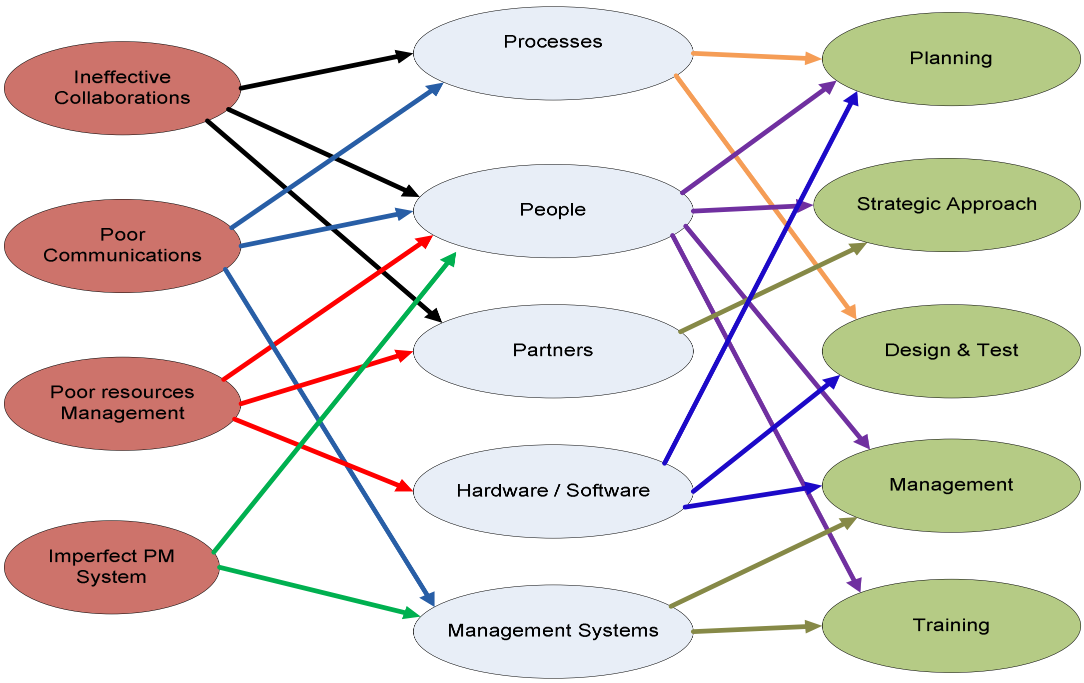

Fig. 5-10. Comparative analysis showing LOFAR project weaknesses linked to generic causes.

Common themes from the workshop discussions, presentations, notes and narratives were linked these topics, and useful lessons-learned emerged for analogous high-technology projects. These are set out in Table 5-6.

Table 5-6. Generic lessons learned derived from common themes from LOFAR project

'Cause' Topic	**Lessons learned**
Planning	• Include a detailed project communications plan • Ensure broad input to the plan, including sufficient science engagement • Be diligent when plotting the timing for major project events • Ensure sufficient time and people resources at critical project phases, especially the research phase • Be extremely clear about responsibilities and authorities of people and partnering organisations
Strategic Approach	• Give deep consideration to differing cultures in international projects, and the associated risks to the project • Be extremely clear about expectations regarding stakeholders, especially their direct involvement • A 'mission-assurance' function could be developed to provide added confidence of project trajectory to management.
Design & Test	• Design processes need to be procedurised and optimized • Be alert to possible needless duplication in design
Management	• Implement formal management systems for (i) information control, (ii) document and data control, (iii) financial management. • Management systems need to be 'right-sized' for the project
Training	• Early consideration of training needs for the above initiatives, where these are not traditional approaches or within the project organisation's current skill set

5.4.3 Applying the lessons

To fully complete the post-project review process, there must be a well-understood link to the conduct of future projects in order to turn knowledge into action. The question of how this might happen within the ASTRON/LOFAR organisation was asked of the workshop participants; however very few suggestions or ideas were forthcoming.

I found this lack of ideas from staff for carrying forth learnings into future ASTRON projects was both surprising, and expected. One the one hand, the intellectual power within the workshop established an atmosphere of creative problem-solving that came to an abrupt end at this question. On the other hand, it reflects and supports the broad research and the focused casework of this thesis, in that the conversion of organisational wisdom into practical value for further project endeavours is a generic weak-spot.

As facilitator, I then explored what protocols and/or systems are currently implemented at ASTRON/LOFAR for control of documents and data, and what management meetings might be appropriate to consider project management improvement initiatives. The group also explored some avenues involving personal learning. Ideas from this session are presented below in Table 5-7, as possible future initiatives for ASTRON/LOFAR.

Table 5-7. Suggestions to improve capture and implementation of lessons learned for future ASTRON/LOFAR projects

1.	Create a folder or marker within the document management system for project lessons learned, and file this report there, together with any prior or subsequent material concerning improvements to medium/large scale projects.
2.	Create a new (or adapt an existing) project management guide document. This needs careful editing to accurately reflect the culture and practices within ASTRON, and most importantly have a periodic review to embed lessons learned and updated approaches and procedures. It should be released as the official handbook for projects at ASTRON, and be an auditable document.
3.	An early chapter of the ASTRON project management guide (see above) needs to contain a step that ensures that the project manager takes official time to examine previous similar projects to obtain information about success or failure factors. The results of this study must be documented in the new project execution plan.
4.	The results of any project reviews, or lessons learned activities, should be announced at a general staff meeting, and possible presented as a short technical talk.
5.	Ultimately, an ASTRON 'knowledge database' could be established, with provision for entering of lessons learned by any staff member, with the data searchable by topic for easy retrieval.

5.4.4. Workshop Conclusions

The LOFAR lessons learned workshop worked well from a research tool perspective, and judging from the positive post-event feedback, was worthwhile for participants. Anecdotal comments to the ASTRON organisers indicate that the participants found the process and investigative approach a useful exercise, and that their opinions were heard and noted. The ASTRON Director communicated his satisfaction with the event and hinted at further similar reviews in other ASTRON domains.

The workshop followed the prepared program which was a satisfactory, though very intensive day. Future reviews of this type should allow at least a further hour for activity #3 (the break-out groups and feedback presentations).

In terms of the findings, while the four success factors and four weakness factors were very LOFAR specific, the key topics concerning the most important drivers of success in high-tech mega-projects were in close alignment with the research and conclusions I present in chapter 4 of this thesis. However two important differences were noted; first, 'Mission Assurance' did not arise as a topic or function within LOFAR, although group discussion supported the concept. Second, technical competence emerged as a very important factor in the successful delivery of LOFAR as an instrument, pointing to the wisdom of adding this topic to future post-project reviews, and as an essential success driver to be considered at the AFE stages in future high-tech projects.

5.5 Chapter Summary

In chapter five, I presented further research into four areas allied to high-tech project success.

First, I examined the pivotal and demanding role of the person appointed to be in charge of the high-tech mega-project, whether that person is its Director, leader, manager, or some combination of these roles. Eight less-explored aspects of this crucial position were investigated, as well as the identification of five key initiative areas that are shown to underpin success.

Second, I looked at authentic intent in high-tech projects, and how the dubious nature of management, project administration, or success measures, can signal that the protagonists goals may not be fully aligned with partner members or funding agencies. Outright fraud is rare, but incompetence and mismanagement likely impacts on the potential returns from national investment in science and engineering research. Perhaps most concerning is the sinister effects of research groups operating in environments with little or no consequences for performance failure, and a focus only on out-year funding that can divert effort.

Next I presented a deep investigation of project reviews, their process, effectiveness, and analysis approaches. I show that the post-project review activity especially can offer most organisations a handsome return on effort in terms of organisational, and individual, learning, and that this knowledge is readily convertible to intellectual property of high value to subsequent project endeavours.

Last, I describe the processes and activities associated with a practical example of a high-tech post-project review workshop, using ASTRON's recently commissioned LOFAR project. In one sense this was an experiment with a willing partner ready to offer a platform for expressing many of the research ideas and conclusions within this thesis. Equally important, the workshop demonstrated the value of conducting a project history-day, how the lessons learned are extracted and made relevant in the organisational context, and the importance of linking the learning to systems that permit later interrogation.

In the next chapter, I review all the key ideas resulting from the research effort contained in the present study, and build these into a practical tool available to project practitioners, funding approval agencies, reviewing panels, and project auditors.

Chapter 6 – Checklist for high-tech project success

6.1 Development and application of the CHiPS tool

Having identified and validated the key indicator areas of high-tech project success, some form of practical tool may be derived that can be applied by project practitioners, funding approval agencies, reviewing panels, and project auditors. I considered several forms for such a tool, including:

- A published article in a professional journal describing the research and reasoning behind the success indicators, and supported by a list of success drivers in an appendix.
- A simple checklist document, perhaps with some weightings applied, that would produce a 'likelihood of success' score
- An on-line, or PC tablet style data collector tool, configured to produce some graphic representation of achievement across the indicator range.

Further thought and discussions with two 'ISO Standard' management system audit agencies[50] indicated that a self-contained document in the style of a Management System Standard would be an appropriate format. The ISO style Standards (e.g. ISO 9000 series) were examined, and while these offer a structure against which an effective audit can be planned and conducted, they require significant training and experience to apply. A better model was found with the UK developed Investors in People (IiP) model[51] which although not a globally accredited Standard, has gained a solid following in many countries through its simple portrayal of principles, indicators, and evidence – all in plain English.

I adopted this general style (though not any IiP content) as a model for development of the **C**hecklist for **Hi**gh-tech **P**roject **S**uccess (CHiPS) Tool included as Fig. 6-1 in this chapter.

The CHiPS Tool is essentially a carefully constructed, empirically validated, checklist document that sets out the key success indicators for high-tech mega-projects, grouped by project phase. Against each of the 60 indicators I present example evidence that might

[50] NCS International Pty Ltd, Sydney; and Global Mark Pty Ltd, Sydney.

[51] The Investors in People assessment program is based on a simple, outcome focused, standard. It outlines what needs to be achieved, without prescribing how. This flexible approach allows many different organisations to use the same framework. See http://www.investorsinpeople.co.uk

support validation of the indicator being satisfied, and thus performing as a success driver for a particular science/engineering project. The tool is most usefully applied at the conceptual stage and re-applied at the AFE stage, although the indicators bear review throughout execution. The aim is to achieve a repeatable, objective assessment of where the requirements are addressed, and where gaps remain.

The version of the CHiPS Tool included in this thesis is protected by the author's Copyright, but may be freely reproduced and used.

The Checklist for High-tech Project Success (CHiPS) Tool ver 1.4

Project Phase	Key Indicators	Example Evidence	Findings	✓ or X
Inception and preliminary analysis	1. The mission is understood, agreed as a genuine endeavour, and credible.	Records of exchanges between recognised experts supporting the project mission and goal(s), and identifying principal risks.		
		Evidence of sufficient available resources that can be dedicated to the project.		
	2. Project complexity is manageable, and science/engineering challenges are feasible.	Early system concept descriptions support probability of success based on expert opinion, with knowledge and/or technology gaps identified.		
	3. The conditions and requirements required of the external project environment are analysed.	Records of discussion with appropriate agencies indicating no insurmountable (physical, economic, social, or legal) conditions or barriers to project construction or deployment.		
	4. The required and potential collaborators and stakeholders are identified.	Early planning documents identify and confirm interim list of government, industry, and institutional partners – with at least one contact name each.		
	5. The project budget and schedule are broadly defined, and in line with analogous projects.	Early planning documents describe the project road-map with preliminary budgets and schedules, and benchmark these against at least one analogous project in terms of scale and technical challenge.		

The Checklist for High-tech Project Success (CHiPS) Tool ver 1.4				
Project Phase	Key Indicators	Example Evidence	Findings	✓ or X
Planning & Concept Design (project feasibility)	6. The mission and objectives are clear.	The overall project mission, and underlying objectives, are agreed by the Participating Organisations, and captured in an approved documented form.		
	7. The Participating Organisations (PO) are known, and there is a strategy for effective collaboration.	There is a documented, agreed, and adequately resourced scheme for the identified POs to work together.		
		A documented review of PO capability and role exists.		
	8. Lessons-learned from analogous projects are consulted and interpreted for the current project, and communicate to planners.	An exercise is underway (or planned) to diligently research lessons-learned from analogous projects		
		A system of transferring this data to current project planning is in place.		
	9. Governance models have been examined and appropriate structure and legal entity selected.	A report exists (from a qualified source) containing informed recommendations for project governance, and shortlisted legal entity options.		
	10. Commitment from POs is evident.	A Statement of Commitment (or equivalent) is available from each PO, bearing high level name & signature.		
	11. The technical challenge and complexity is not overwhelming. There are indicators to solutions to fundamental problems. Investment in strategies to solve problems and/or prove concepts are evident.	Concept design plans and costings are externally reviewed and approved.		
		Technical hurdles requiring breakthrough solutions have feasible forward plans.		
		Pathfinder initiatives have funded plans that are integrated to the project.		

The Checklist for High-tech Project Success (CHiPS) Tool ver 1.4				
Project Phase	Key Indicators	Example Evidence	Findings	✓ or X
Planning & Concept Design *(project feasibility)*	12. A risk analysis has been conducted including identification of technical, programmatical, and institutional risks, risk controls, and cost/schedule impacts. Risk planning has accounted for unknown unknowns.	Project risks have been exposed through an inclusive process.		
		Risks are categorised, rated in terms of potential severity, and associated mitigation factors, controls, and impacts are postulated.		
		Documents show that unexpected negative events, and possible impacts, have been considered.		
	13. Budget and schedule estimates are benchmarked against specific analogous projects, and contain realistic budget and schedule contingency.	Top-down budgets and schedules are developed.		
		Budgets and schedules are benchmarked against at least two other projects of similar size and complexity.		
		Budgets and schedules include identified contingency components that reflect potential impacts within risk plans.		
	14. Ambiguities are identified and (mostly) resolved. Uncertainties are identified and conditionally qualified.	Project plans clearly identify areas where information is currently ambiguous, or uncertain. Uncertainties are defined in terms of possible solutions and (possibly compromised) outcomes.		
	15. Preliminary project reviews (e.g. CoDR, PDR) are conducted by independent experts, and have firm time criteria for response.	A process exists to conduct major reviews, including panel selection, conduct, and guidance for reporting, and consequent response/actions.		

The Checklist for High-tech Project Success (CHiPS) Tool ver 1.4				
Project Phase	**Key Indicators**	**Example Evidence**	**Findings**	**✓ or X**
Planning & Concept Design *(project feasibility)*	*(from above)* Prelimin project reviews (e.g. CoDR, PDR) are conducted by independent experts, and have firm time criteria for response.	Records of early project reviews articulate findings clearly, and are complete in terms of timely project response.		
	16. High level funding sources are identified, and match anticipated levels, including contingency.	The project plan contains a statement of future cashflows, identifying sources and applications of funds, including retained and unassigned project reserves.		
	17. Procurement strategies are in place that describe strategic engagement, scouting, sourcing, and purchasing.	A documented procurement strategy exists that contains or refers to project acquisition policies, guidelines, expectations, and procedures.		
		The procurement strategy contains (or refers to) early industrial engagement activities to identify capability and early strategic participation by industry.		
	18. Protocols are in place to manage project information and communication channels.	A project Management Information System is described, with scope and responsibilities identified. The scope extends beyond technical documentation, and embraces meetings, telecons, IP, and media interactions.		
	19. Task allocations are clear, both in the Project Office, and the POs.	A staffing plan exists for the Project Office, and for POs, with responsibilities and authorities identified.		
	20. Project stakeholders are engaged	Documents show adequate exchanges and interactions with stakeholders.		

The Checklist for High-tech Project Success (CHiPS) Tool ver 1.4				
Project Phase	Key Indicators	Example Evidence	Findings	✓ or X
Approval for expenditure	21. Genuine top level commitment is in place. The POs demonstrate authentic support for mission objectives.	Commitment letters, signed by participant's Government, Agency or Project Organisation Managing Director.		
	22. The collaboration arrangements for POs are agreed	Collaboration agreements (or equivalent) are signed and available.		
	23. The technical challenge and complexity is understood and matched by resources from the POs. Solutions to fundamental problems are apparent or close.	Project technical challenges are described in documents and cross reference the science/engineering goals. System complexities have been calculated, rated, or otherwise evaluated.		
		Strategies, activities, and resources to solve key problems and/or prove concepts are evident.		
	24. Risks have been analysed in detail, including identification of technical, programmatical, and institutional risks, risk controls, and cost/schedule impacts. Risk planning acknowledges unknown unknowns and appropriate contingency identified.	A risk register has been compiled through a discovery process involving all or most stakeholders.		
		Risks are categorised, rated in terms of potential severity of raw and residual risk, and associated mitigation factors, controls, and impacts are described.		
		Documented risk plans consider unexpected negative events, and describe preparations to minimise thereat/impact.		

The Checklist for High-tech Project Success (CHiPS) Tool ver 1.4				
Project Phase	Key Indicators	Example Evidence	Findings	✓ or X
Approval for expenditure	25. There is a detailed project budget and schedule containing realistic budget and schedule contingency for both identified risks and unknown unknowns. Optimism tendencies are exposed and corrected. Resources are allocated for capturing project lessons. The project scope can genuinely be accomplished within the proposed budget and any contingency reserves.	Detailed budget for project commencement plus 2 years. Medium level budget for remainder of project lifecycle. Contingency reserves are calculated or otherwise assessed, and valued. Detailed schedule with critical path and project dependencies identified. Budgets are based on traceable cost models or data, with adequate margins, and benchmarked against analogous situations, or certified for accuracy by qualified cost accountant. Schedules are independently reviewed and certified as practicable. The budget includes provision for post-project reviews.		
	26. The project mission, broad goals, and specific objectives are clear. Project success criteria and critical success factors are expressed.	Project mission, goals, and specific objectives are declared in project documentation. Success criteria and critical success drivers are recorded, and reflected in project artefacts.		
	27. A coherent and complete system description, and systems engineering approach, is embodied in project plans	Project plans contain a clear description of the project system, interconnects, and dependencies. A systems engineering approach is underpins all artefacts.		

The Checklist for High-tech Project Success (CHiPS) Tool ver 1.4				
Project Phase	Key Indicators	Example Evidence	Findings	✓ or X
Approval for expenditure	28. Interim approvals are in place regarding the external environment, and physical location (if appropriate).	Approval instruments are available (or official documents of intent), supported by legal opinion. Approvals exist concerning legislative or conditional compliance for site facility construction. and operation		
	29. An appropriate project structure designed, and legal entity (with Managing Board) selected.	The project legal entity is formed and supported by registration (incorporation) documents. The Management Board are identified.		
		The project structure is approved and documented.		
	30. Recruitment of top level roles with specialist skills & attributes is ready to commence.	Recruitment agency (or dept) has been identified, and role/job descriptions prepared.		
		Interview notes include questions concerning key selection criteria, specialist traits, experience, behavioural responses, and example scenarios, relevant to the special requirements of big science/engineering projects.		
	31. A staffing plan, supported by recruitment (or transition) strategy is ready to deploy.	The staffing plan exists. It contains statements concerning staff transitions into the project (if appropriate).		

The Checklist for High-tech Project Success (CHiPS) Tool ver 1.4				
Project Phase	Key Indicators	Example Evidence	Findings	✓ or X
Approval for expenditure	*(from above)* A staffing plan, supported by recruitment (or transition) strategy is ready to deploy.	The plan includes practical actions and required resources for recruiting new personnel into the project, including immigration procedures, re-settling resources, in-country/in-project briefings and training, and staff relocation policies.		
	32. The type, quality, and requirements for project management system tools are defined.	Evidence that program management systems tools have been selected based on proper matching to the project environment and requirements. Integration of project data across the tools has been considered.		
		Training needs are identified.		
	33. Project information control systems are in place. Project IP categories (including 'brand)' are identified, and protection protocols established	Project information flows are mapped, and policies and procedures are in place centrally to manage document control and information flows.		
		Project IP policies and procedures exist.		
	34. Funding sources are confirmed, and match anticipated levels including contingency	Documents available to demonstrate funding commitment. Total funding committed meets total budget.		
	35. Procurement strategies, policies, and arrangements are defined. Procurement challenges are addressed with solutions.	Procurement strategies, systems procedures, tendering and contract instruments exist. Procurement authorities are approved.		
	36. All project stakeholders are identified and informed.	Evidence of managed system to effectively inform project stakeholders.		

The Checklist for High-tech Project Success (CHiPS) Tool ver 1.4				
Project Phase	Key Indicators	Example Evidence	Findings	✓ or X
Project commencement	37. Formal approvals are in place regarding the external environment, and physical location (if appropriate).	All required Acts enabled, and permits, approvals, and associated guidelines exist, or evidence of surety sighted.		
	38. The Project Office is established and operating funds are available, accessible, and reflect top level commitment in POs.	The Project Office has accessible operating financial resources (e.g. bank account) funded from POs deposits that match planned commitments.		
	39. Project Management System tools are identified and agreed for use across the project POs. Protocols are established for project records access and security.	Project Management tools and applications are installed (or being procured for installation), by the project office and POs. Training needs have been identified. Protocols exist for project data security and control.		
	40. Data from project planning are transcribed into a secure project baseline.	Project execution documents accurately reflect budget and schedule data in approved planning documents, and are identified as approved project baselines.		
	41. Legal entity (with Managing Board) registered and established. Transactional instruments are enabled, and project office systems are in place.	Documents of registration, incorporation, signed treaty, or equivalent project entity evidence available. The project entity has established transactional facilities (financial control systems, bank account, contractual templates, payroll systems, utilities).		
	42. The mission goals and objectives are clear and consistent in 'kick-off' documentation	The mission, goals, and specific objectives are documented, and reflect agreed purpose stated by the POs.		

The Checklist for High-tech Project Success (CHiPS) Tool ver 1.4				
Project Phase	Key Indicators	Example Evidence	Findings	✓ or X
Project commencement	43. Project Office has key staff appointed. Decision-making protocols are established and communicated.	The Project has an identifiable physical or virtual presence, and an organisation chart exists with responsibilities and authorities defined. Decision-making pathways, including escalation authorities, are documented.		
	44. A procurement function is established with appropriate authorities for contractual transactions and approvals. Methods and instruments are approved for contracted services and project acquisitions.	The procurement function is clearly identified within the Project Office structure, and appropriate authorities defined.		
		Procedures, authorities, and artefacts for purchasing, and contract awarding processes, are available.		
	45. The Project Leader/Manager has commenced and set /demonstrated expected project behaviours and standards, instilled an ethical and non-discriminatory culture, and project pace.	The Project Leader/Manager has clearly communicated expected behavioural standards concerning ethics, professional interactions, and Project Office rules. Discipline and project pace (sense of urgency) has been explicitly covered.		
	46. A Mission Assurance specialist position is established, reporting to the Project Leader.	A Mission Assurance function is filled (or recruitment underway).		
	47. Proto-task forces (tiger teams) are recruited, and systems invoked for periodic briefings	Evidence of specialist personnel approached and agreeing to appointment as proto-taskforce(s). A schedule for periodic briefings exists.		
	48. A system for capturing lessons learned has been established.	A lessons learned database (or equivalent) has been implemented, and knowledge retrieval demonstrated.		

The Checklist for High-tech Project Success (CHiPS) Tool ver 1.4				
Project Phase	Key Indicators	Example Evidence	Findings	✓ or X
Project execution and review	49. The project mission and objectives are regularly communicated throughout the project.	Reviews and project meeting (and briefing) records verify that the overall mission and objectives are periodically refreshed and announced.		
	50. A System Engineering approach is the prime driver of technical execution.	Project audit records and system data confirm adequate investment to Systems Engineering as a project driver.		
	51. Controls are in place to rigorously review stakeholder contribution and value. There are real consequences for performance failure.	Project review reports, and independent audits in place to monitor stakeholder performance, including qualitative assessment. Failure incurs real penalties.		
	52. Project information, technical data, and communication is under tight control	Evidence of effectiveness of the project information management system in controlling technical data, financial data, project communications, and media.		
	53. A change management system is established, and protocols deployed to enforce use.	Examples available of changes approved and prosecuted through the PM system, captured within design and execution systems, and communicated to stakeholders.		
	54. A 'sense of urgency' is embraced and apparent, set by project leadership	The project exhibits a palpable sense of urgency and seriousness in meeting schedule commitments. The pace is both set and reflected by top management.		

The Checklist for High-tech Project Success (CHiPS) Tool ver 1.4				
Project Phase	Key Indicators	Example Evidence	Findings	✓ or X
Project execution and review	55. Risk exposure and risk encountered is continually monitored. Cost/schedule impacts are communicated to stakeholders. Risk contingency takes account of risk retirement and 'burn'.	Audits and risk review reports indicate attention and monitoring of real and potential risk, including cost/schedule impacts.		
		Risk 'burn' and contingency reserves are frequently assessed.		
	56. Independent project reviews are conducted, and have firm time criteria for response. Reviews are informed by salient data presented in consistent dashboard style, and reported against secure baselines.	Records of independent reviews are available, and show adequate planning, scope, and diligence in conduct and reporting.		
		Review reports enable consistent representation of quality data, reported against traceable baseline information.		
	57. Lessons learned from project execution and reviews are captured as retrievable knowledge	A system exists for project-wide capture of project errors, corrections, unforeseen events, audit and review findings, and positive outcomes.		
		Tests verify that lessons learned are available to all project managers, teams and individuals.		

The Checklist for High-tech Project Success (CHiPS) Tool ver 1.4				
Project Phase	Key Indicators	Example Evidence	Findings	✓ or X
Final Review and learning	58. The project is effectively reviewed through the lens of a representative group of project management, staff, and other stakeholders including key vendors.	A process exists that describes the intent for post-project review(s). The process has specific budget allocation, and appears in the top level project timeline.		
		The process includes personnel from project teams, key stakeholders, suppliers, and customers (users).		
	59. The results of the post-project review are (or formally intended to be) captured and analysed effectively to reveal root causes.	Post project review procedures include the requirement for results analysis for root cause analysis. There is evidence of this activity (as appropriate).		
	60. Barriers to organisational learning are understood and addressed, and captured lessons learned for ready retrieval.	Knowledge gained from project review activities is actively managed to enable continuous learning throughout the organisation, and in accordance with the project/organisational culture.		
		There is evidence of application of prior learning within planning for new projects.		

*Fig. 6-1. The **C**hecklist for **Hi**gh-tech **P**roject **S**uccess (CHiPS) Tool*

Chapter 7 – Application of this research to the Square Kilometre Array (SKA) project

7.1 Application of this thesis to the SKA project

The previous chapters of this thesis considered the general principles, problems and characteristics associated with the successful planning and execution of high-tech mega-projects. I now turn to a practical illustration. In almost every way, the characteristics of the Square Kilometre Array (SKA) project typify the kind of high-tech mega-project discussed throughout this thesis. Its lofty science goals, massive and dispersed infrastructure needs, cutting edge technologies, multi-billion dollar budget, and sheer complexity combine to make this global collaboration a very serious challenge indeed.

7.2 The Square Kilometre Array (SKA) project

The SKA will be a revolutionary international radio telescope for the 21st Century designed to address unanswered fundamental questions about our Universe (Refer Appendix I for a fuller description of the SKA instrument and project timelines).

The total collecting area will be approximately one square kilometre giving 50 times the sensitivity, and 10,000 times the survey speed, of the best current-day telescopes. With receptors extending out to distances of 3,000 km from the centre of the telescope, the SKA project stretches the limits and risk profiles of several leading edge technologies such as phased array sensors, low-noise signal amplification, and computational speed.

More than 70 institutes in 20 countries, together with industry partners, are participating in the scientific and technical design of the SKA telescope which will be located in either Australasia or Southern Africa extending to the Indian Ocean Islands. The site decision, based on criteria such as radio-quietness, and infrastructure support, will be handed down in 2012 from an eminent and independent Site Selection Committee. The target construction cost will be at least €1,500 million, with preconstruction for stage one (10% SKA) planned to commence in 2014, and first science anticipated by 2020.

7.3 Application of findings to the SKA project

In this section I extract many of the most important success drivers shown scientifically and empirically to be vital to mega-project success, and draw out strategies, factors, and observations for consideration and application to the SKA at the earliest opportunity.

7.3.1 SKA governance and project management

Table 7-1, presents seven key areas where management attention is required to establish the governance and project management control baselines for the SKA.

7.3.2 Special characteristics of the project manager

This section deals with the practical role of running the project. The leadership of the SKA project, in terms of a single actual person rather than a guiding Board or Committee, may be assigned to a (often notable and charismatic) scientist who is charged with launching and directing the project. Case study fieldwork for this thesis indicates that such people, while possessing the required 'gravitas', political adeptness, and technical knowledge of big high-tech projects, do not often possess the qualifications and experience matching the industrial model of projectification that the SKA will demand. Collins (2001) argues that great organisations need three people – a leader, a manager, and a financial disciplinarian. In the case of an eminent scientific appointee to the role of SKA project figurehead or Director, it is strongly recommended that a professional Project Manager also be appointed; someone with the proven track record of stewarding very large science-based projects to successful fruition, or having the clear potential to do so. Moreover, whatever scope the project head may be accountable for, the SKA Directorate should commence recruitment processes as soon as possible.

The fundamental skills, experience and qualifications will be determined and built into the role description and job profile. However research within this thesis indicates that eight personal characteristics, traits, or skills are strongly indicated as subtle, though significant, factors in driving success within scientific and engineering mega-projects. These are shown in Table 7-2 and suggested as added selectors in the selection process for this pivotal position.

Table 7-1. Governance and project management implications for the SKA

Key Strategy	Descriptor	Thesis reference section	Background context and Management Implications for the SKA Project
1	*Legal entity & location of project headquarters*	3.1.1	A PrepSKA initiated study into viable legal entity options for the SKA project concluded that a Dutch foundation, a UK company limited by guarantee, and a US not-for-profit corporation incorporated in Delaware were equally suitable for the purposes of the SKA project. Given the limited funding from the US at the pre-construction phase, the potential tax efficiencies available in the UK, and the ease of transition from the (UMAN hosted) SPDO organisation, the UK is indicated as the most appropriate location for at least an interim legal entity and office to conduct pre-construction procurement activities. International offers were solicited in early 2011, with responses from Germany, the Netherlands, and the UK. A site at Jodrell Bank (Cheshire, UK) has been announced by the SKA Founding Board.
2	*Establishment of an appropriate project and team structure*	3.1.4	Large high-tech projects are shown to function best in a hierarchical organisation model where there is clarity around reporting lines and allocation of resources. That is not to say that matrix type organisations are not found or do not work – simply that they actually operate closer to the traditional behaviours than perhaps the model name suggests. If a matrix organisation is implemented, it should err towards a 'functional authority' model (rather than product authority). Integrated Project Teams (IPTs) are shown to be effective groupings for high-tech projects, and instil a tribal accountability more likely to deliver against targets. Team diversity has a net positive value for teams, with the proviso that any emerging dominance is managed tightly. Teams should include a cross-section of shapers, deliverers, and knowledge custodians. Ideally, teams should be co-located; however this is unlikely for the SKA. Nevertheless, periodic face-to-face meetings are considered essential for successful cohesion.
3	*Project Management systems*	4.3.1	It will be essential for the SKA Project to adopt an integrated project management system, and equally important, instil the disciplines associated with its effective deployment and use. No particular application or product is recommended from this study; however the following general features are indicated. The software package must:

Key Strategy	Descriptor	Thesis reference section	Background context and Management Implications for the SKA Project
			• Be right-sized for the project, and not be weighted with needless modules, nor incapable of required functionality • Permit networked use at pre-defined levels of access authorities • Be comprehensive i.e. able to hold, manage compute, predict and report by real-time tracking and assignment of financial, effort, and materials data • Be efficient at integrating and alerting in relation to change management • Allow for single entry of any data • Be largely intuitive to operate, and require minimal training, especially for report generation • Be capable of importing data in formats from other common PM IT platforms • Contain a reporting engine with advanced report building capability
4	*Deployment of effective project task forces*	3.3.4.4 5.1.4.2	Task forces are effective structures for tackling specific and unexpected problems, but work less well when assembled reactively. The SKA project should, as part of its organisational formation, recruit Task Force members in readiness for their inevitable deployment. Task force groups should be convened for programmatical, science, and technical challenges, and be periodically briefed.
5	*Effective information management*	3.3.4.3	The most effective means of establishing a disciplined information controlled environment is to introduce it early, drive it through management example, and most importantly, dedicate resources to maintaining it. The SKA should implement a Project Information Office (PIO) as the central control of project information, documents and data (i.e. the project Management Information System – PMIS). Further, I strongly suggest that the PIO maintain resources and responsibility for arranging and recording meetings and teleconference, moderating official on-line networks, wikis, and blog sites, and management of communication outputs. The PIO should also hold authority for approval and recognition of any satellite group information needs, including the use of project templates, branding, intellectual property (IP), and single point management media interfaces. The elevation of the traditional 'Outreach' department to a full PIO will not only improve information command and control, but also demonstrate a new level leadership in high-tech mega-project management.

Key Strategy	Descriptor	Thesis reference section	Background context and Management Implications for the SKA Project
6	*Application of a mission assurance approach*	3.3.4.6 5.1.4.4	The SKA project should appoint a specifically titled Mission Assurance person (or function) at project approval for expenditure (AFE) stage. This function (part auditor, part advisor, part 'devil's advocate') should be organisationally placed outside of mainstream project delivery, yet close enough to have ready participation in critical testing, meetings, and reviews, and with access to top level project management. The role is principally one of questioning and checking that activities, deviations and changes, particularly at project interfaces, pose no unrecoverable threat to execution and performance. In terms of job description, the focus of mission assurance is to monitor the established design criteria and standardised control design practices to ensure that the design and execution of the SKA is capable of: • Functioning properly during the required instrument lifetime • Minimizing or eliminating potential sources of human or material-induced failures • Practical assembly, test, fault isolation, repair, servicing, and maintenance without compromising safety, reliability, quality, and performance • Being constructed at the selected site; i.e. the site selection assumptions remain soundly based.
7	*External stakeholders*	2.5.1 3.2.3.1 3.3.4.5 4.3.7	The global, scientific, and political nature of the SKA project requires that serious effort and competence is applied to (a) establishing partnership style collaborations for the science and engineering interactions, (b) industrial style contractual arrangements for work-package allocation and delivery commitment, and (c) formal, respectful, yet bold engagement with Government agencies charged with handling the plethora of legislation, operating permits, etc. In each of these arenas, a balance must be struck between tactful compromise and a sense of urgency in gaining firm outcomes. The excellent level of public outreach activity requires to be maintained.

Table 7-2. Key subtle attributes of the high-tech project manager

Key Attributes	Descriptor	Thesis reference section	Management Implications for the SKA Project
1	*The ability to deal with the temporary and uncertain nature of mega-projects*	5.1.3.1 5.1.3.4	The person will likely be drawn following conclusion of a similar scale project, and be used to very challenging international assignments running for 5-10 years, often with high uncertainties involved.
2	*Having and demonstrating personal authenticity*	5.1.3.2	The person may not necessarily exude charisma, but demonstrate soundness, good judgement under pressure, be *au fait* with the general science area (but not an expert), and have a track record of consistency, fairness, tenacity, and project commitment.
3	*Applying skill in the management of collaborations*	2.6 3.2.4.9 5.1.3.3	The SKA project manager will be faced with the complexities of an international industrial scale project and will require a sound understanding of mechanisms for cross-cultural, multi-disciplinary groups. Practical experience, especially in dealing with dispersed R&D teams, is essential. Meetings will require skilful preparation and management to be effective in obtaining commitment to deliver against promised actions.
4	*Having an appropriate balance of management and leadership talent*	4.3.6 5.1.3.4	Managers do not always transform into good leaders, or vice versa. Management is largely about coping with complexity and process, and by monitoring results. Leadership is concerned with directing change and aligning people by communicating an inspirational vision. To achieve success in big high-tech projects, a balance between both areas of skill is needed. Managing a project like the SKA will demand critical thinking (intellectual [IQ]); team development (managerial [MQ]); and influence / motivation / conscientiousness (Emotional [EQ]).The supervisory demands of the SKA, characterised by creative technical people operating in environments of minimal formal supervision and reporting relationships resonates well with the transformational leadership (TL) style. Such articulate an attractive vision (excite, inspire, and support) that fuels high

Key Attributes	Descriptor	Thesis reference section	Management Implications for the SKA Project
			performance and results. The SKA project will demand a combination of transformational leadership and management skills including someone who is: • Qualified, and experienced, in complex technical projects • Obsessively mindful of the critical path, and always driving forward • Effective delegator, but not afraid to 'get hands dirty' when needed • Ready and able to do 'what it takes' to remove roadblocks • Sets the example in terms of ethics, behaviour, and standards • Maintains an intellectually demanding environment • Maintains a systems engineering view, but is not stuck at that level • Knows what to communicate, to whom, and when.
5	*Motivating strategic influence through persuasion, encouragement, and negotiation*	4.3.6 5.1.3.5	The SKA project manager will need to foresee, mitigate, and manage a wide range of problems and stakeholder expectations through skilled and sensitive persuasion and negotiation flair. Moreover, he/she will require the confidence that comes with experience and maturity to strategically influence outcomes. These challenges can be usefully grouped into three areas, each requiring deft handling: • Procurement, commonly assigned to a specialist department, will likely have some accountability to the project manager, especially when involving any major, strategic, or critical path acquisitions. Such activities draw on persuasion and negotiating skills as a key characteristic for successful contract execution and procurement logistics. • Funding, where the political landscape will likely change over the project lifecycle, and uncertainties will appear to affect the project environment.

Key Attributes	Descriptor	Thesis reference section	Management Implications for the SKA Project
			• User groups (scientists), which will inherently attempt to drive scope and performance change with little appreciation of the implications.
6	*Building trust in a diverse cultural environment*	3.2.4.9 4.3.6 5.1.3.6	Trust will be a key ingredient in forming and maintaining collaborative social relationships in the international SKA project. The Project Manager will need to personally adopt the task of developing shared value sets to underpin the building of a strong project culture, including example-setting in relation to knowledge sharing. The SKA project will benefit strongly from capitalising on the trust residing in skilfully managed 'heritage' teams. This research indicates that when 20-40% of the team members have past associations, strong collaboration was evident at the start. Trust issues will also be important concerning care with delicate and confidential matters.
7	*Having a personal profile well matched to the project*	5.1.3.7	The SKA Directorate will no doubt implement fair, open, and non-discriminatory practices in the recruitment of a Project Manager. Nevertheless, while observing such policies, it may be useful to be informed by contemporary research of the more subtle aspects that might (for example) separate two apparently equal candidates. • More complex and challenging projects increases the potential of success factors generally. Project managers should not be assigned to projects below their management capabilities. • European project managers rated success factors as averagely important, significantly lower than other parts of the world, although no differences appeared in management performance based on gender. • Project success may be determined differently according to ethnic background. Western trained managers emphasise project time, cost, and quality, whereas

Key Attributes	Descriptor	Thesis reference section	Management Implications for the SKA Project
			Chinese project managers see relationships as the main criterion for overall success. The Indian IT industry generally identifies functionality within scope as the foremost success criteria. • Age is a factor, with more senior managers reflecting more confidence commensurate with experience. Older project managers assign higher importance to teambuilding, and link competencies to experience. Many authors found a significant correlation between project manager experience and project success. • Project managers responsible for the wider project life cycle (not just planning, execution and close-out) tend to be more successful. Project managers should be assigned at the earliest stages and lead their project to the commissioning stage. • Project managers working in their own culture tend to be more successful than expatriates • The mega-project manager needs the intellectual maturity and discipline to manage beyond the rational, objective, and universal representations of the project. He/she needs skills to analyse and judge the ambiguous, fragmented and political reality of project situations, as well as the emotional intelligence that reflects deep personal identification with project goals. The present study found it is this rare mix of intelligent gravitas, technical awareness, social proficiency, and political confidence that sets outstanding mega-project managers apart.

Key Attributes	Descriptor	Thesis reference section	Management Implications for the SKA Project
8	*Driving a clear sense of project urgency*	3.4.4. 4.3.7 5.1.3.8	The SKA project, with its typically long construction and operation time, will present many opportunities to exhibit actual or potential project disasters. The Project Manager must be alert to the 'inherent silent power of time' and instil a sense of pace into the team on the basis that urgent projects demonstrate a greater ability to secure resources than projects viewed as routine. Ultimately a key characteristic of mega-project managers is the enthusiasm and determination to keep driving the project forward, and to effectively communicate this 'sense of mission' throughout the team. Mega high-tech enterprises have voracious appetites for funds, even during quiescent periods, and maintaining progress on all possible fronts is crucial to success. It is critical that project managers apply judgement to position stress levels between lethargy and team fatigue. This is perhaps most obvious when unplanned deviations occur. The skill to juggle resources, quickly re-plan, and restore the critical pathway requires a special, multi-dimensional intellect and the ability to maintain a balance between unproductive stress and pressure, and motivating urgency.

7.3.3 Procurement strategies

The SKA project is currently in its preparatory stage (PrepSKA), and expected to begin phase one construction around 2016. At this time, the project organisation must be operational and prepared to begin a wide range of procurements across the globe. The topics shown in Table 7-3 describe key areas where prevailing wisdom and lessons learned can help shape strategies for procurement success.

Table 7-3. Key areas for shaping procurement success in high-tech projects

Key Strategy	Descriptor	Thesis reference section	Management Implications and strategic actions for the SKA Project
1	*Early establishment of procurement office structure, resources, processes, roles and responsibilities, and information management systems.*	3.2.3 3.2.4.1 7.3.3.1	Begin consideration of staffing and other resource requirements for the SKA procurement office, including a capital and operating estimate for early approval. Commence recruitment.
2	*Formally approve procurement policies, strategies, and plans, and document these within a concise approved Project Procurement Plan.*	3.2.3 3.2.4.2	Drawing on the work of PrepSKA Work Package 5, approve and implement an SKA procurement policy and associated strategy, responsibilities and authorities, and operating procedures.
3	*Obtain full understanding of global capability scouting information, and employ appropriate approaches and instruments with terms and conditions supporting project goals.*	3.2.3.2 3.2.4.3	Ensure the global industry capability assessment process is completed, and reports available to procurement personnel. Develop, review and approve procurement instruments.
4	*Establish the contracting model, aligned with the legal entity. Develop relationships with principle contractors and the supply chain.*	3.2.4.4 7.3.3.1	Work with SKA governance board to align the SKA legal entity with the adopted models for contractual relationships with suppliers.
5	*Ensure competitiveness in contracting, through carefully*	3.2.4.2 3.2.4.5	Procurement management to devise acquisition strategies that ensure value for money, and respect *juste retour* agreements.

Key Strategy	Descriptor	Thesis reference section	Management Implications and strategic actions for the SKA Project
	planned pricing strategies, and a 'value for money' approach.		
6	*Apply purchasing specifications that are appropriate to the goods or services required, are flexible for optimal outcomes, and developed with input from industry.*	3.2.3 3.2.4.6	Procurement management to devise and apply purchasing approaches that match required goods and services. Consult with strategic industry partners to the SKA (e.g. SoMI signatories).
7	*Understand and actively manage procurement risk, including the critical early stage engagement phases.*	3.2.3 3.2.4.7	Devise and implement an active system for identifying and tracking procurement risk. Consider contingency reserves.
8	*Evaluate and select project contractors using a fair and balanced process, executed against standardised procedures, and focussed on criteria weighted in favour of mission success parameters.*	3.2.3 3.2.4.8	Ensure that a competent system and team is established to undertake formal assessment of SKA supplier offers. Implement sound and defensible assessment criteria, and records management.
9	*Implement fair and transparent procurement processes, and exploit open strategic partnerships while allowing for evidence based supplier inspections.*	3.2.3 3.2.4.9	Procurement management to work with legal advisers in preparation of specific and generic contracts documentation. Establish processes and resources for supplier-based inspections.

7.3.3.1 Proposed practical arrangements for an SKA-type interim procurement office

During the pre-construction phase of the SKA and onward, there will be a need for an operational procurement office to manage industry liaison for supply of goods and services, control purchasing data, select and negotiate with suppliers, issue and administer Requests for Tender (RFT) and contracts, supervise dispersed purchasing, and arrange payments (Perna et al., 2011). The prescriptive nature of the following commentary is acknowledged, and offered as advice derived from the research material forming this thesis.

Functionality - The proper and effective functioning of a mega-science procurement office depends on a professional and disciplined approach. Apart from respecting the responsibilities and authorities invested in the procurement team, the SKA community will need to understand and comply with procurement policies and procedures, especially regarding the centralised control of purchasing data (e.g. specifications, drawings, et.) approved for issue by the SKA Senior Engineer. This is particularly at risk in the case of dispersed, and/or 'in-kind' procurement in a country other than the procurement office. It will be incumbent on the SKA Executive to give early consideration to these matters, and firmly explain and enforce the centralised authority of the procurement function.

Funding, and defined authorities - The legal entity for procurement (which may differ legally from the SKA project office) will require seed, operational, and transactional funding for its proposed UK base. Seed funding will be required to pay for establishment costs (legal and incorporation fees, rental bond for premises, capital outlays for office equipment, furniture and systems, and sundry support items). These are anticipated to cost in the region of £40,000[52]. Operational expenses (salaries and on-costs, communications, office rental and utilities, insurances, expendable items etc) to match anticipated staffing plans are anticipated to cost £30,000 per month. Transactional outgoings will reflect procurement contracts, and may range from thousands to millions in Euro currency depending on the level of dispersed (i.e. through the SKA Consortia) procurement undertaken.

Authorities will need to be defined for expenditure approvals. In particular, for transactional approvals of contractual payments, a hierarchy of approval stages is recommended, with breaks at defined levels, each requiring a higher (or dual) level of approval. For transactions over €1 million, or approval of in-kind credits from member states, Executive approval should be required.

[52] The figures quoted are indicative estimates only, based on 2011 costs, and presented in currencies appropriate to the expenditure locale. The capital cost of a new or existing building is excluded.

Policies and procedures and disciplines - Prior to commencement of any interim or pre-construction procurement activities, the following SKA framework and operational documents will be required:

- Procurement strategy (i.e. the procurement approach and guidelines). The SKA Project Execution Plan envisages a distributed procurement model, based on Work Packages defined and approved at the SKA Project office, and awarded on a bid basis to SKA Participating Organisations (POs), industrial organisations, or consortia of both. Assuming this model (or an alternative) is ratified, a clear documented description will be required to ensure the parties have full awareness of their roles and responsibilities.)
- Procurement policies (e.g. ethics, fairness, *juste retour*, balancing, sourcing approach, management of dispersed and in-kind procurement, methods of price enquiries, jurisdiction of contracts, capacity building policies).
- Procedures (e.g. interfacing with suppliers, pre-qualifying suppliers, quality assurance requirements, tender management, tender selection procedures, contract administration, management of dispersed procurement, payment procedures, management of purchasing data (specifications etc.), management of SKA records (all media), office management guidelines). In the case of dispersed procurement (including in-kind member supply models), it will be critical that the processes for allocation of work packages, the ongoing monitoring of delivery, and accounting methods for tracking earned and claimed value are documented and followed.
- Templates (e.g. RFI/RFT/RFQ, purchasing agreements and contracts, supplier evaluation forms, terms and conditions).

7.3.4 Actual and potential resilience of the SKA project

The attitudinal environmental and launch conditions empirically shown in this thesis to be influential in project success can be usefully considered for the SKA project[53]. As a test of the research conclusions, and to identify target areas for action, I undertook a review of the early phase SKA project by applying the technique of participant-observer (Yin, 2009).

[53] See section 3.3 ‘Project shaping and building resilience’.

Against each special resilience factor from this study, personnel from the SPDO Office[54] were asked (using a Likert scale where 1 = *none* and 5 = *totally*) to evaluate (i) the importance of each factor to the SKA, and (ii) the extent of current manifestation[55]. The results were averaged and appear in column 1 of Table 7-4. Documentary and oral evidence was used to judge the extent of application or acknowledgement in the project, and the status captured in short narrative form in column 2 of Table 7-4. In Column 3, I suggest potential project initiatives for improvement of factor realisation.

Table 7-4. Summary of 'special' resilience factors showing the extent of current application, and potential for improving factor realisation, in the SKA project.

1. **Special Resilience Factor** (Team ratings)	**2.** **Current extent of application or acknowledgement in the project**	**3.** **Potential initiatives to improve factor realisation.**
Realism (IMPORTANCE = 3.8 MANIFESTNESS = 2.0)	The Team applies a realistic approach to costing, with good understanding of broad costs and risks of optimism. The broad schedule is acknowledged, albeit with acceptance of probable slippage considered within the norms for such a project. The technical challenge of the SKA is known.	1. Immediately resolve budget scope and cost caps for Phases 1 and 2, especially those concerning site works. 2. Ensure that costs are fully defined, traceable to sources, and future estimates are defendable to approval Committees.
Lessons Learned (IMPORTANCE = 3.8 MANIFESTNESS = 1.8)	Limited formal or coherent effort to seek lessons learned from like-projects, however sub-teams have done this. Many of the Team consult with personal contacts (e.g. the ALMA project) and draw from self experience. Personnel with experience from other radio-astronomy projects populate SKA committees.	1. Appoint an additional Systems Engineer and commence an immediate knowledge 'roundup' exercise. Implement a searchable knowledge system tool. 2. Develop a direct 'lessons learned' channel with other analogous projects (e.g. LOFAR, HiPER, VLT).
Project Ambiguity (IMPORTANCE = 3.5	Team members with industrial backgrounds find the ambiguous requirements challenging, however complexity is addressed competently across the Team. Geographically	1. Conduct Team based workshop to harmonise industrial level approach to project phases, peripety, reporting, and management responses.

[54] Six SPDO technical domain specialists from the SKA Design and Cost Team.
[55] For 'importance', n = 6 and Std Dev = 0.3414. For 'manifestness', n = 6, Std Dev = 0.4417.

1. **Special Resilience Factor** (Team ratings)	2. **Current extent of application or acknowledgement in the project**	3. **Potential initiatives to improve factor realisation.**
MANIFESTNESS = 2.2)	remote collaborative institutional groups, charged with developing pivotal technologies, operate quasi-autonomously.	2. Shift to centralised control, reporting, and decision inclusivity for remote groups.
Mission & Goals (IMPORTANCE = 4.7 MANIFESTNESS = 2.3)	The SKA has stated science goals, a Design Reference Mission, and a Phase 1 Project Execution Plan is under preparation.	1. Define precisely (with boundaries) the design and cost scope, and trade-offs. 2. Immediately define and declare the critical success indicators and metrics.
Reporting and Decision Structure (IMPORTANCE = 4.0 MANIFESTNESS = 2.5)	The reporting and decision-making structures appear clear in documents, but are actually complex and variable, typifying the science community decision-making behaviour. Participation in standing committees and at decision meetings is inconsistent. Tiger teams (task forces) are formed as required but work effectively once running.	1. Implement transition to structured and coherent meeting and reporting in conformance with centralised authority processes. 2. Create formal process for as-needed task force formation, assignment, conduct, and reporting.
Information Control (IMPORTANCE = 4.2 MANIFESTNESS = 2.0)	SKA design and cost data has yet to be brought under a formal control system, and there is no formal PMIS in place yet. Domain managers maintain personal control of SKA data and information, and a rudimentary document numbering and approval scheme is in place.	1. Acquire and implement an appropriately scoped PMIS, with surrounding processes. 2. Establish a project information central function, to improve control and distribution of ‘satellite’ group data, and information sent externally.
Risk & Contingency (IMPORTANCE = 4.0 MANIFESTNESS = 2.2)	Team based project plans consider some risks, and a risk register is in place. The costing strategy foreshadows a contingency component. There is high awareness of *a priori* risks within the professional team, and a traditional approach to risk appraisal.	1. Implement project contingency, and proto-task forces in readiness for *unknown unknowns*. 2. Watch for, and formally recognise uncertain risks within the risk register, and pre-plan initial responses for fast containment.

1. **Special Resilience Factor** (Team ratings)	2. **Current extent of application or acknowledgement in the project**	3. **Potential initiatives to improve factor realisation.**
External Environment Aspects (IMPORTANCE = 4.3 MANIFESTNESS = 2.8)	There is Team awareness of project environmental aspects - mostly funding scenarios and site host issues. These are dealt with by the Project development Work Packages, and overseen by the SKA Project Executive.	1. Ramp up monitoring and assisting management of the host site environmental and regulatory issues to prevent slippage on SKA site decision. 2. Through the pre-cursor telescopes on SKA candidate sites, pro-actively identify local approval channels and recruit protagonists
Mission Assurance (IMPORTANCE = 4.3 MANIFESTNESS = 1.3)	Current budget restrictions preclude establishment of a formal Mission Assurance function. However external Engineering reviews and internal PDRs, together with Project Executive, play some role as mission assurance.	1. As part of the Team transition to the SKA Project Office, appoint a Mission Assurance Officer. 2. Commence a project definition exercise and verification audit alongside the Project Manager.
Project Complexity (IMPORTANCE = 4.3 MANIFESTNESS = 2.7)	The SKA project is very complex technically and logistically, and this is recognised by the team. The SKA community has high general awareness of system complexity, and there is general acknowledgement of the SKA as a complex adaptive system.	1. Describe and reflect the degree of complexity explicitly in project structures, artefacts, deliverables and strategies. 2. Define boiler-plate responses to system engineering challenges.

7.3.5 Mega-project success drivers - Implications for SKA management

The key success drivers for high-tech mega-projects are derived and presented in chapter four, as the core section of this thesis. These may be usefully considered across the life-cycle of the SKA project. Assigning the identified success drivers to the SKA project phases and activities shown below, will ensure that the key concepts are embedded at the most productive point. The reference letters [X] relate to the full descriptions of the key success drivers shown in Table 4-2 of this thesis. The commentary offered in the Management

Implications column of Table 7-5 should be applied as a validator that such aspects and actions have received due attention[56].

Table 7-5. SKA project phases referenced against success drivers from the present research.

Key Strategy	SKA Project Phase	Management Implications for the SKA Project
1	**Conceptual Planning**	This is the time for clarifying the project definition, scope and goals, and if required, the business case [B]. Sponsor commitment must be in place, and client/user expectations agreed [D, G].
2	**Post Concept Approval**	Strategies are now developed for dealing with operations in the host environment [Q], key resources are identified and secured [I] (including management [O]) and a detailed risk review undertaken [N].
3	**Project Approval**	Strategies are implemented for project policies [A], systems engineering, site acquisition, procurement [Q], information management (including outreach and Public Relations) [C], and staffing.
4	**Project Commencement**	Planning, execution, and review systems, operating procedures, and document controls [A] are now instigated. Project baselines and phases are defined [E]. Change management, continuous improvement [P], and configuration control [M] is established. Strategic relationships are commenced with key suppliers [R]. Project team governance is asserted early through the project manager's approach to leadership, motivation, and social competence [F]. Especially important now is the assignment of accountabilities [L], aligning staff perceptions of goals and success, and instilling a sense of project momentum [J].
5	**Periodic Reviews, and Post-**	Periodic reviews to report and assess progress against planned milestones are crucial. The formal conduct of a post-project review involving at least the core execution team is

[56] This table may be considered a much abbreviated version of the CHiPS tool in chapter six.

Key Strategy	SKA Project Phase	Management Implications for the SKA Project
	Project Reviews	also essential. Careful planning for this event at around 1-3 months after project (or major stage) is closed is recommended.

7.3.6 Documenting the project rationale

The foregoing sections of this chapter set out much of the detailed thinking, preparation, and pre-cursor activity that must be taken into account in order to tune a high-tech mega-project such as the SKA for success. However, simply working through the headings, considering the management implications, and devising the strategies is insufficient. These prescriptions need to be collated within a logical, succinct and compelling project rationale ready to present to stakeholders, and especially funders.

Rhatigan et al. (2007) authored a highly informative paper[57] that not only elegantly sets out the background and contextual direction of a high-tech, high value program, but also deals very efficiently with the range of topics required of a compelling project business case document.

Drawing on Rhatigan's (2007) model, the project rationale for the SKA should certainly cover the *a priori* topics of science goals, investment profile, global collaborations, and industry engagement. It should also not shy away from addressing the more difficult subjects such as risky transition technologies, budget constraints, collaboration challenges, cultural issues, and realism in cost and schedule. It also needs to tackle the project office functionality, mission assurance matters, decision-making structures, workforce and project tools, requirements setting and procurement. In short, the aspirational topics, and the thorny problems, are paralleled in the world of big space missions, and are fully relevant to the SKA project. For example, NASA's Constellation's Advanced Projects Office is a feature of Rhatigan's project rationale – a concept comparable to the alternate receptor technologies program for SKA phase one.

[57] Their interesting paper researches the reasons and ramifications behind the termination of NASA's Return to the Moon program, and is titled *"Formulation of NASA's Constellation Program"*.

7.3.7 Learning lessons from the SKA

Despite incorporating the amassed knowledge contained in this thesis, and applying the techniques and controls, strategies and drivers described above, the unique character of the SKA project will certainly throw up new situations and new challenges which will demand novel responses and solutions.

It will therefore be vitally important for the project organisation to design and implement at an early stage some form of capture method to add to the pool of wisdom and lessons-learned from the execution of high-tech mega-projects. The actual solution for this requirement will very much depend on the project management systems adopted.

Project review events are particularly targeted as convenient and appropriate points where a lessons-learned item can be added to the agenda before the review is considered complete. This is especially important for the post-project review (project post-mortem) where time and resources should be formally allocated. The design of the post-project review could follow that described in section 5.4.

Finally, two actions are recommended at the AFE stage for the SKA:

1. Create a folder or marker within the document management system for project lessons learned. File these together with any prior or subsequent material concerning improvements to medium/large scale projects.

2. Ultimately, an SKA ‘knowledge database’ could be established, with provision for entering of lessons learned by any staff member, with the data searchable by topic for easy retrieval.

7.4 Chapter Summary

In this chapter, I brought out and referenced the most important success drivers shown scientifically and empirically to be vital to mega-project success, and presented these observations for consideration and application to the SKA at the earliest opportunity.

Chapter 8 – Summary and conclusion

'Insanity is doing the same thing over and over again and expecting different results.'

Dr. Albert Einstein, Physicist 1879-1955

8.1 Study summary

This study of success drivers in high-technology mega-projects set out to:

- Conceive, design, and conduct investigations via the relevant literature, and at several science/engineering facilities, to understand the relevance of past project experience and lessons learned as future success indicators;
- Identify specific pre-cursors of success in large high-tech projects that are influential in shaping projects and building resilience;
- Test any causal links to project outcomes in contemporary science/engineering mega-projects, and identify key drivers for project success;
- Examine the applicability of key success drivers and high-tech project management characteristics to the Square Kilometre Array project; and
- Develop a plausible, empirically proven, set of predictive indicators of project success, and present these as a practical process tool.

The work embodied in this thesis, and in the conclusions presented in section 8.2, contributes to the understanding of mega-project success drivers through new analyses and application of reported data and phenomena, and from new knowledge extracted and tested through casework and newly devised processes.

My research was underpinned by a comprehensive review of the published literature on the topic of project success and adjacent subjects, as well as broad reading of related project management texts, institutional and project reports, recorded interviews, and articles from in-house and public publications. Motivated primarily by practical imperatives and distinguished by the production of working insights, the study has also extended theoretical boundaries around success criteria in areas such as the implications of characterising complexity, project resilience, decision-making, and project review methodologies.

Importantly, I completed on-site field investigations at many high-tech mega-project sites (listed again for convenience in Table 8-1). Evidential data and project artefacts were gathered at these facilities, however it was the 'lived experience' related by project management and staff that was most enlightening, and which cannot be obtained through desktop research. This case study material proved immensely valuable in validating the conclusions derived from the meta-study of published literature.

Table 8-1. List of case study projects and organisations

Project Acronym	Location	Description
ALMA	Northern Chile	Radio telescope array of ~66 dishes.
ASKAP	Mid-West of Western Australia	Radio telescope array of 36 dishes, and precursor for the SKA project.
ATCA	Northern NSW, Australia	Radio telescope array of 6 dishes completed in 1988.
HIPER	Site not yet decided.	High power laser-driven fusion experiment.
ILC (DESY) XFEL (DESY)	Site not yet decided. Hamburg, Germany	Dual opposing linear colliders of super high power. X-Ray high power free electron laser
ITER	Provence, France.	Thermonuclear experimental reactor.
LHC	Beneath the French-Swiss border.	Large Hadron Collider – a gigantic particle accelerator.
LIDAR	Davis Station, Antarctica.	Light detection and ranging instrument configured to probe the mesosphere .
LOFAR	Centred in Northern Netherlands	Radio telescope consisting of thousands of omni-directional dipole antennas.
MeerKAT	Northern Cape of South Africa.	Radio telescope array of 7 dishes (to be expanded to ~80), and SKA A precursor.
OPAL	South of Sydney, Australia.	20 mega-watt open-pool research reactor.
SKA	Either Southern Africa, or Australasia.	Giant radio telescope with 1 million square metres of collecting area.
SYNCH (Australian Synchrotron)	Melbourne, Australia.	A particle accelerator accommodating 30 beamlines.
TOPSAT	RAL (UK). TOPSAT is still in earth orbit	A micro-satellite with advanced, down-looking, imaging cameras.
VISTA	Northern Chile	A visible and infra-red survey telescope.

This thesis commenced by placing project success philosophy in the context of modern history, and with a description of how the professionalization of project management over recent decades has spawned its own genre within management science. I showed how success definition has altered over time, that failure for some might later count as success by others, and that unambiguous success has remained elusive.

Even allowing for failure tolerance as a necessary feature of the risk-taking that produces science/engineering breakthroughs, I reasoned that expensive high-tech mega-projects fail too frequently, and often in dispiriting ways such as schedule and cost blow-outs, capability de-scopes, impacts from unplanned events, or simply mission myopia. The first chapters looked closely into what success means for high-tech (including IT) projects, what factors are considered critical, and the relevance of project success criteria. I explored the struggle to understand project complexity, and the requirements for collaboration management and funding arrangements.

Project shaping was examined in chapter three, covering the operating entity, governance, and the establishment of effective arrangements for high-tech partnerships and collaborations. Project structures, teams, and their tribal characteristics were reviewed. Two vital 'pre-cursors' to high-tech mega-project success were deeply examined – procurement, and resilience building, and each summarised with practical strategies for project success. The programmatical aspects of large science and engineering projects were briefly presented, including insights concerning the project management system elements of project planning, lifecycle management (phasing), cost estimations, and scheduling.

In chapter four I presented a meta-study of large project success factors covering 2,820 cases, of which 928 were classed as high-tech. Following numeric analysis through application of the Analytical Hierarchy process (AHP), 18 success drivers were derived and ranked by scored relative importance. The highest ranked drivers were further examined, and implications for management shown. This separately published work underpins the thesis conclusions, validated through field casework.

This thesis then dealt with the remaining important considerations from research concerning execution of the project. Considerable attention was given to the project manager topic, given his/her profound influence on project realisation and outcome. I especially emphasised the more subtle attributes that are highly influential to project success, and which might prove useful during project manager recruitment. Topics drawn out in this section include a sense of urgency, task force formation, project information management, and mission assurance - each attaining significance in my study conclusions. I followed this with an examination of authenticity in high-tech projects, and described the risks of mis-stating or adjusting success goals, and the susceptibility of high-tech projects to become frauds.

I concluded chapter five with a detailed study of project review processes, including their relationship to project phases, and the efficacy of project reviews. Through an examination of processes, I showed that project post-mortems, and lessons learned activities, are pivotal to project improvement, and organisation learning. I closed this chapter by describing an experimental post-project review session conducted for the Dutch LOFAR telescope project.

In chapter six I presented my Checklist for High-tech Project Success (the CHiPS Tool). This, in effect, is where the learnings from the present study are captured as a practical aid for project approvers and practitioners. Chapter seven then offered an application analysis of how the findings from this thesis may be directly applied to a contemporary science and engineering mega-project – the Square Kilometre Array (SKA). I presented a number of tables where success strategies and drivers are offered as responses to issues facing the SKA, and as an approach to building project resilience.

This final chapter provides a summary of the thesis work, and presents the key conclusions.

8.2 Study conclusions

Four conclusions became apparent early in my research:

- Despite considerable literature concerning project failure, and management of large projects, there is little published material concerning discovery and practical application of success drivers for specialist high-technology mega-projects.
- High-technology projects are increasingly becoming global endeavours of great complexity, with budgets frequently extending into the billions of dollars.
- By and large, stakeholders of large science-engineering projects continue to be disappointed by project performance despite the efforts of both researchers and those charged with project execution.
- To understand the challenges and ‘lived experiences’ in complex mega-projects, it is necessary to conduct on-site investigations and personnel interviews.

My investigations support the following detailed conclusions:

1. Notwithstanding present financial constraints, the world is currently in an era of great innovation realised through many large science/engineering projects (e.g. the Large Hadron Collider, the ITER Fusion Reactor, and the Square Kilometre Array).

These breakthrough projects, by their nature, have inherent high-risk, yet their international scale and huge cost implications demand that success measures are achieved and project performance maximised. Success criteria must be objectively set via analysis of hard and soft critical success factors. Traditional project management and execution techniques are insufficient to meet the demands placed on high-tech mega-projects, and a fuller understanding of success drivers – professionally applied in the early stages – is required to lift project performance.

2. Large high-tech projects, while not 'wicked' problems, are more than just complicated and difficult. Their sheer complexity, with inevitable multiple flaws, demands constant attention from project systems and people, yet are unlikely to be fully understood. However project complexity can be assessed by mathematical analysis or an analysis of characteristics, thus offering a useful classification to inform detailed project planning. Collaborations introduce another dimension of complexity and uncertainty through compatibility and cultural issues (including institutional-industry differences), balancing of individualism with group-think, and information management. The arrangements for collaborative relationships need to be clear, with transparent technical contribution arrangements and with power centres identified and respected.

3. High-tech mega-projects require their own identity and preferably a separate operating legal entity, although a case exists for building on existing institutions where this is practicable and early progress is important. Member obligations must be extremely clear, with shares, credits, and *juste retour* policies agreed and formally stated. Locating the project headquarters in close proximity to the site is shown to be beneficial. Beyond appointment of a governing Board and Steering Committee, project leadership must be determined, and the advantages considered of the role being shared between an eminent and influential science/engineering figure, and an experienced, respected and qualified project practitioner. While a matrix functional structure was commonly reported by high-level management, casework finds high-tech project staffing to actually operate successfully closer to traditional (hierarchical) lines through Integrated Process Teams. In any case, clear responsibilities and authorities are essential. It is likely that new, more dispersed forms of employment will encourage innovative working systems and methods, offering both improved productivity and communications.

4. Procurement, once seen as largely a supporting administrative task, is shown to strategically important to success, and an essential foundation function of the high-tech project. An informed, holistic approach to procurement can improve the effectiveness of the process, and underpin more productive and open relationships with suppliers. Nine key strategies are identified to position the procurement function as a precursor for 'high-tech' project success. These are:

- Early establishment of procurement office structure, resources, processes, roles and responsibilities, and information management systems.

- Approval of procurement policies, strategies, and plans; documented within a concise approved Project Procurement Plan.

- A full understanding of global supplier capability information, and implementation of appropriate contractual instruments with terms and conditions supporting project goals.

- Establishment of the contracting model, aligned with the legal entity. Development of positive relationships with principle contractors and the supply chain.

- Competitiveness in contracting, through carefully planned pricing strategies, and a 'value for money' approach.

- Application of purchasing specifications that are appropriate to the goods or services required, flexible for optimal outcomes, and developed with input from industry.

- Understanding and active management of procurement risk, including the critical early stage engagement phases.

- Evaluation and selection of project contractors using a fair process, executed against standardised procedures, and focussed on criteria weighted in favour of mission success.

- Implementation of fair and transparent procurement processes that exploit open strategic partnerships while allowing for evidence based supplier inspections.

5. Project resilience - the building of robustness during project shaping - is identified as a precursor to project success. Three 'attitudinal' resilience factors are identified where a focused effort can lift the chances of project success. Enthusiasm for optimising the project picture must be spotted and curbed, and facts faced with realism. The use of analogous lessons-learned should be part of up-front research to inform stakeholders of the risks and major challenges ahead. Project management needs to be cognisant of project complexity, periods of ambiguity, peripety (shifts of fundamental understanding enabling project evolution), and uncertainty management.

6. The quality of resilience is also shown to be strengthened through six manageable 'launch conditioning' factors. The early setting of project mission and success definitions are strongly indicated, as are clear and consistent structures and processes for reporting and decision-making. There are benefits to establishing an holistic project information office (with a remit extending beyond the technical arena) to cover all data and media traffic, including branding matters, conferences, meetings, and teleconferences. Traditional risk management practices do not adequately prepare the high-tech project organisation for unknowns – those events that cannot be pre-identified, but statistically are likely to occur. An effective response strategy is to pre-form one or more task force(s) in readiness to act swiftly in the face of any threat to mission delivery – coupled with a quarantined contingency reserve. Compliance obligations, particularly for infrastructure in sensitive locations and involving national authorities, need careful and dedicated stewardship at (or before) project start-up. Finally, resilience is strengthened by the formation of a mission assurance function to add intellectual rigour to early project definition and requirements setting activities. Mission assurance works best alongside project management, supporting the project teams and reporting at Director level.

7. While the detailed programmatical aspects of large high-tech projects are not central to this thesis, the tools and applied techniques of project management are shown to underpin the strategy on which to build success. Thorough planning requires the baseline description at project start – a bundled set of dynamics incorporating

stakeholder assumptions, constraints, and a reference point from which to plan, measure, and if necessary, deviate. To be a supportive tool, the project plan must (at least) describe the project lifecycle and contributing phases. A cornerstone of the project plan is the project cost and schedule budget, founded on early estimates, and which my research shows to be almost always optimistic. Even with cost planning tools and techniques, a possible doubling of budget should not be ruled out. The premature announcement of project budget estimates often leads to disappointing corrections later as cost uncertainty is reduced. (See Fig. 8-1). Casework shows that, even when a sense of pace is instilled, the ‘marching army’ effect of big projects denies the likelihood of any cost or schedule slippage over 20% being materially recovered.

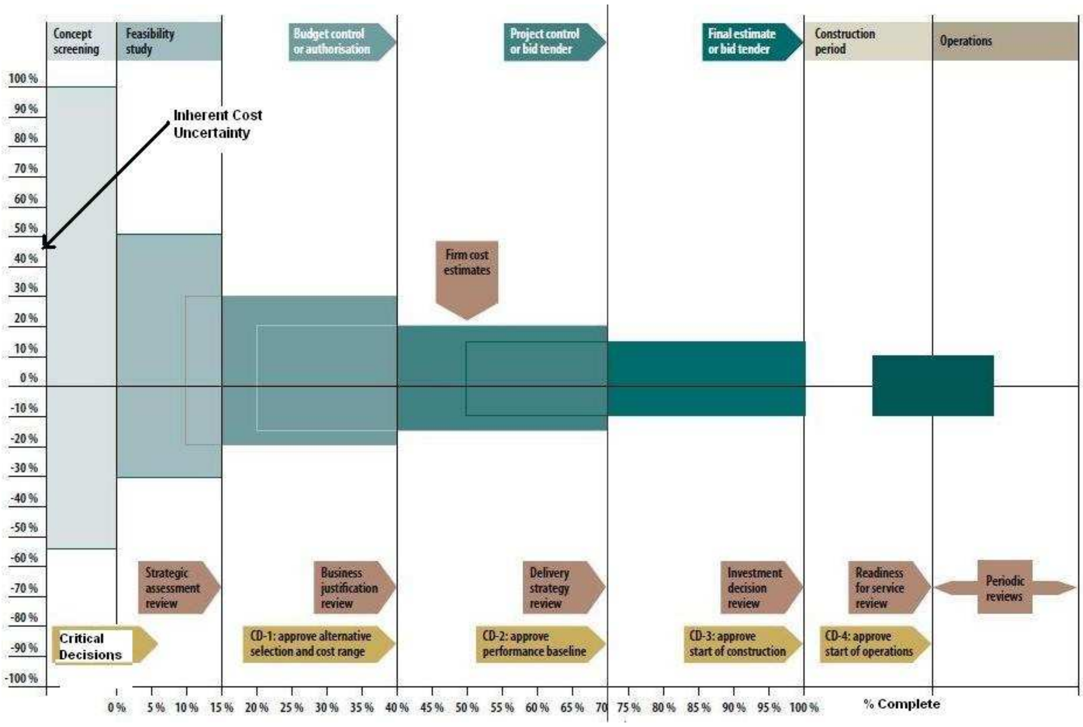

Fig. 8-1. Project cost evolution and approval stages (adapted from European Commission, 2010 p. 14)

8. The new meta-study of project success factors (based on 2820 cases) that forms core work in this thesis concludes that sound project management control and execution systems, and a clear project definition and goal set, are by far the two most important drivers of project success. Competent information management systems rank third in importance, followed by 15 other significantly important factors shown to markedly improve project outcomes (See Table 8-2). Many of these success drivers are wholly or partly newly ranked ‘soft’ drivers, indicating the importance of leadership,

motivation, expectations, and team engagement. The findings, each with implications for high-tech project management, strongly correlate to fieldwork investigations across the case-studies listed in Table 8-1, and are supported by the LOFAR lessons learned exercise outlined in section 5.4.

Table 8-2. Success drivers tabled by occurrence within the study population literature

Success Driver	Ranking
Project management (PM) control & execution systems in place, with robust policies, planning, procedures, document control, audit, etc	*1*
Clear project definition, requirements, goals, objectives, scope, and project mission; sound business case	*2*
Mature project communication, information systems; effective public relations management	*3*
(Top) management (or sponsor) support with sustained commitment, appropriately engaged	*4*
Project baseline, estimates accuracy, project phasing, effective project performance (reviews) and measurement	*5*
Leadership skills, PM experience & stability; motivating & socially capable PM	*6*
Agreed realistic customer / user expectations; frequent customer contact	*7*
PM/Organisational understanding & competence in project management	*8*
Adequate resourcing of the project	*9*
Aligned perceptions of project goals & success - management and team; sense of urgency instilled	*10*
Effective stakeholder engagement / partnership (e.g. client, contractors, etc)	*11*
Organisational responsibilities assigned to right-sized capable team	*12*
Mature, effective project management change control process; effective deviations handling & configuration control	*13*
Understanding & continuous management of risk; visibility of risk register	*14*

Project Manager & PM systems matched to project complexity, and culturally aligned	*15*
Effective means of learning from experience and continuous improvement environment	*16*
Full understanding, and early engagement, of host government environment and institutional requirements	*17*
Right-sized systems engineering; managing and procuring in right sized project 'chunks'	*18*

9. More subtle attributes associated with high-tech project success were revealed through an investigation of the less obvious characteristics of successful project managers. While a definitive set of personal qualities is idealistic, research for this thesis points to eight personal characteristics, traits, or skills are strongly indicated as subtle, though significant, factors in driving high-tech project performance, and have application for recruitment. These are:

- The ability to deal with the temporary and uncertain nature of mega-projects;
- Having and demonstrating personal authenticity;
- Applying persuasive skill in the management of collaborations;
- Having an appropriate balance of management and leadership talent;
- Motivating strategic influence through persuasion, encouragement, and negotiation;
- Knowledge-sharing and trust-building in a diverse cultural environment;
- Having a personal profile and competence well matched to the project; and
- Driving a clear sense of project urgency while managing deviations.

A further five management initiative factors were shown to be positively related to project success. These are:

- Establishment of an appropriate project and team structure and regulatory levels;
- Creation and deployment of effective project task forces for problem solving;
- Effective information control, exchange and dissemination;

- Application of a project assurance approach sensitive to mission threat; and
- Competent management of complexity, and courage to take calculated risk.

10. Practice guides, often in the form of 'Books of Knowledge' (e.g. PMBoK) contain much good task oriented material covering the creation of project artefacts, deployment of the project against defined resources, and tracking of progress against milestones. They also have some application in project manager certification. However the guides (and associated qualifications) are of limited use for developing and managing success strategies in the very complex environment of high-tech projects, especially in areas such as the maturity of experience required for effective deployment of task forces, collaborative structures, mission assurance functions, and competency matching. Recently introduced maturity models (e.g. CMMI, and ICCPM's Behaviour Engineering model) offer more promise as effective frameworks for execution and assessment of complex projects.

11. Although each of the case studies in this thesis presents as an authentic technical endeavour, often with a social good and spin-off benefits, approvers and reviewers of high-tech projects must be constantly alert to deceit. Rarely are there cases where high-tech success is claimed fraudulently, however doubtful practices do emerge where aims are distorted and success metrics meaningless. The literature reveals examples such as unrealistic promises, potential fad-science, and report embellishment to secure ongoing funding. In times of financial constraint, expensive high-tech projects are more closely scrutinised and court action is not unknown where dubious practice is uncovered. If 'blue-sky' research is being undertaken, it is essential that all stakeholders are aware of the risks and the basis of project approval.

12. Project reviews are not only essential to monitor and measure authentic intent and effort, but also to mark progress and allow for important course corrections and decisions concerning adjusted or renewed funding. The present research supports the adoption of, or shift towards, an industrial model for project monitoring using formal stage gates (rather than the loosely identified reviews common in institutional projects (e.g. the SKA). These should be mapped to project phases at defined intervals (typically 3-4 months), followed by a time-bound 'issues' close-out process

to ensure prompt and accountable responses. Such reviews are efficiently served by dashboard style reports, populated with reliable data against fixed baselines.

13. Both the casework and the literature show post-project reviews (or post-mortems) to be infrequently held. I conclude that a post-project review reveals extremely useful knowledge for both individuals and the organisation, and it is unwise to ignore this valuable avenue of process improvement. In this thesis I suggest a process (with example report) for the conduct and data analysis of a post-project review, and posit that such events should include participants outside the high-tech project team such as support staff, contractors and customers (users). For added effectiveness, I propose subsequent cognitive mapping techniques using cause-chains to reveal useful intelligence for the organisation – and for the high-tech mega-project community.

14. Although a useful exercise in itself, the post-project review will have limited effect if the outcomes are not formally captured within an effective knowledge system or database within the host organisation. If project amnesia is to be avoided, the lessons learned (tacit knowledge) must be transferred to the organisation so that searches by the wider project organisation can readily source and apply the information. Research on this topic shows that a learning culture is critical to lifting organisational performance, and may prove advantageous when competing for funds.

In the introduction to this thesis I stated my research aim in a two-part question:

1. *Is there a better, more robust process using theoretical and/or empirical predictive indicators derived from the relevant literature and from best practice contemporary science projects that can be generally applied to lift the probability of success of high-tech mega-projects?*
2. *How might this be useful for perhaps the largest science project to be undertaken over the next 15 years – the Square Kilometre Array?*

My conclusions against these questions are:

1. *Yes. This is supported through completion of a research effort involving a thorough and targeted literature review and extensive on-site investigations, with a series of conclusions founded on a combination of some new knowledge and many re-interpreted concepts.*

2. *The outcomes of this research effort are presented as a practitioner's aid in the form of the CHiPS tool included in chapter six. The practical application of the outcomes are highly relevant and useful for the SKA project, as shown in chapter seven.*

8.3 Future research

The limitations of the present study offer pointers to future areas of research.

The core work on success factor meta-data in chapter four could be built on using further contemporary and imminent project related studies. Analysis across modern project management technique eras might indicate future directions in terms of success definition. As a discrete analysis, more tightly defined success headings, and weighting of sample studies (e.g. complexity), would likely strengthen validation of rankings. A deeper (possibly numeric) exploration of how different success dimensions might sway the rankings could be tackled in a future paper.

The views of high-tech funding agencies (possibly including Defence Departments) could be investigated, focussing on their role and operations, and influence on success. The potential for exploiting funds and in-kind contributions from commercial or defence 'offset' accounts resulting from international contracting policies could be explored.

Continued research to benchmark the performance of large high-tech projects (e.g. the SKA) against the application of the success drivers identified in this thesis would deepen understanding of causal factors for project success. This work could also explore and compare success drivers in more specific areas, e.g. IT projects, space instrumentation, etc.

The research into project manager characterisation could be broadened through adding a time dimension with numerical analysis to show effectiveness of high-tech project management trends over recent decades. The study also reveals a yet incomplete understanding of the application of transformational management in high-tech projects, and the relationship between charisma and success. Further investigations of the *impact* of various project manager traits are also recommended, as is the success rate of project teams formed from previously teamed members.

Processes to handle intellectual property within collaborative high-tech project structures have yet to be broadly examined in terms of project management practice. Further work to improve methods of efficiently managing global mega-project site selection is indicated.

The **C**hecklist for **Hi**gh-tech **P**roject **S**uccess (CHiPS) tool will be offered to industrial and institutional users through publication and professional networking. The widespread application of the tool will no doubt stimulate ideas for improvement, most likely including refinement of the indicator descriptors. Variants may emerge for specific high-technology project situations, e.g. within Treaty organisations.

8.4 Final note

Researching the literature and conducting investigations at several of the world’s most advanced technology facilities over recent years has been a rare privilege. I was often deeply impressed by the capacity and competence of project personnel as they delivered science/engineering solutions and infrastructure of extraordinary complexity. However I sense the coming decade heralds a new landscape for both medium and large high-tech projects. Nations are questioning the societal returns from multi-billion dollar investments (e.g. USA’s Constellation Program, SKA), and full funding of some in-progress global collaborations (e.g. ITER, JWST) looks in doubt. In an environment of ever more ambitious instruments and simultaneous cost constraint (Jones, 2011), it is understandable that the days of automatic continued funding of runaway high-tech projects appear to be over.

Addressing this situation requires a fundamental change of attitude. For example, courage is required to insist on sufficient contingency reserves *before* project commencement, and it takes an enlightened Board to sanction the appointment of a professional project manager *alongside* the eminent scientist project director. Project governance must look to industrial models where plans are more formally monitored and there are consequences for non-performance. As I have shown, there are many other strategies to build resilience, optimise execution, and ensure that project organisation is a *learning* organisation. I hope that any knowledge I have contributed in this thesis will play some modest part in improving the success record for future high-tech mega-projects.

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Index

APPENDICES

Appendix A

Project Investigation – Enquiries & Question Guide Used for Casework Interviews

Project Title:
What is it?
Location:

Principle Infrastructure:
Principle Science Goal:

Governance & Rules
Ownership
Legal Framework
Board & policy creation
Approvals regime
Priority setting
Host environment issues

Funding Source & Model:
Initial Budget:
Current Budget:
Operations Budget:

Time span:
Current Stage:

Management Model:
Project office
Project structure
Project mgmt system/tools
Planning/scoping framework
Project review method
Team management
Quality management
Financial control
Approvals regime
IP control
Project support

Procurement Policy/Model:
Industry Engagement Model:
Supplier Selection criteria?
Focus? Price, delivery, quality?
Innovation level:

Risk Management & Profile
Personnel Dependencies
Technical Dependencies
Communications Management:
Staffing profile:

Complexity Assessment

Key Research Questions (explored in depth by interview)

Part A, **Project Management Practice**

A1, Has the project goal remained clear from inception?
If the goal varied, what was the impact of this?

A2 , Was a core team established early, or later in the program?
If the core team has changed, why did this happen?

A3, Was a detailed project plan developed?
Who participated in developing it?
Were milestones and deadlines negotiated with sponsors?,
Did the critical path change? How was that dealt with?
How is progress monitored and reported?
How is information management achieved?

A4, What role does top management play in supporting the project?
Supportive (political/practical), realistic, demanding, meddling? Etc,

A5, Was there customer/user involvement early in the project?, ,
Are customer/client expectations being met?

A6, How are customers/users kept informed of project progress?,

A7, Does the project have a detailed budget?
How well do project controls help keep the project on budget?

Part B, **Critical incidents**

B1, What critical incidents occurred on the project?
Could they have been predicted?
If negative, what could have been done to avoid/alleviate them?

B2, What success factors were applied to this project, drawn from others?,
Did those success factors/measures work effectively in this project?,

Part C, **Project Performance**

C1, Were there any significant deviations to the orginal plan/expectations?,

C2 , What was the cause?
(Planning? Foresight? Technology? Expectations? Random?)

Part D, **Suggestions for the future**

D1, What lessons can be learned from this project for;
Managing major deviations to scope, performance, budget, etc
Change to design, technology, specifications etc
Managing socio-environmental matters
Project management and/or organisation

Part E, Complexity and Perceptions

What areas of the project were initially thought to be complex?
What areas were actually complex in practice?

To what extent did previous experience(s) from other projects influence this project?
(Draw out any causal link between previous - & + experiences, and this project.
How is experience & learning being captured in **this** project?

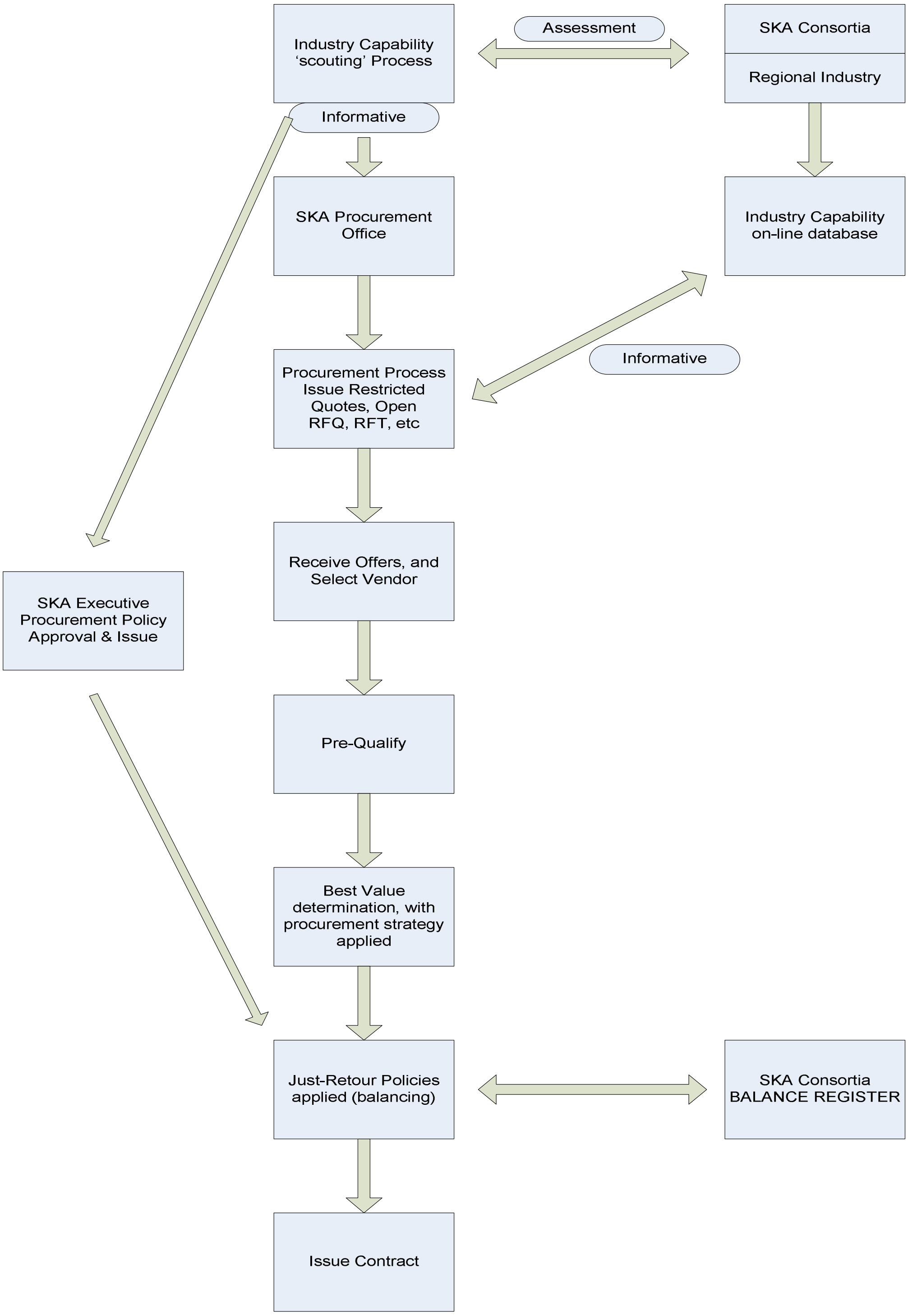
What early factors/signs might have suggested or predicted later + or **-** outcomes?
Looking back, how should/could the project have responded to those early factors/signs?

How do the project managers describe 'success' in this project?
How do other stakeholders describe 'success'?

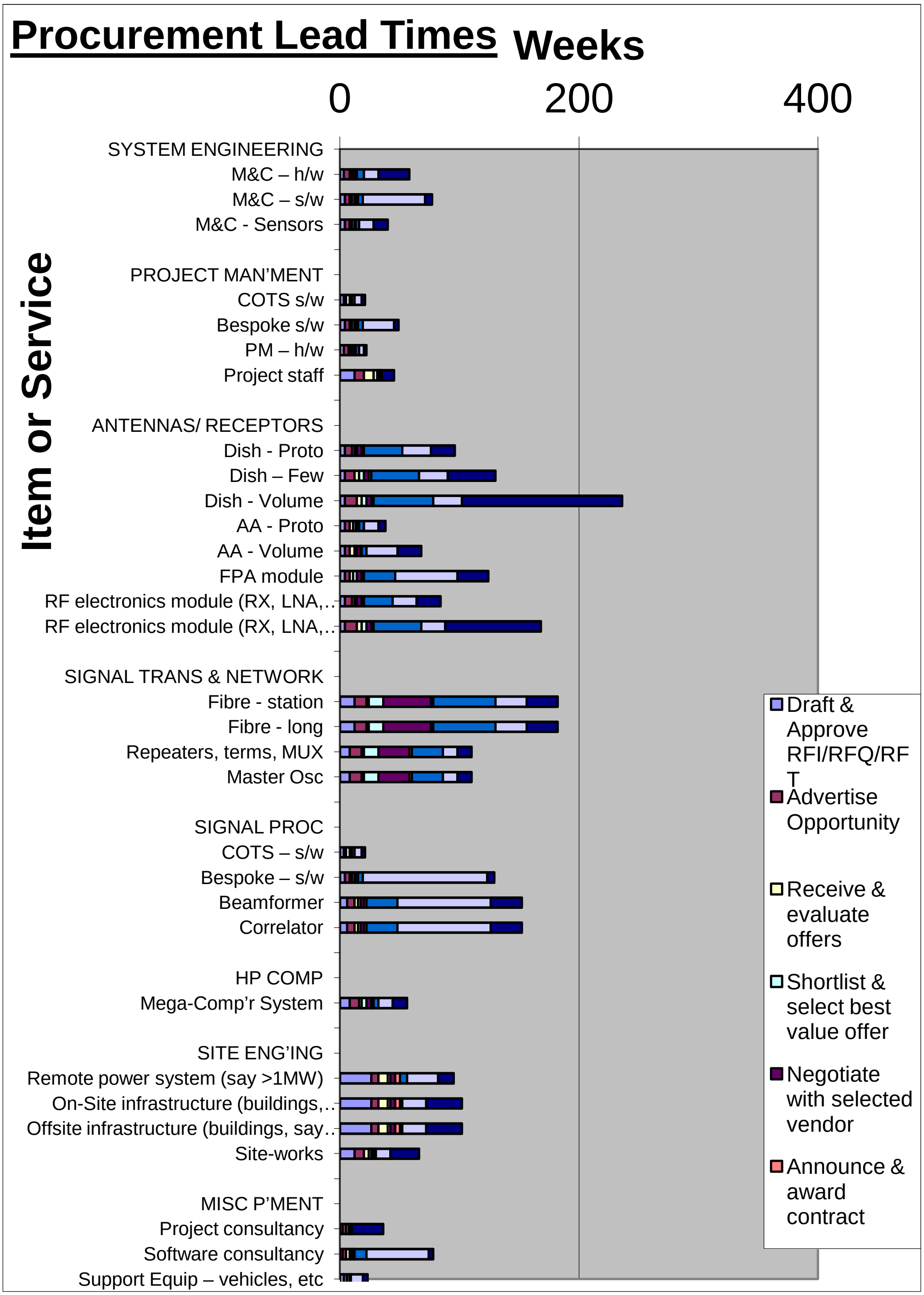
What influence did the project governance have on achievement of success?
Did the 'success' goalposts move as a result of risk mitigation/retirement?

Appendix B

Process Flow (proposed) for SKA Project

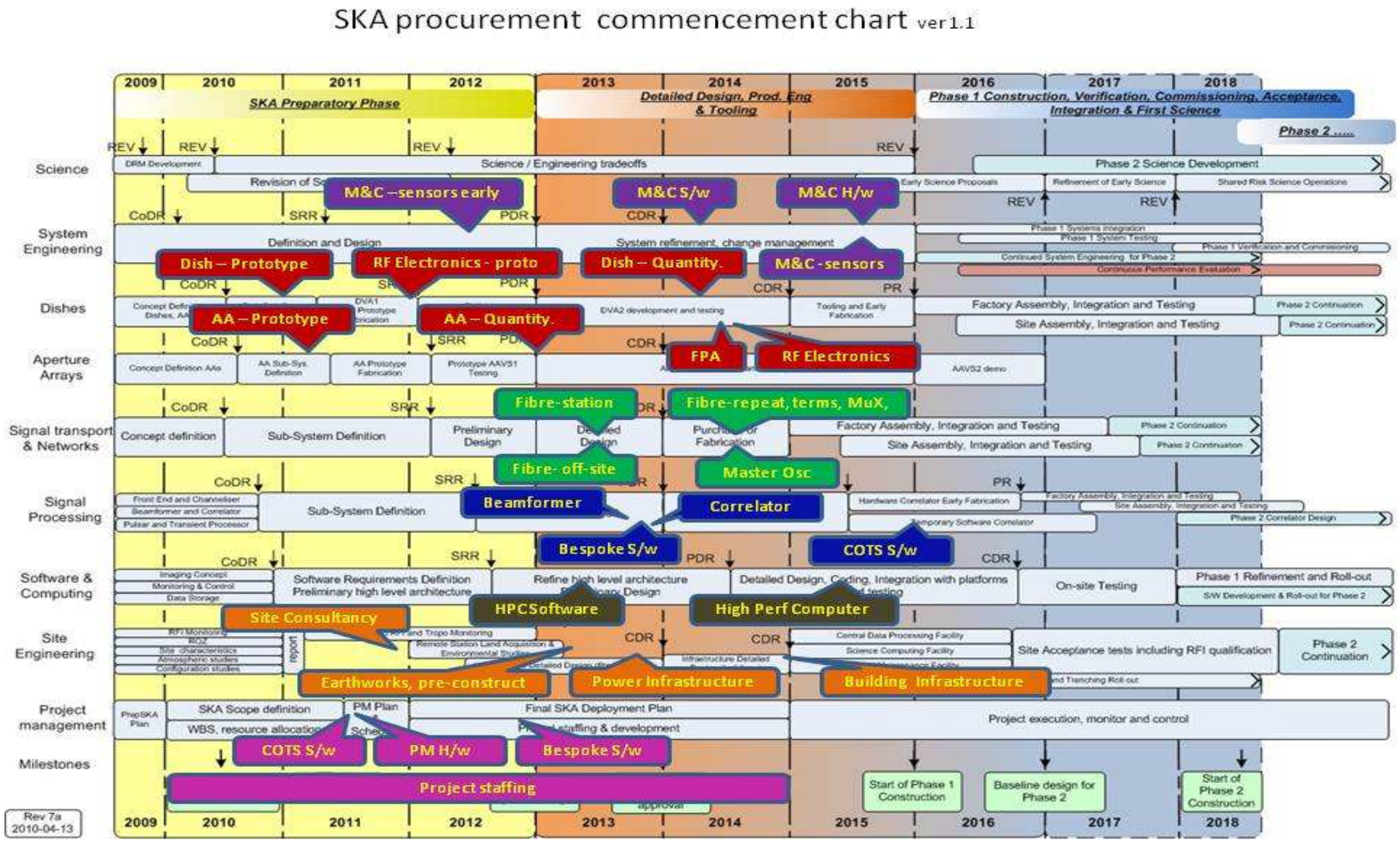


Procurement Lead Times Chart for SKA



Appendix D

Procurement commencement chart for the SKA



Appendix E

Contracting models for high-tech mega-projects

KEY

O = Owner Organisation

E = Engineering / Design

C = Prime Contractor

S = Subcontractor

M = Management Contractor

I = In-kind support (Member State)

P1 = Project Manager

P2 = Project Services Contractor

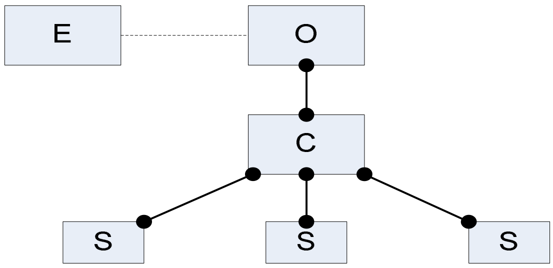


Fig. a: Owner Organisation Managed - Single Contractor. The Owner organisation has direct contact with a prime Contractor.

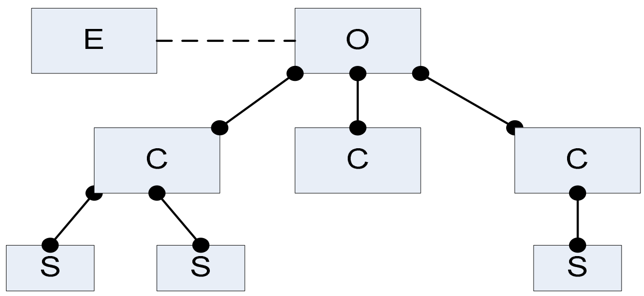


Fig. b: Owner Organisation Managed – Multiple Contractors. The Owner organisation has direct contact with several main Contractors; Contractors may have many subcontractors.

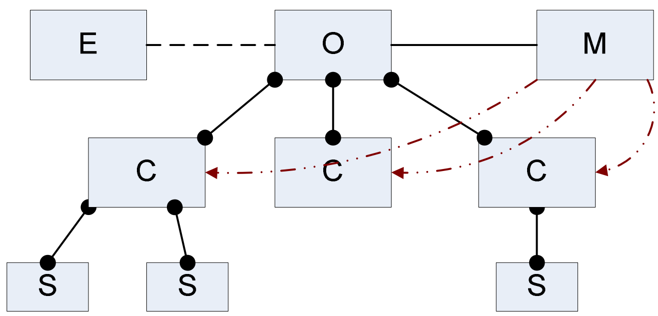


Fig. c: Management Contractors. Owner organisation engages a Management Contractor (MC) to assist planning, supervise work, and check performance. The MC may direct contractors, but contracts are between the Owner and Contractors.

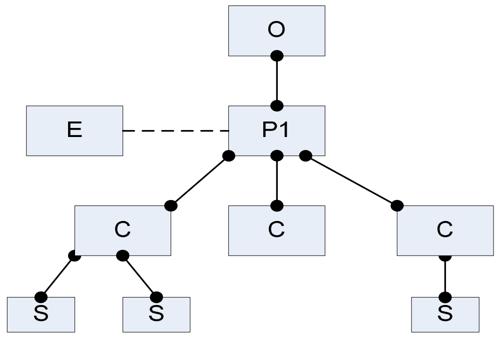


Fig. d: Project Manager. Owner organisation engages a Project Manager (PM) to coordinate and supervise the work. The PM has some project performance accountability, and contracts are between the PM and Contractors. Highly successful in the case of the OPAL Research Reactor, Australia.

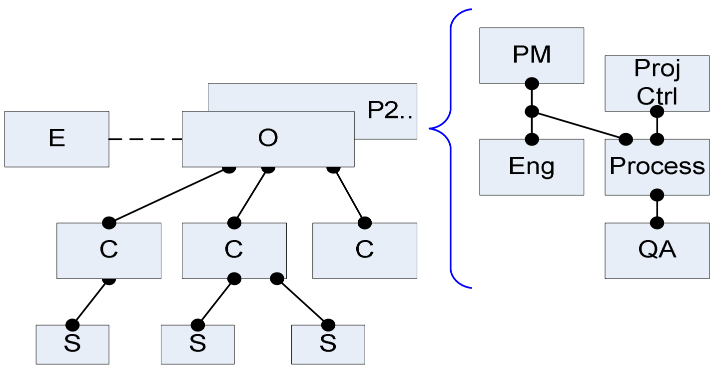


Fig. e: Project Services Contractor. The Project Services Contractor joins the Owner organisation project management team. Staff from the two groups work jointly, but contracts are between the Owner and Contractors, with potential loss of contract knowledge.

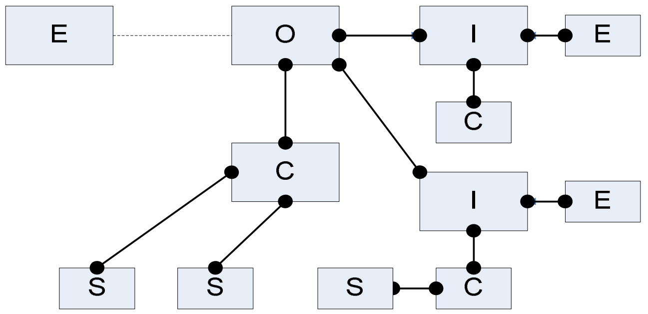


Fig. f: The Owner organisation shares the contractual responsibility with member States who have agreed to manage 'in-kind' contributions (refer ITER model). Responsibility for cost/schedule variations requires clarity between the parties.

Appendix F

Method and calculations supporting ranking of success drivers

The process of ranking success drivers uses the mathematics and calculation techniques developed by Saaty (Coyle, 2004) and are described within the generic Analytical Hierarchy Process (AHP). This is one approach to multi-criteria decision-making (MCDM) that can involve qualitative data. The method employs a reciprocal decision matrix obtained by pair-wise comparisons introduced by Fechner and developed by Thurstone (Alonso & Lamata, 2006). In the AHP, the input can be actual values, or scores from subjective opinion such as preference, judgement etc. and the approach has unique advantages when elements of the decision are difficult to quantity or compare. Decision situations to which the AHP can be usefully applied include choice, prioritisation, and ranking by importance (Teknomo, 2007).

Input data were drawn from examination of success factors from 29 general studies of project management encompassing 2,820 cases, as well as two success factor summaries drawn from cited papers within those general studies. These sources are listed in Table 4-1 in the body of this thesis, with numbers of individual case studies shown for both general and high-tech cases.

From each study, the listed or described success factors (derived from questionnaires, statistical analyses, or both) were grouped into common headings. This process resulted in the most common occurring findings being captured under 18 pragmatically themed success drivers which were given designators A through R. These were then tabulated by occurrence for all projects, and the sub-set high-tech projects, as shown in Table F-1 below. (For convenience, they are sorted by occurrence frequency for 'all projects'.)

A pair-wise comparison process was then carried out for both 'all data' and 'high-tech data' by constructing a matrix for each with dimensions n=18, reflecting the number of success driver headings. Calculations for 'all data' and for 'high-tech data' are shown below in Fig. F-1 and Fig. F-2 respectively. For each of the 153 possible pair-wise success factor comparisons, a value was inserted in the upper triangle of the matrix corresponding to the difference in the number of occurrences reported.[58] This value reflects either more or less support of one success driver over another. The lower triangle of each matrix shows the reciprocal value.

Having completed the upper matrix, approximations of the Eigen vectors were then computed. This was achieved by dividing each element of the upper matrix by the sum of its own column, thus normalising the relative weights which are then correspondingly displayed in the lower matrix. The normalised Eigen vectors showing relative 'weights' are obtained by averaging across the rows. From this data, ranking is clearly indicated, as well as the relative importance of each success driver.

[58] Since a score of one (1) must equate to zero difference in occurrences, the entered value is actually the value + 1. This is not required to be an absolute value, merely a consistent scale.

The consistency of the original data was then tested. Aω (the 18 element vector) is obtained by summing the products of each input value (by row) with its associated Eigen vector (by column). Since AHP theory says that $A\omega = \lambda max^{\omega}$, close approximations for λmax (the principal Eigen value) are derived by dividing each result by the corresponding Eigen vector value. The mean of these values gives an estimated λmax with which to calculate consistency ratios as shown in Fig. F-1 and Fig. F-2.

Saaty argues that a consistency ratio of >10% indicates unreliability (with a CR >90% close to randomness). In this study, the consistency ratios for 'all' data and high-tech data are 7.28% and 4.99% respectively, and are therefore consistent.

Table. F-1. Success drivers tabled by occurrence within the study population literature

Success Driver	**Designator**	**Occurrences -all projects**	**Occurrences-high-tech projects**
Project management (PM) control & execution systems in place, with robust policies, planning, procedures, document control, audit, etc	*A*	*20*	*15*
Clear project definition, requirements, goals, objectives, scope, and project mission; sound business case	*B*	*20*	*14*
Mature project communication, information systems; effective public relations management	*C*	*15*	*11*
(Top) management (or sponsor) support with sustained commitment, appropriately engaged	*D*	*13*	*10*
Project baseline, estimates accuracy, project phasing, effective project performance (reviews) and measurement	*E*	*13*	*10*
Leadership skills, PM experience & stability; motivating & socially capable PM	*F*	*11*	*8*
Agreed realistic customer / user expectations; frequent customer contact	*G*	*9*	*6*
PM/Organisational understanding & competence in project management	*H*	*9*	*6*
Adequate resourcing of the project	*I*	*8*	*5*

Aligned perceptions of project goals & success - management and team; sense of urgency instilled	*J*	*8*	*5*
Effective stakeholder engagement / partnership (e.g. client, contractors, etc)	*K*	*8*	*5*
Organisational responsibilities assigned to right-sized capable team	*L*	*7*	*4*
Mature, effective project management change control process; effective deviations handling & configuration control	*M*	*7*	*4*
Understanding & continuous management of risk; visibility of risk register	*N*	*5*	*3*
Project Manager & PM systems matched to project complexity, and culturally aligned	*O*	*5*	*3*
Effective means of learning from experience and continuous improvement environment	*P*	*4*	*2*
Full understanding, and early engagement, of host government environment and institutional requirements	*Q*	*4*	*2*
Right-sized systems engineering; managing and procuring in right sized project 'chunks'	*R*	*3*	*2*

Designator	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
Occurances	**20**	**20**	**15**	**13**	**13**	**11**	9	9	**8**	**8**	**8**	7	7	**5**	**5**	4	4	**3**
A	1.00	1	6	8	8	10	12	12	13	13	13	14	14	16	16	17	17	18
B	1.00	1.00	6	8	8	10	12	12	13	13	13	14	14	16	16	17	17	18
C	0.17	0.17	1.00	3	3	5	7	7	8	8	8	9	9	11	11	12	12	13
D	0.13	0.13	0.33	1.00	1	3	5	5	6	6	6	7	7	9	9	10	10	11
E	0.13	0.13	0.33	1.00	1.00	3	5	5	6	6	6	7	7	9	9	10	10	11
F	0.10	0.10	0.20	0.33	0.33	1.00	3	3	4	4	4	5	5	7	7	8	8	9
G	0.08	0.08	0.14	0.20	0.20	0.33	1.00	1	2	2	2	3	3	5	5	6	6	7
H	0.08	0.08	0.14	0.20	0.20	0.33	1.00	1.00	2	2	2	3	3	5	5	6	6	7
I	0.08	0.08	0.13	0.17	0.17	0.25	0.50	0.50	1.00	1	1	2	2	4	4	5	5	6
J	0.08	0.08	0.13	0.17	0.17	0.25	0.50	0.50	1.00	1.00	1	2	2	4	4	5	5	6
K	0.08	0.08	0.13	0.17	0.17	0.25	0.50	0.50	1.00	1.00	1.00	2	2	4	4	5	5	6
L	0.07	0.07	0.11	0.14	0.14	0.20	0.33	0.33	0.50	0.50	0.50	1.00	1	3	3	4	4	5
M	0.07	0.07	0.11	0.14	0.14	0.20	0.33	0.33	0.50	0.50	0.50	1.00	1.00	3	3	4	4	5
N	0.06	0.06	0.09	0.11	0.11	0.14	0.20	0.20	0.25	0.25	0.25	0.33	0.33	1.00	1	2	2	3
O	0.06	0.06	0.09	0.11	0.11	0.11	0.20	0.20	0.25	0.25	0.25	0.33	0.33	1.00	1.00	2	2	3
P	0.06	0.06	0.08	0.10	0.10	0.13	0.17	0.17	0.20	0.20	0.20	0.25	0.25	0.50	0.50	1.00	1	2
Q	0.06	0.06	0.08	0.10	0.10	0.13	0.17	0.17	0.20	0.20	0.20	0.25	0.25	0.50	0.50	1.00	1.00	2
R	0.06	0.06	0.08	0.09	0.09	0.09	0.14	0.14	0.17	0.17	0.17	0.20	0.20	0.33	0.33	0.50	0.50	1.00
Sum	3.36	3.36	15.18	23.03	23.03	31.44	49.04	49.04	59.07	59.07	59.07	71.37	71.37	99.33	99.33	115.50	115.50	133.00

Pairwise Comparisons.
AHP method & calculations
Sources; Coyle 2004, Teknomo 2007

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	Normalised Eigenvector	%	Aω	Approx λmax
A	0.298048173	0.298048173	0.395386861	0.347340129	0.347340129	0.290332311	0.24468395	0.24468395	0.220090293	0.220090293	0.220090293	0.196170014	0.196170014	0.161073826	0.161073826	0.147186147	0.147186147	0.135338346	0.237210715	**23.72**	5.673832437	23.91593041
B	0.298048173	0.298048173	0.395386861	0.347340129	0.347340129	0.290332311	0.24468395	0.24468395	0.220090293	0.220090293	0.220090293	0.196170014	0.196170014	0.161073826	0.161073826	0.147186147	0.147186147	0.135338346	0.237210715	**23.72**	5.673832437	23.91593041
C	0.049674696	0.049674696	0.06589781	0.130252548	0.130252548	0.145166156	0.142732304	0.142732304	0.135440181	0.135440181	0.135440181	0.126109295	0.126109295	0.110738255	0.110738255	0.103896104	0.103896104	0.097744361	0.113440848	**11.34**	2.650838398	23.36758262
D	0.037256022	0.037256022	0.021965937	0.043417516	0.043417516	0.087099693	0.101951646	0.101951646	0.101580135	0.101580135	0.101580135	0.098085007	0.098085007	0.090604027	0.090604027	0.086580087	0.086580087	0.082706767	0.07846119	**7.85**	1.731285664	22.06550365
E	0.037256022	0.037256022	0.021965937	0.043417516	0.043417516	0.087099693	0.101951646	0.101951646	0.101580135	0.101580135	0.101580135	0.098085007	0.098085007	0.090604027	0.090604027	0.086580087	0.086580087	0.082706767	0.07846119	**7.85**	1.731285664	22.06550365
F	0.029801817	0.029801817	0.013179562	0.014472505	0.014472505	0.029033231	0.061170987	0.061170987	0.06772009	0.06772009	0.06772009	0.070060719	0.070060719	0.070469799	0.070469799	0.069264069	0.069264069	0.067669173	0.052418224	**5.24**	1.089372578	20.78232522
G	0.024837348	0.024837348	0.009413973	0.008683503	0.008683503	0.009677744	0.020390329	0.020390329	0.033860045	0.033860045	0.033860045	0.042036432	0.042036432	0.05033557	0.05033557	0.051948052	0.051948052	0.052631579	0.031653661	**3.17**	0.613639518	19.38605194
H	0.024837348	0.024837348	0.009413973	0.008683503	0.008683503	0.009677744	0.020390329	0.020390329	0.033860045	0.033860045	0.033860045	0.042036432	0.042036432	0.05033557	0.05033557	0.051948052	0.051948052	0.052631579	0.031653661	**3.17**	0.613639518	19.38605194
I	0.022926783	0.022926783	0.008237226	0.007236253	0.007236253	0.007258308	0.010195165	0.010195165	0.016930023	0.016930023	0.016930023	0.028024288	0.028024288	0.040268456	0.040268456	0.043290043	0.043290043	0.045112782	0.023071131	**2.31**	0.427889852	18.54654859
J	0.022926783	0.022926783	0.008237226	0.007236253	0.007236253	0.007258308	0.010195165	0.010195165	0.016930023	0.016930023	0.016930023	0.028024288	0.028024288	0.040268456	0.040268456	0.043290043	0.043290043	0.045112782	0.023071131	**2.31**	0.427889852	18.54654859
K	0.022926783	0.022926783	0.008237226	0.007236253	0.007236253	0.007258308	0.010195165	0.010195165	0.016930023	0.016930023	0.016930023	0.028024288	0.028024288	0.040268456	0.040268456	0.043290043	0.043290043	0.045112782	0.023071131	**2.31**	0.427889852	18.54654859
L	0.021289155	0.021289155	0.007321979	0.006202502	0.006202502	0.005806646	0.006796776	0.006796776	0.008465011	0.008465011	0.008465011	0.014012144	0.014012144	0.030201342	0.030201342	0.034632035	0.034632035	0.037593985	0.016799197	**1.68**	0.301975766	17.97560674
M	0.021289155	0.021289155	0.007321979	0.006202502	0.006202502	0.005806646	0.006796776	0.006796776	0.008465011	0.008465011	0.008465011	0.014012144	0.014012144	0.030201342	0.030201342	0.034632035	0.034632035	0.037593985	0.016799197	**1.68**	0.301975766	17.97560674
N	0.018628011	0.018628011	0.00599071	0.004824168	0.004824168	0.004147604	0.004078066	0.004078066	0.004232506	0.004232506	0.004232506	0.004670715	0.004670715	0.010067114	0.010067114	0.017316017	0.017316017	0.022556391	0.009142245	**0.91**	0.16609133	18.16745618
O	0.018628011	0.018628011	0.00599071	0.004824168	0.004824168	0.004147604	0.004078066	0.004078066	0.004232506	0.004232506	0.004232506	0.004670715	0.004670715	0.010067114	0.010067114	0.017316017	0.017316017	0.022556391	0.009142245	**0.91**	0.16609133	18.16745618
P	0.017532245	0.017532245	0.005491484	0.004341752	0.004341752	0.003629154	0.003398388	0.003398388	0.003386005	0.003386005	0.003386005	0.003503036	0.003503036	0.005033557	0.005033557	0.008658009	0.008658009	0.015037594	0.006625012	**0.66**	0.124961348	18.86205549
Q	0.017532245	0.017532245	0.005491484	0.004341752	0.004341752	0.003629154	0.003398388	0.003398388	0.003386005	0.003386005	0.003386005	0.003503036	0.003503036	0.005033557	0.005033557	0.008658009	0.008658009	0.015037594	0.006625012	**0.66**	0.124961348	18.86205549
R	0.016558232	0.016558232	0.005069062	0.003947047	0.003947047	0.002639385	0.002912904	0.002912904	0.00282167	0.00282167	0.00282167	0.002802429	0.002802429	0.003355705	0.003355705	0.004329004	0.004329004	0.007518797	0.005083494	**0.51**	0.099219746	19.51802074
																					Estimate λmax	**20.0029324**

Consistency Index = $\frac{(\lambda max-n)}{(n-1)}$ = 0.117819553

Random Consistency Index (for n=18) 1.6181 (Source: Alonso & Lamata, 2006)

Consistency Ratio (CI/RCI)= **0.07281352**
CR 7.28% (Test for CR<10%=reliable)

Fig. F-1. Pair-wise analysis for 'all' projects in the study

Designator	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**	**P**	**Q**	**R**
Occurances	**15**	**14**	**11**	**10**	**10**	**8**	**6**	**6**	**5**	**5**	**5**	**4**	**4**	**3**	**3**	**2**	**2**	**2**
A	1.00	2	5	6	6	8	10	10	11	11	11	12	12	13	13	14	14	14
B	0.50	1.00	4	5	5	7	9	9	10	10	10	11	11	12	12	13	13	13
C	0.20	0.25	1.00	2	2	4	6	6	7	7	7	8	8	9	9	10	10	10
D	0.17	0.20	0.50	1.00	1	3	5	5	6	6	6	7	7	8	8	9	9	9
E	0.17	0.20	0.50	1.00	1.00	3	5	5	6	6	6	7	7	8	8	9	9	9
F	0.13	0.14	0.25	0.33	0.33	1.00	3	3	4	4	4	5	5	6	6	7	7	7
G	0.10	0.11	0.17	0.20	0.20	0.33	1.00	1	2	2	2	3	3	4	4	5	5	5
H	0.10	0.11	0.17	0.20	0.20	0.33	1.00	1.00	2	2	2	3	3	4	4	5	5	5
I	0.09	0.10	0.14	0.17	0.17	0.25	0.50	0.50	1.00	1	1	2	2	3	3	4	4	4
J	0.09	0.10	0.14	0.17	0.17	0.25	0.50	0.50	1.00	1.00	1	2	2	3	3	4	4	4
K	0.09	0.10	0.14	0.17	0.17	0.25	0.50	0.50	1.00	1.00	1.00	2	2	3	3	4	4	4
L	0.08	0.09	0.13	0.14	0.14	0.20	0.33	0.33	0.50	0.50	0.50	1.00	1	2	2	3	3	3
M	0.08	0.09	0.13	0.14	0.14	0.20	0.33	0.33	0.50	0.50	0.50	1.00	1.00	2	2	3	3	3
N	0.08	0.08	0.11	0.13	0.13	0.17	0.25	0.25	0.33	0.33	0.33	0.50	0.50	1.00	1	2	2	2
O	0.08	0.08	0.11	0.13	0.13	0.17	0.25	0.25	0.33	0.33	0.33	0.50	0.50	1.00	1.00	2	2	2
P	0.07	0.08	0.10	0.11	0.11	0.14	0.20	0.20	0.25	0.25	0.25	0.33	0.33	0.50	0.50	1.00	1	1
Q	0.07	0.08	0.10	0.11	0.11	0.14	0.20	0.20	0.25	0.25	0.25	0.33	0.33	0.50	0.50	1.00	1.00	1
R	0.07	0.08	0.10	0.11	0.11	0.11	0.20	0.20	0.25	0.25	0.25	0.33	0.33	0.50	0.50	1.00	1.00	1.00
Sum	3.17	4.89	12.78	17.10	17.10	28.55	43.27	43.27	53.42	53.42	53.42	66.00	66.00	80.50	80.50	97.00	97.00	97.00

Pairwise Comparisons.
AHP method & calculations
Sources, Coyle 2004, Teknomo 2007

	A	B	C	D	E	F	G	H	I
A	0.31587	0.4086358	0.39111	0.3508283	0.3508283	0.2802413	0.2311248	0.2311248	0.2059282
B	0.157935	0.2043179	0.312888	0.292357	0.292357	0.2452112	0.2080123	0.2080123	0.1872075
C	0.063174	0.0510795	0.078222	0.1169428	0.1169428	0.1401207	0.1386749	0.1386749	0.1310452
D	0.052645	0.0408636	0.039111	0.0584714	0.0584714	0.1050905	0.1155624	0.1155624	0.1123245
E	0.052645	0.0408636	0.039111	0.0584714	0.0584714	0.1050905	0.1155624	0.1155624	0.1123245
F	0.0394838	0.0291883	0.0195555	0.0194905	0.0194905	0.0350302	0.0693374	0.0693374	0.074883
G	0.031587	0.022702	0.013037	0.0116943	0.0116943	0.0116767	0.0231125	0.0231125	0.0374415
H	0.031587	0.022702	0.013037	0.0116943	0.0116943	0.0116767	0.0231125	0.0231125	0.0374415
I	0.0287155	0.0204318	0.0111746	0.0097452	0.0097452	0.0087575	0.0115562	0.0115562	0.0187207
J	0.0287155	0.0204318	0.0111746	0.0097452	0.0097452	0.0087575	0.0115562	0.0115562	0.0187207
K	0.0287155	0.0204318	0.0111746	0.0097452	0.0097452	0.0087575	0.0115562	0.0115562	0.0187207
L	0.0263225	0.0185744	0.0097778	0.0083531	0.0083531	0.007006	0.0077042	0.0077042	0.0093604
M	0.0263225	0.0185744	0.0097778	0.0083531	0.0083531	0.007006	0.0077042	0.0077042	0.0093604
N	0.0242977	0.0170265	0.0086913	0.0073089	0.0073089	0.0058384	0.0057781	0.0057781	0.0062402
O	0.0242977	0.0170265	0.0086913	0.0073089	0.0073089	0.0058384	0.0057781	0.0057781	0.0062402
P	0.0225621	0.0157168	0.0078222	0.0064968	0.0064968	0.0050043	0.0046225	0.0046225	0.0046802
Q	0.0225621	0.0157168	0.0078222	0.0064968	0.0064968	0.0050043	0.0046225	0.0046225	0.0046802
R	0.0225621	0.0157168	0.0078222	0.0064968	0.0064968	0.0038922	0.0046225	0.0046225	0.0046802

	J	K	L	M	N	O	P	Q	R	Normalised Eigenvector	%	Aω	Approx λmax
A	0.2059282	0.2059282	0.1818182	0.1818182	0.1614907	0.1614907	0.1443299	0.1443299	0.1443299	0.238730867	**23.87**	5.19516856	21.76161221
B	0.1872075	0.1872075	0.1666667	0.1666667	0.1490683	0.1490683	0.1340206	0.1340206	0.1340206	0.195346941	**19.53**	4.314533994	22.0865193
C	0.1310452	0.1310452	0.1212121	0.1212121	0.1118012	0.1118012	0.1030928	0.1030928	0.1030928	0.111792904	**11.18**	2.398637954	21.45608406
D	0.1123245	0.1123245	0.1060606	0.1060606	0.0993789	0.0993789	0.0927835	0.0927835	0.0927835	0.08955448	**8.96**	1.870887172	20.89105057
E	0.1123245	0.1123245	0.1060606	0.1060606	0.0993789	0.0993789	0.0927835	0.0927835	0.0927835	0.08955448	**8.96**	1.870887172	20.89105057
F	0.074883	0.074883	0.0757576	0.0757576	0.0745342	0.0745342	0.0721649	0.0721649	0.0721649	0.057924489	**5.79**	1.152382518	19.89456498
G	0.0374415	0.0374415	0.0454545	0.0454545	0.0496894	0.0496894	0.0515464	0.0515464	0.0515464	0.033659326	**3.37**	0.634207486	18.84195422
H	0.0374415	0.0374415	0.0454545	0.0454545	0.0496894	0.0496894	0.0515464	0.0515464	0.0515464	0.033659326	**3.37**	0.634207486	18.84195422
I	0.0187207	0.0187207	0.030303	0.030303	0.0372671	0.0372671	0.0412371	0.0412371	0.0412371	0.02370534	**2.37**	0.432971097	18.26470758
J	0.0187207	0.0187207	0.030303	0.030303	0.0372671	0.0372671	0.0412371	0.0412371	0.0412371	0.02370534	**2.37**	0.432971097	18.26470758
K	0.0187207	0.0187207	0.030303	0.030303	0.0372671	0.0372671	0.0412371	0.0412371	0.0412371	0.02370534	**2.37**	0.432971097	18.26470758
L	0.0093604	0.0093604	0.0151515	0.0151515	0.0248447	0.0248447	0.0309278	0.0309278	0.0309278	0.016369565	**1.64**	0.294790673	18.00846083
M	0.0093604	0.0093604	0.0151515	0.0151515	0.0248447	0.0248447	0.0309278	0.0309278	0.0309278	0.016369565	**1.64**	0.294790673	18.00846083
N	0.0062402	0.0062402	0.0075758	0.0075758	0.0124224	0.0124224	0.0206186	0.0206186	0.0206186	0.01125559	**1.13**	0.205344418	18.24377168
O	0.0062402	0.0062402	0.0075758	0.0075758	0.0124224	0.0124224	0.0206186	0.0206186	0.0206186	0.01125559	**1.13**	0.205344418	18.24377168
P	0.0046802	0.0046802	0.0050505	0.0050505	0.0062112	0.0062112	0.0103093	0.0103093	0.0103093	0.007824212	**0.78**	0.148256329	18.94840362
Q	0.0046802	0.0046802	0.0050505	0.0050505	0.0062112	0.0062112	0.0103093	0.0103093	0.0103093	0.007824212	**0.78**	0.148256329	18.94840362
R	0.0046802	0.0046802	0.0050505	0.0050505	0.0062112	0.0062112	0.0103093	0.0103093	0.0103093	0.007762431	**0.78**	0.146417457	18.86232104
												Estimate λmax	**19.37347257**

Consistency Index = (λmax-n)= 0.0807925
(n-1)

Random Consistency Index= 1.6181 (Source: Alonso & Lamata, 2006)
(for n=18)

Consistency Ratio (CI/RCI)= **0.0499305**
CR= 4.99% (Test for CR<10%=reliable)

Fig. F-2. Pair-wise analysis for 'high-tech' projects in the study

Appendix G

Example of DAPTIV© style Project Report

Project Status Report

Date: 24/05/11 Time: 12:03

Project Start: 01/07/07	Portfolio:	Theme:	Project Manager:

PROJECT HEALTH

Overall	Scope	Time	Cost	HR	Risk	Procurement	HSE
ON PLAN	ATTENTION	ON PLAN	ON PLAN	ON PLAN	ATTENTION	ON PLAN	ON PLAN

EXECUTIVE SUMMARY

Last Updated: 5-05-2011

Software – TOS version 0.3.0 was released (via the new TOS metapackage) and has been used for early testing of the Digital Receiver in MATES. Good progress was made on designing and implementing a pre-averaging algorithm for calibration which is expected to give a significant performance improvement.

Integration –Involvement in the Pawsey 1A Early Adopters Program progressed with larger and larger simulations being run, as well as providing feedback to iVEC on the stability and usability of the system.

SKA – Tim worked on a report to WP2.6 - an estimate of SKA1 processing costs, based on simulations using [redacted]Soft.

HR – One of the issues re contract term extensions (reported last month) has been resolved.

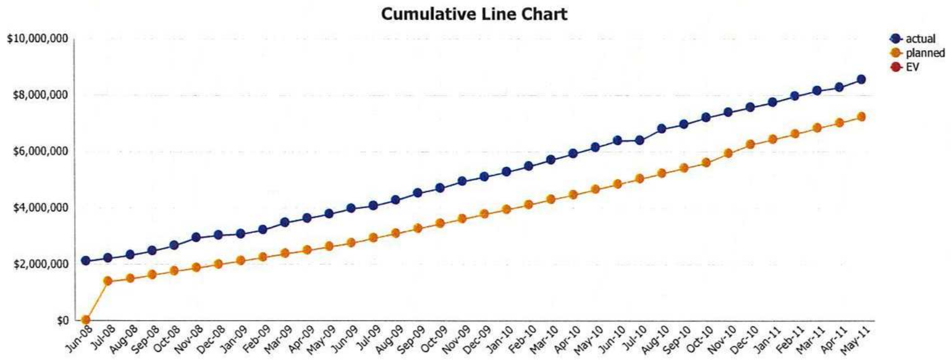
Project management – Procurement commenced to acquire the TOS hardware required for BETA. Also, procurement estimates were revised to acquire the additional hardware required for [redacted] 18, as well as the full [redacted] 36. Also, the major project milestones were updated on discussions with the SEIC team and the SEIC schedule aligned to CMPT deliverables.

Next steps – The majority of time over the next few weeks will be focused on fixing bugs, debugging the TOS software in MATES and preparing the next release of TOS (version 0.4.0).

PROJECT FINANCIALS

Budget	*YTD Plan*	*YTD Actual*	*LTD Plan*	*LTD Actual*
$15,325,000	$2,387,205	$2,165,671	$7,228,288	$8,549,482

Note: *'LTD Plan' and 'YTD Plan' include the planned costs to the end of the current month.*



EARNED VALUE ANALYSIS (PROJECT LTD)

BAC:	$15,325,000	Budget At Completion: 'the budget'
CPI:		Cost Performance Index: 1.0 is on cost; >1 is ahead; <1 is behind
SPI:		Schedule Performance Index: 1.0 is on schedule; >1 is ahead; <1 is behind
EAC:	0	Estimate At Completion: the current forecast, derived from earned value
VAC:	0	Variance At Completion: the difference between the budget and current forecast
PV:	$7,228,288	Budget assigned to the work planned for the specified period
AC:	$8,549,482	Total cost incurred of the work performed for the specified period
EV:	0	Value of the work performed (expressed in terms of its assigned budget)

MILESTONES

- Page 1 of 3 -

Project Status Report

Date: 24/05/11 Time: 12:03

Project Start: 01/07/07 Project Finish: 18/10/13 Financial Reporting Period: LTD	Portfolio: *Radio Astronomy Portfolio*	Theme: [redacted]	Project Manager: [redacted]

Milestone Name	Planned	Actual	
(R) MS_TOS_0.3 (install/config of ACC & TOS server in MATES)	15-Apr-11		▲
(R) MS_TOS_0.4 (install/config of BCC in MATES)	6-May-11		▲
(G) MS_TOS_0.5 [redacted] Ready' (install/config of PTBDR1 & PTBDR2)	10-Jun-11		
(G) MS_TOS_0.7 'Alpha Ready' (install/config of ACC + KVM, TRCC, BCC, TOS servers & FC storage)	5-Aug-11		
(G) Review Science Processing Readiness	4-Oct-11		
(G) MS_TOS_BETA_Phase1_Software_Release	3-Nov-11		
(G) MS_TOS_0.10 'BETA Phase1 Ready' (install/config of BETA Phase 1 computers)	4-Nov-11		
(G) MS_CP_BETA_Phase1_Software_Release	2-Dec-11		
(G) MS_CP_BETA_Phase2_Software_Release	1-Jun-12		
(G) MS_TOS_BETA_Phase2_Software_Release	1-Jun-12		
(G) Deployment of Central Processor onto Petascale system at [redacted]	30-Apr-13		

MAJOR OPEN ISSUES

Subject	*Owner*	*Priority*	*Due Date*	*% Done*
Setup apache test environment for Redmine/subversion/Trac on mimosa.	[redacted]	Immediate		40.00%
Enable power switch buttons on Configuration View of Engineering GUI	[redacted]	Urgent		100.00%
Merge existing wiki pages and discussion on release process to a single wiki page.	[redacted]	Urgent		10.00%
Support use of [redacted] synthesis code by [redacted] partners	[redacted]	Urgent		40.00%
The Dependency._add_path() method needs to be cleaned up.	[redacted]	Urgent		10.00%
Upgrade ptbdr1 to lenny	[redacted]	Urgent		10.00%
Create debian package as part of release process	[redacted]	High	24-Dec-10	20.00%
Define standards for logging	[redacted]	High		0.00%
Develop pluggable solver infrastructure	[redacted]	High		0.00%
Documen[redacted] Science Archive Pawsey Centre Requirements	[redacted]	High	14-Mar-11	0.00%

MAJOR OPEN RISKS

(R) Insufficent archiving capability

Risk Owner: [redacted] **Date Raised:** 24-03-11 **RRR:** 1,000

Failure of IM&T to deliver foundational archiving capabilities may result in the inability to archive [redacted] data within required timeframe.

Mitigate
Work closely with the IM&T team to scope and implement a solution that meets the needs of [redacted]
If the above proves to be an unfeasible option, change the project plan to produce the [redacted] archive in-house.

MAJOR CHANGE REQUESTS

Change Reference	*Description of Change*	*Change to*	*Approval Status*	*Approval Outcome*
[redacted] Centre Petascale HPC slippage	Commissioning work of [redacted] Soft on [redacted] y's Petascale system can only start after the handover has occurred. Therefore, [redacted] commissioning will now commence from July 2013 earliest.	Milestone Delivery Date	Not Required	Approved to change project plan
Schedule Change	A complete re-write of the project schedule to align with current objectives and terminology (aligned with the Redmine milestones being tracked weekly by the team)	Milestone Delivery Date	Not Required	
Science archive sub-contracted to [redacted]	Decision taken to sub contract the Science archive development work. [redacted] T group is interested to take on this development as they have expertise in this area. Currently, the estimated contract value is $500,000 (to fund the development work over 3 years to end 2013) and this amount has been earmarked within the [redacted] budget.	Project Scope	Not Required	Approved to change project plan

PROCUREMENT OVERVIEW

Financial Reporting Period: LTD

Number of Open POs	*Value of Open POs*	*Number of Closed POs*	*Value of Closed POs*
6	$51,273	19	$11,794

Appendix H

SKA Project Review – Action Table

Sample text shown in red

Review Type (CoDR/PDR/CDR/Periodic Review/Final Review)

Review Team:

Review Date:

Ref#	Review Issue	Agreed Action & 'do by' date	Resp	Closed Out
1	There are discrepancies concerning the planned dates and intervals of pre-construction activities as shown on programme charts in the PEP document and other plans.	The plans and associated charts will be re-examined and corrected for consistency. By 30 March 2011	Cloete	
2	The panel are concerned that the procurement lead times shown on these charts are optimistic	The procurement lead times will be validated by a further round of industry consultation, and any amendments corrected in the documentation. By 15 April 2011	Crosby	
3	Since the arrays interact with the electromagnetically-complex ground, and may have aperiodic spacings, it is difficult to determine the characteristics of antennas, either individually or collectively as part of a beamforming system. From the supplied data, we cannot see if pattern multiplication yields reasonable results on which to base the design.	The data underpinning the beamforming assumptions will be provided, together with modelled interactions between dishes. By 28 March 2011	Dewdney	

Review Team Leader: Signed ________________________ Date ____________

Project Director: Signed ________________________ Date ____________

Circulate to:

Appendix I

<u>SKA Fact Sheet for scientists and engineers</u>

The Square Kilometre Array
Fact sheet for scientists and engineers

Exploring the Universe with the world's largest radio telescope

What is the SKA?

The SKA will be a revolutionary radio telescope with about one square kilometre of collecting area, giving 50 times the sensitivity and 10,000 times the survey speed of the best current day telescopes.

It will give astronomers insight into the formation of the first stars and galaxies after the Big Bang, how galaxies have evolved since then, the role of magnetism in the cosmos, the nature of gravity, and studies in astro-biology. And, if history is any guide, the SKA will raise more questions about the Universe than answer old ones.

The SKA is a global project in which astronomers and engineers from more than 70 institutes in 20 countries, together with industry partners, are participating in the scientific and technical design of the telescope through development programs, design studies, and pathfinder telescopes.

Where will it be located?

Two candidate locations are under consideration: Australia – New Zealand and Southern Africa. In the first case, the core region would be in Western Australia with remote stations stretching across Australia to New Zealand. In Southern Africa, the core would be in the Northern Cape Province in South Africa with remote stations scattered throughout the rest of South Africa and several countries in the region including the Indian Ocean islands. The core region in either location will have to accommodate up to three sub-cores, each approximately 5 km in diameter – one for the dishes, one for sparse aperture array dipoles and one for dense aperture array tiles.

Major site selection criteria include the current and future radio quietness of the sites, and the infrastructure capital and operations costs. Ongoing site characterisation includes measurement of the radio-quietness of the core regions and representative remote stations, as well as measurement of tropospheric and ionospheric stability.

What will it look like?

The SKA will employ antenna systems to cover, initially, the frequency range from 70 MHz to 10 GHz (4 m to 3 cm wavelength), with potential for a future extension to 25 GHz or more. Fifty percent of the total antenna collecting area will be concentrated in the core region, 15-20 km across, with the remainder in outlier stations at distances of up to at least 3000 km to provide very detailed images of the cosmos.

In the higher part of the frequency band, the antennas will comprise up to 3000 dishes each of about 15 m diameter and carry low noise innovative feed and receiving systems. In the lower part of the band, the antennas will be fields of aperture array tiles and dipole arrays, with no moving parts, able to observe a number of large areas of the sky simultaneously.

Signals received by the antennas will be transferred to a central signal processing system and high performance computer by optical fibre links carrying up to 420 Gbits/sec per dish and 16 Tbits/sec per aperture array. The special purpose central processing system will process as much as 1 petabyte of astronomical data every 20 seconds, so that exascale computing and exabyte data storage will be required.

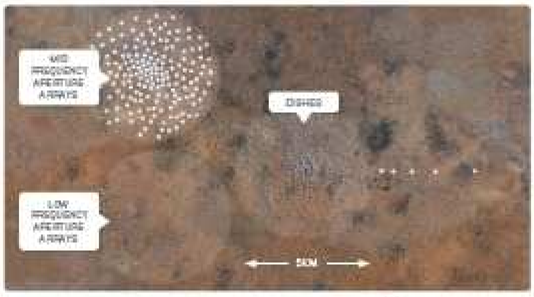
A sophisticated data archive and distribution system will provide access to the data by astronomers and physicists anywhere in the world.

Timeline and cost

2008–2012	Preparatory phase in which the system design and cost are determined, and the site decision and initial construction funds are ratified by the participating governments.
2013–2015	Pre-construction phase – detailed design.
2016–2019	Initial construction of Phase 1, commissioning, integration and first science. Ratification by governments of funds for the full SKA.
2020–2023	Completion of construction, commissioning, acceptance, integration, and shared-risk science.
2024	Science operations.

The target cost for the SKA construction is €1,500 million.

Artist's impression of the three arrays of receptors



The sparse aperture arrays, for the lowest frequencies of observation, are shown as arrays of 'droopy dipoles', one for each polarisation. The sparse aperture arrays are arranged into stations.

At mid-frequencies the dense aperture arrays are closely packed antennas arranged in tiles within stations. The size of the dense aperture array stations is likely to be about 60 m diameter.

Parabolic dishes are used for high frequencies. These are arranged into stations at distances beyond about 180 km from the core regions. Each dish is approximately 15 m in diameter.

For further information contact:

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SPDO March 2011

LOFAR Project – post-project and 'lessons learned' review.

Dwingeloo, 5 April, 2011 ver. 0-4

Phil Crosby & Albert-Jan Boonstra

April 2011

Background

Evidence from a range of successful and unsuccessful high-technology mega-projects indicates that much can be gained from examining the experiences from previous and/or analogous projects. While these 'lesson-learned' cannot avoid all problems, and difficulties grow with ever-increasing project complexities, it is clear that a formal post-project review can contribute organisational knowledge that can be usefully applied in future projects.

Post-project reviews (also known as 'post-mortems') should represent the final phase of project execution, and ideally include a lessons-learned and knowledge transference activity. All the standard project management texts (e.g. the PMBOK, IPMA Competence Baseline, PRINCE2, APM, etc.) highlight the importance of a final review; as well as prominent authors on the topic such as Williams (2003, 2008), Anbarai (2008), Cerpa and Verna (2009), and Crawford and Cooke-Davies (1999). NASA too understands the costly failure to learn from past mistakes and has addressed this through an Agency-wide 'lessons-learned' case study initiative that has shown to lift project performance across the organisation. Yet despite the obvious benefits of analysing a project's successes and shortcomings in order to lift future performance, post-project reviews remain sporadic.

Within organisations, post-project reviews offer project staff opportunities to learn and re-use lessons (Davies & Hobday, 2005), and post-mortem results can be stored within organizational knowledge systems, or communicated directly to other teams (Collier et al., 1996). The formal conduct of a post-project review involving at least the core project team is an essential post-project success driver for early stage future projects, an opportunity to empty old baggage, and can provide a cathartic effect for the team. Post-mortems should not dwell just on problems and failures, but also share the learning from successes.

Project reviews are not the place to assign blame or punishment for errors, or criticise individuals or management. Nor should the focus only be on issues and problems; there is likely to be just as much to learn and hand on from project successes and positive achievement.

The LOFAR (see Exhibit 1) 'lessons-learned' workshop is foremost an opportunity to gain insight into events that helped or hindered the project, as well as gain a broader view of how high-technology mega-projects can be managed better and with a greater probability of success. In other words, what can the lessons of LOFAR teach us for future large science/engineering projects?

*Exhibit 1. The **LO**w **F**requency **AR**ray (LOFAR) is a multi-purpose sensor array project costing around €120 million (including about 30 million of in-kind contributions). Its main application is astronomy at low frequencies (10-250 MHz) but also has geophysical and agricultural applications. The array is centered in the Northeast of the Netherlands with stations dispersed over the whole country and gradually across Europe. LOFAR was developed by a consortium of knowledge institutes, universities and industrial parties, led by ASTRON. The telescope is considered an important pathfinder for the Square Kilometer Array (SKA) in demonstrating the potential of (sparse) aperture arrays, in developing solutions to major calibration issues that are directly applicable to the SKA, and in paving the way for the mass-production and operations of such large distributed*

Purpose and Scope

This highly interactive ‘lessons-learned’ workshop for the LOFAR project aims to:

a) benefit and enrich the ASTRON organisation by capturing the experiences, thoughts and ideas from the LOFAR team in relation to significant positive and negative events during the project’s execution;

b) help gain an improved understanding of the project management and technical domain ‘lessons-learned’ in a contemporary mega-science project; and

c) enable ASTRON to be better prepared to support the SKA project;

The following scope and conditions set the framework for the workshop:

- The focus of the review was on LOFAR’s project management aspects. The number of aspects considered and the depth in which these aspects are discussed is obviously limited due to several factors. First, there was limited time available (one day) for the face-face workshop. Second, no external parties were present at the workshop which meant that relations with the outer world were considered only from within.

- A factor which influenced the course of the LOFAR project and which complicates the review-analysis is that many external, often non-technical factors have influenced the project. As some of the workshop participants may not be aware of these external constraints, these were outlined to the group at the start of the workshop. A key external factor was a split of the consortium in the early phases of development, causing a resource problem due to the transference of some of the design activities from previous consortium partners.

- Although the participants represented a fair cross-section of ASTRON employees contributing to LOFAR, not all aspects discussed during the day were covered by the main players. For example, the external relations were discussed from an ASTRON perspective only, and roll-out aspects were not significantly discussed at all. For this reason, the LOFAR workshop is considered *an* evaluation, and part of a larger evaluation process.

- People have different knowledge and variable depths of knowledge of different aspects of the project. The project management system for example, has different branches, not known to all. Moreover, most people were unaware of the organisation of the project financial systems, and project planning tools were available but used in various degrees of thoroughness. In this respect it, is more the way the tools are used than the availabilities of those tools that became significant.

- Where relevant and useful, lessons-learned will be shared with the broader mega-project community

Process

Planning and Preparation

Planning and preparation of the workshop processes and draft documentation was carried out by Phil Crosby (SPDO). The review process described by Collier et al. (1996) offered a basic framework, which was considerably modified to match the LOFAR project environment, and compress the activity into one intensive day. Logistical planning was undertaken by Dr. Albert-Jan Boonstra (ASTRON). Detailed planning meetings were held at ASTRON on 28 January and 4 April 2011 with LOFAR's Project Director, Dr. Michiel van Haarlem. A detailed 7-step approach to the workshop planning was devised and followed, as per Table A. An invitation to participate, together with a workshop outline and program (shown in Attachment 1) was sent to a broad cross-section of the LOFAR project team.

Table A – The 7-step approach to planning the LOFAR lessons-learned workshop

	Preparation	Output	Activity
Step 1- initiating the process	Identify the broad critical success factors (CSF) to frame the 'lessons learned' event. Consult ASTRON personnel to gain agreement to proceed, and the approx 20 CSF	Clear understanding of the CSF areas appropriate to LOFAR Shared understanding of the focus and goals of the workshop	Prepare a list of around 20 CSF areas, plus allow for a few other areas to arise from the workshop. Obtain required approvals and resources.
Step 2 – planning process	Consult key project team members re: availability Prepare workshop program	Date, place, and participants agreed Draft plan for the review activity	Announce review date and location to all participants
Step 3 – assign responsibilities	Determine roles required, get agreement from people to accept	Roles and responsibilities assigned in the plan	Assign activities as required Circulate plan with

			event information
Step 4 – Conduct the review	Book venue, get materials ready Explain the program	Facilitator prepared, with CSFs identified, and program understood.	Conduct review using appropriate approach for the organisation[1]
Step 5 – Conclude the review	End of workshop summarisation	Notes and materials collected	Drafting of workshop review report
Step 6 – Disseminate knowledge	Decide on audience, and best media, for the 'lessons learned'.	Finalisation of 'lessons-learned' workshop report	Disseminate as agreed
Step 7 – archive & add to knowledge base	Develop (or append) 'lessons-learned' to knowledge database	Archived material securely stored and accessible	Lessons learned readily retrieved by subject, and applied in subsequent projects

Participants

A total of 26 ASTRON-LOFAR staff attended the workshop from all levels/departments of the LOFAR project, plus Albert-Jan Boonstra who acted as Chair and Coordinator and Phil Crosby as Facilitator. Importantly, Prof. Mike Garrett, ASTRON Director, was among the participants. Each participant was allocated to one of the following five 'break-out' teams: **Astronomy; Hardware; Software; Observatory; and Management and Finance.**

Methodology

Prior to the workshop, a questionnaire was developed (Attachment 2) designed to stimulate consideration of LOFAR's successes and challenges. The first 18 key topics were taken from research into mega-project success drivers undertaken by Crosby*, and carefully adapted for the LOFAR project. Since it was anticipated that the participants would introduce commentary about the LOFAR's technical successes or challenges, this was added as topic 19. A further undefined box (topic 20) was added to capture any remaining factors that anyone felt strongly influenced project success, or constituted a major challenge to LOFAR. It was agreed that the questionnaires would be anonymous.

The workshop program was devised around four main activities. In activity #1, participants were issued with the workshop questionnaire and asked to independently identify LOFAR's three strongest and three weakest success factors, according to their view and experience. Once completed, the questionnaires were collected and analysed to produce a consensus result. In activity #2, the group discussed the highest and lowest performance factors and examples of project events to illustrate the findings and associated ideas.

In activity #3, LOFAR's technical domain performance was examined against the factors confirmed in activity #2. Working in their technical domain break-out groups, each team were asked to focus on the highest and lowest ranking factors, consider root causes, and develop lessons-learned. Each team was asked to capture their ideas on flip-chart paper, and present these back to the entire workshop group.

Lastly in activity #4, the group summarised the key findings of the workshop, and discussed ways to best capture lessons-learned in projects. The participants were given an opportunity to describe any personal lessons that they will take forward to new projects.

* Crosby, P. In Print. (2012). Key success drivers – meta study findings applicable to large high-technology projects, *International Journal of Information Technology and Project Management,* 3 (2).

Findings

The collated results from activity #1 are shown in Attachment 3. Three strongest and three weakest success factors were anticipated from activity#1, however four of each actually emerged, plus one factor where views were moderately strong, yet opposed. The findings are summarised in Table B.

Table B – The highest ranked strongest and weakest project factors for LOFAR

Strongest success factors	Weakest success factors
Technical challenges	Collaborations, cultures, standards, obligations
Top level commitment and support	Resources – human, financial, physical
Socio-political environment, early engagement. Physical, infrastructure, technical, economic, social, political	Project management systems (PMS) and controls, discipline, tools, document systems applications
Procurement & contractor management	Project communications and information

	management
Group Ambivalence	
Project management (all levels) competency, leadership	

Against each of the successful and the weakest factors, the participants were first asked to respond as a group, and then as technical domain teams. (In fact, the technical domain teams each chose to focus only on the weakness area). See Table C and Table D.

Table C – Responses from discussion of LOFAR key success factors

Factor	Group Response
Meeting technical challenges	• General agreement that LOFAR did well in tackling technical challenges and overcoming engineering design problems, and that this was a vital feature of LOFAR's success • Suggested to identify high risk items and budget those up-front
Top level commitment and support	• The group agreed that support and commitment from senior levels was clear and consistent
Management of socio-political environment	• There was an appreciation of the challenges of external forces, and the effort of LOFAR management in managing these problems
Procurement management	• This aspect presented a new challenge for ASTRON for the scale of LOFAR, and was considered well managed, especially industry engagement within the Netherlands.

Table D – Responses from discussion of LOFAR key weakness factors

Factor	Group Response	Domain Team	Team Response	Suggested Actions
Ineffective Collaborations	• Project 'split' in 2003 – conditions changed, plus delay in handover • Different cultures meant different approaches • Mismatch of expectations by universities, and industry • Collaborative research takes a long time • Responsibilities in group structures not clear – keep it simple! •	**Astronomy**	• ASTRON-University exchange should go both ways	• Enforce deliverables • Align goals • Align sub-projects to main effort
		Hardware	• Mismatch of expectation & promises • Not optimal design = extra work	• Allow more time • Make clear appointments
		Software	• Double effort ASTRON-USG & BG/L –BG/P	• Improve collaborations with universities
		Observatory	• Involve RO from beginning • Integration testing R&D - RO	• Include Observatory staff in design review Prototype after major design changes
		Management and Finance	• No focus on positive qualities of others • Poor collaboration ability	• No comment

Factor	Group Response	Domain Team	Team Response	Suggested Actions
Poor resources management	• Limited number of software specialists • Better staffing plan would have avoided bottlenecks • University resources not well integrated • End-to-end simulations tested with limited resources may not be realistic	**Astronomy**	• Avoid death by duplication • S/W development never ends	• Don't avoid hard choices • Shift balance from H/W to S/W at right time • Develop the next user generation
		Hardware	• 80/20 phase 1 • 10/20 phase 2	• Ensure early integration
		Software	• No one with a complete end-to-end systems overview • Insufficient resources for long term research (GPUs)	• Make sure enough people for the tasks assigned.
		Observatory	• Shortcuts cause debug problems	• Plan resources for testing
		Management and Finance	• Lack of competent S/W development management	• Ensure sufficient number and expertise of S/W Mgrs

Factor	Group Response	Domain Team	Team Response	Suggested Actions
Imperfect project management systems	• A better requirements management system might have avoided corrections later • Document management system not optimized in terms of searchable data, or distribution control • Financial systems require fuller integration of project & management information	**Astronomy**	• Need input from astronomers	• Need full time managers for project duration (1 mgr for 9 workers)
		Hardware	• No issue in H/Ware	• Excel is sufficient!
		Software	• Not able to get system overview	• Tasking of people not effective
		Observatory	• No Issue in Observatory	• No comment
		Management and Finance	• Project ambitions force ASTRON to professionalize	• Ensure sufficient training and coaching

Factor	Group Response	Domain Team	Team Response	Suggested Actions
Poor project communications	• Too many ways to communicate = not everyone has all required information. • Wikis not the best • Needs a comms plan in place • People need to consider how to best communicate to others, especially program adjustments and technical changes	**Astronomy**	• Lift inclusivity of the science community Can be involved via remote comms • LSM should be main forum for results/info • Should be start-up packet for new Commissioners • Announce project delays and descopes	• Install a good Videocon system • Ensure regular group updates at LSM • Set up for a, wikis, for tracking issues and dispersing info
		Hardware	• Feedback systems essential	• Implement design feedback system
		Software	• Need for single information management system	• Set clear comms rules
		Observatory	• Better comms would help in trading problems	• Improve clarity about problem priorities
		Management and Finance	• No Comment	• No comment

Analysis and Lessons learned

The group and domain team responses from Table D offer three types of data:

(i) ASTRON/LOFAR specific comments and suggested actions (which is left to that organisation to determine appropriate responses)
(ii) Factor specific comments (from the group and domain teams), and
(iii) Topic specific comments (largely from the whole group).

To convert the elicited data into information that can be quickly and usefully understood by the organisation, some consolidation must take place. Comments from (ii) and (iii) can be meaningfully examined using the comparative analysis technique described by Schalken et al. (2006)*, so as to link common concepts back to hypothesised early stage causes of project weaknesses.

Attachment 4 shows the use of a 'concept hierarchy tree' to organise the textual data into project factors that influence the identified success factors. Comparative analysis began by grouping similar or related remarks from the post-project review into common headings. Applying interpretive judgment, lines were then drawn to map these project factors to project components (processes, people, systems, etc). In this case, the main categories were adapted and expanded from those developed for software engineering by Schalken et al. (2006, p40)*. Lines then linked these to common nodes representing underlying 'seed' or 'cause' areas from which practical lessons learned can be derived. The goal is to bring out discriminating concepts that are neither too broad nor specific. From the analysis, five cause topics were derived as shown in Table E.

* Schalken, J., Brinkkemper, S., van Vliet, H., A method to draw lessons from project postmortem databases, *Software Process Improvement and Practice,* 11, 2006. pp 35-46.

Table E – Generic lessons learned derived from common themes from LOFAR project

'Cause' Topic	**Lessons learned**
Planning	• Include a detailed project communications plan • Ensure broad input to the plan, including sufficient science engagement • Be diligent when plotting the timing for major project events • Ensure sufficient time and people resources at critical project phases, especially the research phase • Be extremely clear about responsibilities and authorities of people and partnering organisations
Strategic Approach	• Give deep consideration to differing cultures in international projects, and the associated risks to the project • Be extremely clear about expectations regarding stakeholders, especially their direct involvement • A 'mission-assurance' function could be developed to provide added confidence of project trajectory to

	management.
Design & Test	• Design processes need to be procedurised and optimized • Be alert to possible needless duplication in design
Management	• Implement formal management systems for (i) information control, (ii) document and data control, (iii) financial management. • Management systems need to be 'right-sized' for the project
Training	• Early consideration of training needs for the above initiatives, where these are not traditional approaches or within the project organisation's current skill set

Next Actions

To fully complete the post project review process, there must be a well-understood link to the conduct of future projects in order to turn knowledge into action. The question of how this might happen within the ASTRON/LOFAR organisation was asked of the workshop participants; however very few suggestions or ideas were forthcoming.

The workshop facilitator (Phil Crosby) explored what protocols and/or systems are currently implemented at ASTRON/LOFAR for control of documents and data, and what management meetings might be appropriate to consider project management improvement initiatives. The group also explored some avenues involving personal learning. Ideas from this session are presented below in Table F, as possible initiatives for ASTRON/LOFAR.

Table F – Suggestions to improve capture and implementation of lessons learned for future ASTRON/LOFAR projects

1. Create a folder or marker within the document management system for project lessons learned, and file this report there, together with any prior or subsequent material concerning improvements to medium/large scale projects.
2. Create a new (or adapt an existing) project management guide document. This needs careful editing to accurately reflect the culture and practices within ASTRON, and most importantly have a periodic review to embed lessons learned and updated approaches and procedures. It should be released as the official handbook for projects at ASTRON, and be an auditable document.
3. An early chapter of the ASTRON project management guide (see above) needs to contain a step that ensures that the project manager takes official time to examine previous similar projects to obtain information about success or failure factors. The results of this study must be documented in the new project execution plan.
4. The results of any project reviews, or lessons learned activities, should be announced at a general staff meeting, and possible presented as a short technical talk.
5. Ultimately, an ASTRON 'knowledge database' could be established, with provision for entering of lessons learned by any staff member, with the data searchable by topic for easy retrieval.

Conclusions

From the perspective of a research tool, the LOFAR lessons learned workshop worked well. An important success factor was that participants contributed with a positive and mature attitude. Anecdotal comments indicate that the participants also found it a useful exercise, and importantly, that their opinions were heard and noted. The lively discussions, exchanges of views, and the chance to voice opinions in a free 'off-site' environment meant that learning occurred for both the organisation and individuals.

ASTRON's Director later commented that the day, and the report, was very worthwhile.

The workshop followed the prepared program which was a satisfactory, though very intensive day. Future reviews of this type should allow at least a further hour for activity #3 (the break-out groups and feedback presentations).

In terms of the findings, the key topics concerning the most important drivers of success in high-tech mega-projects were in close alignment with research by Crosby (2011). While the four success factors and four weakness factors were very LOFAR specific, further analysis enabled a generic set of lessons learned to emerge that accords well with contemporary research into modern high-tech mega-project management and execution. These are:

Generic Area	Lessons learned
Planning	Plans should take account of broad input (including science), and be clear re: timing. Resources need to be assured for critical project points, and responsibilities and authorities clearly defined. A project communications plan is required.
Strategic Approach	Strategic plans and actions need to be cognizant of culture variations in multi-national projects, and clear about stakeholder expectations. Application of a mission-assurance function adds confidence for management.
Design & Test	Design processes need to be procedurised and optimized. Be alert to wasteful duplication.
Management	Formal management systems and controls are essential, but need to be the right scale and complexity for the project.
Training	• Consider training needs early, especially for tasks beyond the project organisation's skill set

The organisers, Phil Crosby and Albert-Jan Boonstra, thank ASTRON/LOFAR management for making the day possible.

Attachment 1

PROGRAMME

08:30 Arrival and registration

08:45 Welcome, and presentation by on the LOFAR project, including the history and the political, financial and other conditions that have influenced the project. (Michiel van Haarlem)

09:30 Explanation of the workshop by Moderator (Phil Crosby, SPDO)

09:45 Activity #1 – Perceptions of success of LOFAR programme. Participants rate (approx) 20 success factors. (See attached Worksheet).

10:30 Coffee break

11:00 Activity #2 – Group discussions of results of activity #1

What did the project get right? (Highest performance factors)

What did the project get wrong? (Lowest performance factors)

Open forum – recording the key points and ideas

Summarise lessons learned.

12:30 Lunch break

13:30 Activity #3 – Review of technical domain performance

Break into technical groups

Each group works on the highest and lowest ranking factors, investigate root causes, and develop ‘lessons learned’

Present back to workshop

15:00 Coffee break

15:30 Activity #4 – Summing up

Re-cap workshop outcomes

Discuss ways to best capture lessons-learned in projects

Key lessons that people will take forward to new projects

What have we missed? Any other comments?

Attachment 2

Key topics for LOFAR Lessons Learned Workshop - Worksheet for Activity #1.

For each of the topics below, there are two questions to consider:

a) Which of the topics (in your view) were key factors in LOFAR's success? (✓)

b) Which of the topics do you think could have been managed much better? (x)

c) Is there another topic that you would like to add? (do this at Box No. 20)

Place a tick (✓) against the topics you have selected for question (a)
Place a cross (x) against the topics for question (b)

Topic	(✓ or X)	Examples of Issues to Consider
1. Top level commitment and support		- Support from funding agencies down to dir. level ASTRON - Support from LOFAR consortium members - Interest and support of the project at high level - Top level interference in project execution from outside parties or at director level ASTRON
2. Project Mission, goals, objectives, scope, shared purpose, urgency		- Clarity of the project goals - Objectives communicated to all teams - The pace of project execution - Management of the project scope (scope creep / descope)
3. Project management systems (PMS) and controls, discipline, tools, document systems, applications.		- Quality of project tools and applications - Effectiveness of project tools and applications - Match of tools and PMS to the project tasks and organisation culture - How well did people use the tools and PMS?
4. Project management (all levels), competency, leadership		- Match of management style to the project - Skill in building trust, motivation, and confidence - Ability to deal with all internal and external parties - Managed problems and situations effectively
5. Organisation structure, entity, governance, responsibilities & authorities (R&A) , matrix, number & size of teams, diversity		- Match of organisation structure to the project needs - Responsibilities & Authorities in relation to the key positions - The size and make-up of work packages - Interaction between work packages
6. Collaborations, cultures, standards, obligations		- Effective working of project collaborations (between consortium members, Universities) - Matching of work standards and behaviour and trust (accessibility, language) - Delivery against promises
7. Budget & schedule, realism, viability		- Fact based budgets and schedule - Experience based budgets and schedule - Confidence in budget/schedule forecasts
8. Resources – human, financial, physical		- Sufficient people with correct skills - Sufficient resources to sustain project - Promised supplies/support items

9. Project planning & execution, baselines, lifecycles, phasing, monitoring		- Accuracy and detail of project plans - Correctness of project phasing - Adequacy of project supervision and monitoring
10. Project reviews		- Effectiveness of project reviews (PDR,CDR,...)
11. Change management, configuration management		- Effectiveness of project change management - Capability of PMS to deal with changes - Maintenance of project configuration data - Communication of project changes to teams
12. Risk management, contingency		- Preparation of risk management plans and ongoing review and assessments - Communication of risk management plans - Adequacy of project contingency (reserves) - Application of risk contingency (reserves)
13. Project communications and information management		- Effective management of project technical information - Effective control of PMS information - Ambiguity and confusion within the project
14. Task Forces, project emergencies		- Readiness to form and use task forces (tiger teams) - Capability of task forces to address problems
15. Procurement & contractor management		- Effectiveness of procurement function to support the project - Processes to award contracts - Value for money obtained for the project
16. External stakeholder relations		- Relations with suppliers/contractors/users - Strategic engagement to support the project - Satisfaction of user expectations - Collaborative partner engagement - Funding agencies requirements met
17. Socio-political environment, early engagement. Physical, infrastructure, technical, economic, social, political.		- Legislation to enable the project - Host site issues - Economic benefits achieved - Political issues - Industrial spin-offs - Intellectual property - Social and community matters
18. Project complexity, dealing with – technical, environment, operational		- Understanding of project complexity - Management of technical complexity - Adequacy of planning and resources to meet complex project problems - Operational complexities foreseen
19. Technical challenges		- Research and development capability - Technical expertise in the project teams - System engineering, and project interfaces - Solving of technical problems during project execution - Maintenance of technical discipline - Industry capability to meet requirements
20. (Other)		-
		-

Attachment 3

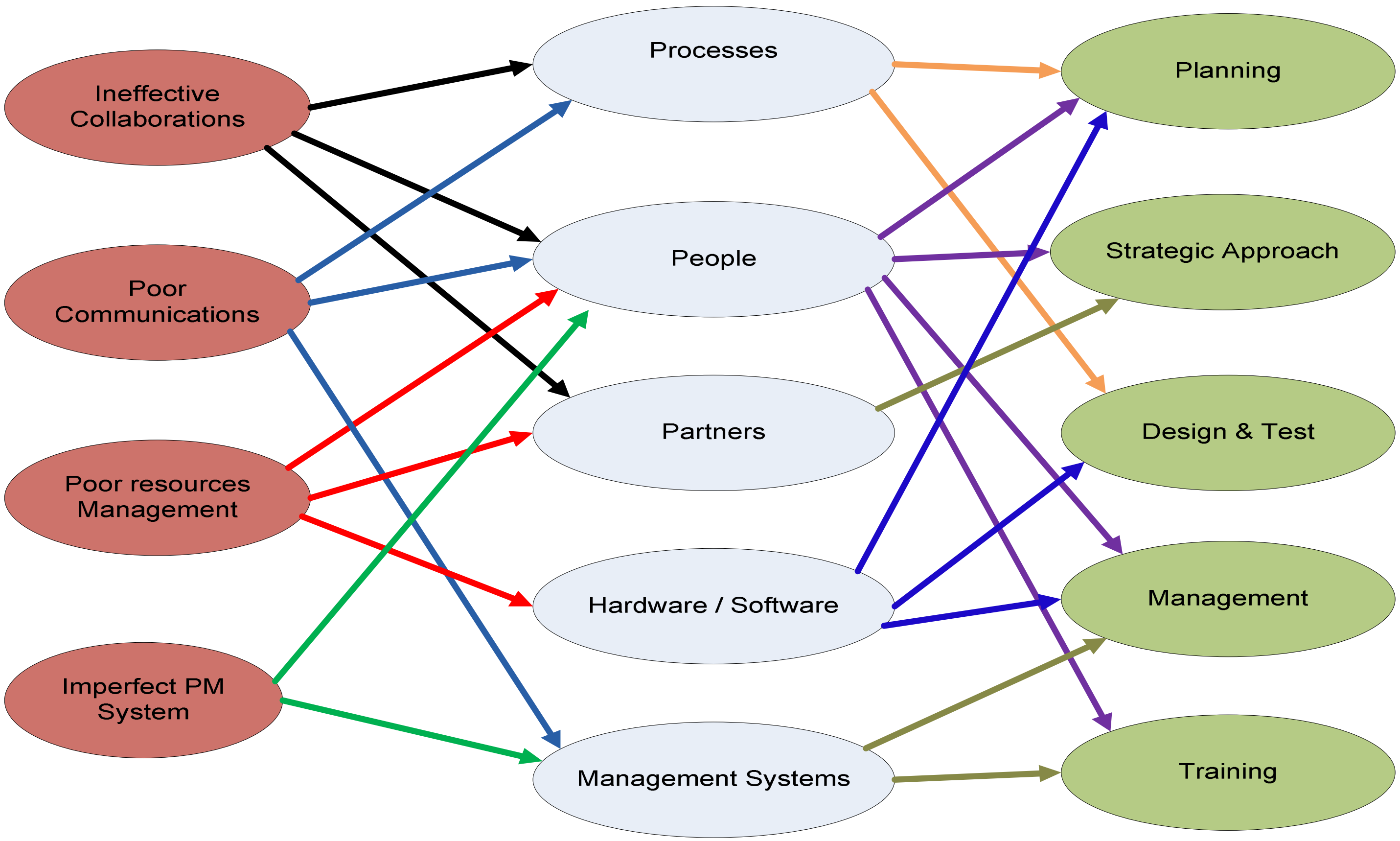
Collated results from activity #1

Topic	(✓)	(X)	Notes
1. Top level commitment and support	11	0	**Rank #2 Success factor**
2. Project Mission, goals, objectives, scope, shared purpose, urgency	2	7	
3. Project management systems (PMS) and controls, discipline, tools, document systems applications	0	7	**Ranked #3 Weakness factor**
4. Project management (all levels) competency, leadership	5	6	Group ambivalence?
5. Organisation structure, entity, governance, responsibilities & authorities (R&A) , staffing matrix, number & size of teams, diversity	3	2	
6. Collaborations, cultures, standards, obligations	1	11	**Ranked #1 Weakness factor**
7. Budget & schedule, realism, viability	0	4	
8. Resources – human, financial, physical	1	10	**Ranked #2 Weakness factor**
9. Project planning & execution, baselines, lifecycles, phasing, reviews, monitoring	4	7	
10. Project Reviews	4	1	
11. Change management, configuration management	1	5	

12. Risk management, contingency	1	3	
13. Project communications and information management	0	6	**Ranked #4 Weakness factor**
14. Task Forces, project emergencies	5	1	
15. Procurement & contractor management	7	2	**Ranked #4 Success factor**
16. External stakeholder relations	1	3	
17. Socio-political environment, early engagement. Physical, infrastructure, technical, economic, social, political.	11	0	**Ranked #3 Success factor**
18. Project complexity, dealing with – technical, environment, operational	2	4	
19. Technical challenges	19	2	**Ranked #1 Success factor**
(Other factors from group) 20.a. Early commissioning & operating involvement	1		
20. b. Software & hardware project management		1	
20. c. Mobilising EU radio-astronomy community	1		
20. d. Engagement of scientists throughout LOFAR development		1	- Pipeline development & interfacing with software developers - Providing adequate access to test data and tools to use it - Documentation about the data products
20. e. Mismatch of cost allocations		2	- Hardware, software science and maintenance (50/50 split?) - Cost-quality balance

Attachment 4

Comparative analysis diagram tracking LOFAR project weakness factors to generic causes



Attachment 5

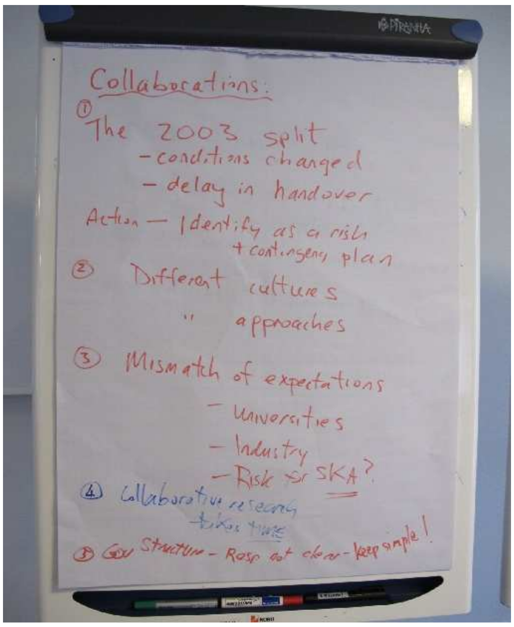
Images from LOFAR ‘lessons learned’ Workshop

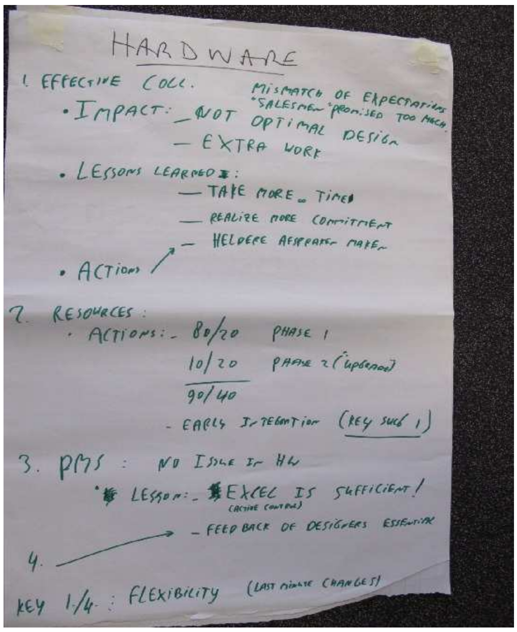
Activity #1 – rating of key project factors

‘U’ shape room format for good interaction

Break-out group discussions

Prepared PC tools for fast initial analysis





Examples of use of flip-charts to capture and display ideas with immediacy

Appendix K

Published peer reviewed papers and presentations in association with this thesis

(Note. Permission has been granted from Journal publishers for use of papers in thesis production)

	Detail of paper and publication and status	Associated Presentations	Page
1	Key success drivers – meta-study findings applicable to large high-technology projects *Int. J. Information Technology Project* Management, Vol 3, No. 2, 2012. In print	PhD Candidacy presentation, **Curtin University**, Perth, WA, 26 March, 2009. *(Early research findings)* (see also [5] below)	343
2	Characteristics and techniques of successful high-technology project managers *Int. J. Project Organisation and Management*, Vol. 4, No. 2, 2012. In print	(see [5] below)	367
3	Procurement strategies enabling success in high-technology mega-projects: Preparatory work for the SKA. Memo 129 *SKA Memo Series***,** http//:www.skatelescope.org. January 2011	Internal staff presentation, **Istituto Nazionale Di Astrofisica** (INAF), Rome, Italy. 9 September, 2010	389
4	Building resilience in large high-technology projects: front end conditioning for success. *Int. J. Information Technology and Project Management*, Vol 3, No. 4, 2012 In print	**NASA Project Management Challenge**, Longbeach, CA, USA, 10 February, 2011 (see also [5] below)	413
5	Presentations of key findings in combined papers 1, 2, & 4	**CSIRO Colloquia Series**, CASS, Marsfield, NSW, 10 August, 2011 **Curtin University**, Faculty of Science & Engineering, Journal Club, Perth, WA, 12 September, 2011 **SKA Program Development Office**, SKA Talk series, Manchester, UK, 28 October, 2011	

Int. J. Information Technology Project Management, Vol 3, No. 2, 2012.

Key Success Drivers – Meta-Study Findings Applicable to Large High-Technology Projects

Phil Crosby, Curtin University, Australia

ABSTRACT

Success in project management, and particularly in large, high-technology/IT projects, is not easily achieved. This paper draws together a significant number of case studies and research efforts relating to the success and failure of projects from the last four decades, in what is believed to be the only modern meta-study of its type. The author posits that there is a body of knowledge within the literature from which a number of key indicators or focus areas can be derived for practical application especially in the early stages of projects. Studies encompassing more than 2,800 projects are examined, and the success factors for general, and high-technology, projects are newly grouped and ranked as strategic success drivers for use prescriptively by project practitioners and approvers. New correlations between success indicators are presented and the principal drivers examined in further detail to reveal sometimes less obvious characteristics influencing project success. In a series of fieldwork interviews with key staff in high-technology projects, these drivers also emerge consistently as important factors in project success.

Keywords: project success; mega-science; success factor; success driver; project performance; risk management; project urgency; lessons learned; system engineering

INTRODUCTION

Much has been written regarding project performance, and the literature is rich in empirical studies of tens, and sometimes hundreds, of projects in an effort to distil factors governing their success or failure. Case study work, involving report analyses, interviews and questionnaires offer much insight through evidential data complemented by qualitative judgement (Grün, 2004). Other studies have derived conclusions through statistical analyses and although meaningful, require more interpretation by the practising project manager.

Many studies stem from a perception that large, publically funded projects, often launched in a fanfare of optimism, frequently overrun in terms of cost and time and occasionally become *fiascos* (Grün, 2004). While many notable 'mega' projects are delivered 'on time, on budget', large projects - especially those underpinned by, or delivering, new technology - are very demanding of management capability, resources, and systems engineering, and too often fail in one or more performance criteria (Merrow, 1988; Morris & Hough, 1986; Hartman & Ashrafi, 2004; UK Ministry of Defence, 2009).

This paper, drawing on case study work and research from the previous four decades, plus contemporary experience, asks; what are the key strategic areas that show strong correlation to project success. Data are examined to discover success factors and success criteria for large engineering and science projects, and compare these with general mega-projects. Findings are presented that contribute new insights for life-cycle project management, most applicable at the planning, formation and approval stages, and show comparative importance of top ranking high-technology ('high-tech') project success drivers.

The precise parameters of large projects (also referred to as 'mega' or 'giant' projects) are not specified, except that these endeavours typically have multi-million or even billion dollar budgets, time-frames usually measured in years, and attract a high level of public or political attention, often due to substantial direct and indirect impacts on the community and the environment. Such endeavours may seem to have little in common with mass production projects (Miller & Lessard, 2000) but the economics of large engineering/science global projects (e.g. the Square Kilometre Array, Large Hadron Collider) are setting aside this division. Flyvbjerg (2009) sets an important context when he states *"mega also implies the size of the task involved in developing, planning, and managing projects of this magnitude. The risks are substantial and cost overruns of 50% are common"*. In this paper, high-tech projects are defined as those involving research and development and/or reliance on IT/science/engineering effort, and having a significant infrastructure requirement.

LITERATURE OVERVIEW

The present research is underpinned by material published from the mid 1970s to the near present, an era broadly covering the professionalisation of project management, and a full cycle of global economic activity. Studies in this period often highlight earlier classic mega-projects such as the Sydney Opera House, the Channel Tunnel, Concorde and space missions as examples of massive time/cost over-runs or performance failure. However the dataset is rich with examples of both successes and failures to learn from.

In considering the components of project success, most authors (Morris & Hough, 1986; Yu et al., 2006; de Wit, 1988; Williams, 1995) point out the triple constraints of scope, time and cost, (commonly termed the ‘iron’ or ‘golden triangle’) and often extend this to include quality, risk, and more recently sustainability factors. Several writers add other useful information such as contractor’s commercial success (Morris & Hough, 1986); personal growth (Dvir et al., 1998); and project safety (Lim & Zain, 1999). Atkinson (1999) notes the maturing of project success factors, yet points to the paradox of projects still being judged against the ‘iron triangle’. Shenhar & Wideman (1996) list 13 success dimensions, interestingly including several client/user aspects such as the extent of customer use, customer satisfaction, market share creation, and new technologies/product lines. Others (Procaccino et al., 2002) suggest that success for one stakeholder (e.g. project management) is not necessarily success in the eyes of another (e.g. the client) thereby illustrating a need to align the project goal or mission as a critical success factor. One five-year study (Crawford, 2000) foreshadowed the approach taken in this paper, by ranking project success factors from post-1995 literature in relation to project manager competence and delivered performance.

Several authors are prolific in the subject area, e.g. Shenhar & Wideman on mapping success to project type (Shenhar & Wideman, 1996); Pinto’s useful Project Management Profile workbook, and collaborations on critical success factors for specific type projects (Pinto & Slevin, 1989); T Cooke-Davies’ (2000) frequently cited work in project success; and Morris & Hough’s research into preconditions of project success (Morris & Hough, 1986).

Several authors (Yu et al., 2006, Dvir et al., 1998 and 2003, Roy et al., 2003, Belassi & Tukel, 1996) have applied statistical techniques to their research to support conclusions, whereas others (Westerveld, 2003; Lim & Zain, 1999; Winch, 1996; Erno-Kjolhede, 2000; Turner, 2004; de Wit, 1988; Rubenstein et al., 1976) have investigated project success from the management theory standpoint, complemented by experiences in the application of project management techniques or models. More targeted publications (Procaccino, 2002; Weck, 2006; Ferratt et al., 2006; Pinto & Slevin, 1989; Moody & Dodgson, 2006; CSIRO, 1998 and 2003; NASA, 2000; Hill, date unknown) have addressed project success factors specifically in high-tech projects.

Although outside the focus of the present study, the nexus between success factors, and how project success is judged, has importance in shaping project drivers (de Wit, 1988; Cooke-Davies, 2002). Many writers discuss the multi-dimensional and multi-criteria nature of project metrics, pointing out dependencies on personal viewpoints and perceptions (O'Brochta, 2002; Crawford, 2000; Muller & Turner, 2007; Westerveld, 2003; Dvir et al., 1998). However work by Shenhar & Dvir (2007), Crawford (2000), Atkinson (1999), Shenhar & Wideman (1996), and Dvir et al., (1998) reach consensus surrounding technical performance, project performance, and internal/external (stakeholder) satisfaction as success criteria.

Publications from the project management professional organisations (e.g. 'Books of Knowledge' or BoKs) also touch on project success, but are aimed more at project structuring and execution and are largely based on contemporary practice, not research analysis (Morris et al., 2006). Nevertheless, the Project Management Institute's Standard for Program Management (2008) offers clear definitions of success measurement in projects, as well as mentioning the benefits of lessons learned. The widely referenced Project Management Book of Knowledge (PMBOK® Guide, 2008) also mentions the use of a 'lessons learned knowledge base' for collecting historical information. However Cicmil et al., (2006), from the Rethinking Project Management study (see below), point to omissions in the PMBOK® and are critical of suggested actions in response to project perturbations that fall short of the 'lived experience' of competent project managers.

One important initiative in adding to the literature is the UK Government funded research activity called Rethinking Project Management (RPM) (Maylor, 2006). Involving a number of leading project management academics and senior practitioners from industry, the network followed a research program framed to question mainstream ideas, the output of which was published in a special issue (no. 24, 2006) of the *International Journal of Project Management (IJPM)*. The present study cites several papers from that publication. The first paper in the compendium (Winter et al., 2006) offers a useful summary of findings and extols the need to embark in new research directions (beyond the rational and intellectual foundations often underpinned by the 'triple constraints' paradigm) and link more directly with project management practice. Of particular note is the need for increased recognition of human issues, and exogenous factors, as potent success drivers. In looking at IT projects, Sauer & Reich (2009) concur with the RPM findings and endorse a pluralistic approach to project complexity beyond the conventional wisdom characterises in the PMBOK®.

DATA & RESEARCH METHOD

Before describing the collection, reduction, and analysis of data employed, it is useful to outline the basis to this meta-case study. Since the nature of the data is non-uniform, this study commenced by considering what and how information can be extracted from the published literature containing, individual assessments (more often than not in case-study form) of a variety of projects by different writers.

Conventional wisdom often indicates that case study research can be useful as a preliminary stage of an investigation, or supplementary to it, but cannot be of value in itself unless linked to a hypothesis. Flyvbjerg (2006) rejects this, arguing that casework reveals 'context-dependent' knowledge that encourages learning maturity from rule-based to virtuoso levels. Flyvbjerg goes on to explain the richness of information in the case narrative, and its ability to describe realities which are hard to reveal or define in scientific parlance. From Flyvberg's range of strategies for case selection, type B. *Information-oriented selection* was chosen to maximize the utility of information from small samples and single cases. Cases are selected on the basis of expectations about their information content. The case study as a research method is supported by Yin (2009), who describes the rigorous methodological approach required for conclusion validity, and usefulness when investigating complex phenomena.

The actual dataset is mainly drawn from peer reviewed journal publications, supplemented by published reports and case study extracts from academic authors. Data were sought from a purposely broad range of studies from the Western world covering the past 35 years, containing diverse project characteristics in terms of purpose, budget, location, engineering innovativeness, and sponsor. The only selection made was to ensure a representative and statistically significant sample of high-tech projects with some systems engineering component identified. These sources were initially selected from literature searches on the keywords *'project success'*, *'mega-project'*, *'critical success factor'*, *'lessons learned'* and *'project learning'*. In total, 29 general studies were examined encompassing 2,820 projects (cases), as well as two success factor summaries drawn from other papers dealing with different projects. A sub-set of 20 studies (928 cases) were classed as applicable to high-tech. Table 1 shows the full study list.

To derive common headings from a wide range of factor descriptors taken from the studies, the author took advantage of contemporaneous research into mega-science project management at several large scientific projects in Europe and Australia. Each project is characterised by having substantial and specialised infrastructure, > US$100 million budget (except the Antarctic LIDAR), and a science goal concerned with astro, particle, or nuclear physics. The author conducted formal interviews with project management representatives, each typically lasting 3-5 hours. This opportunity permitted topical discussion to refine and validate the common headings for grouping the success factors drawn from this study. For example, phrases such as "clear project mission", "defined objectives", "stated project targets" and "documented program goals" were grouped as a single key concept. This process resulted in the most common findings being captured under 18 distinct headings. Appendix B shows the interview list.

Having grouped the success factors and their frequency of occurrence drawn from the literature, calculation techniques from the Analytical Hierarchy Process (AHP) developed by Saaty (Coyle, 2004) were applied in the form of pair-wise comparisons to reveal a ranked set of success drivers, followed by consistency tests to check fidelity of the results. This work is described in detail in Appendix A. No attempt was made to pursue the analysis through weighted criteria to a single choice, since clearly all 18 resulting success drivers are contributors to success.

The output from this analysis is shown in Table 2, which presents the derived project success drivers ranked by relative importance for all projects, and high-tech cases.

In the course of contemporaneous employment funded research into mega-science management, the author conducted a series of investigations at several large scientific facilities in Europe and Australia (Appendix B). The chosen sites each satisfied the criteria of having substantial and specialised infrastructure, > US$100 million budget (except the Antarctic LIDAR), and a science goal concerned with astro, particle, or nuclear physics. Visits of 2-3 days were pre-planned to ensure access to key project management representatives. Formal interviews were conducted, each typically lasting 3-5 hours. Use of a question list ensured a systematic approach and consistency of topic coverage; however interviewees were free to amplify their responses as necessary. This timely opportunity permitted the author to qualitatively corroborate the findings of the present study in terms of initial analysis (groupings), importance rankings, and highly contextual validation using the 'lived experience'. Appendix B shows the interview list.

TABLE 1 – List of studies showing number of individual cases

Lead Author (date)	**Nature of Study / Data Source**	**QuaN or QuaL**	**General Cases**	**high-tech Cases**
Akkermans (2002)[1]	*General research*	*L*	*n/a**	✓
Anbari (2008)	*Post project reviews*	*L*	*n/a*	✓
Belassi (1996)	*Mixed projects*	*L*	*91*	
Blackburn (1994)	*Iridium satellite systems project*	*L*	*1*	✓
Clarke (1999)	*Various projects*	*L*	*n/a*	
Cooke-Davies (2002)	*Variable projects*	*L*	*136*	
CSIRO (1998)	*Big science projects*	*L*	*9*	✓
De Wit (1988)	*UK & US projects*	*L*	*8*	✓
Dvir (1998)	*Qualified by P type*	*N*	*110*	✓
Dvir (2003)	*Defence projects*	*N*	*110*	✓
Ferratt (2006)	*ERP Projects*	*N*	*70*	✓
Grun (2004)	*Few major projects plus other information*	*L*	*4*	
Hartman (2004)	*Mixed projects*	*L*	*5*	
Honour (2004)	*Broad range of technology projects*	*N*	*42*	✓
Hyvari (2006)	*Mixed projects*	*N*	*100*	✓
Katsanevas (2009)	*Survey of physics project managers*	*L*	*n/a*	✓
Kerzner (1987)[2]	*General research*	*L*	*n/a*	
Kleinman (2008)	*Astronomy Survey project*	*L*	*1*	✓
Merrow (1988)	*Large civilian projects*	*L*	*52*	
Milosevic (2005)	*Project Managers*	*N*	*55*	✓
Morris (1986)	*Civil and aerospace projects*	*L*	*8*	✓
Muller (2007)	*General large projects*	*N*	*959*	
Murphy (1974)	*Various projects*	*N*	*646*	
Ninin (1997)	*CERN projects*	*L*	*4*	✓

Pinto (1989)	*R&D Projects*	*N*	*159*	✓
Procaccino (2002)	*IT professionals*	*N*	*21*	✓
Rubenstein (1976)	*Mixed study, some R & D*	*L*	*103*	✓
Turner (2004)	*Various projects*	*L*	*n/a*	
Verner (2005)	*Software projects*	*N*	*122*	✓
Weck (2006)	*Project practitioners*	*L*	*5*	✓
Winch (1996)	*Review of several 'classic' projects*	*L*	*n/a*	
	Total Cases		**2820**	**928**

4. *Extracted from Ferratt (2002)*
5. *Extracted from Lim (1999)*

**n/a = No. of cases not stated*
L/N = Qualitative /Quantitative Study

TABLE 2 – Success drivers ranked by relative importance

#	Success Driver	All Projects Ranking	High-tech Ranking
A	*Project management (PM) control & execution systems in place, with robust policies, planning, procedures, document control, audit, etc*	*23.72*	*23.87*
B	*Clear project definition, requirements, goals, objectives, scope, and project mission; sound business case*	*23.72*	*19.53*
C	*Mature project communication, information systems; effective public relations management*	*11.34*	*11.18*
D	*(Top) management (or sponsor) support with sustained commitment, appropriately engaged*	*7.85*	*8.96*
E	*Project baseline, estimates accuracy, project phasing, effective project performance (reviews) and measurement*	*7.85*	*8.96*
F	*Leadership skills, PM experience & stability; motivating & socially capable PM*	*5.24*	*5.79*
G	*Agreed realistic customer / user expectations; frequent customer contact*	*3.17*	*3.37*
H	*PM/Organisational understanding & competence in project management*	*3.17*	*3.37*
I	*Adequate resourcing of the project*	*2.31*	*2.37*
J	*Aligned perceptions of project goals & success - management and team; sense of urgency instilled*	*2.31*	*2.37*
K	*Effective stakeholder engagement / partnership (e.g. client, contractors, etc)*	*2.31*	*2.37*
L	*Organisational responsibilities assigned to right-sized capable team*	*1.68*	*1.64*

M	*Mature, effective project management change control process; effective deviations handling & configuration control*	*1.68*	*1.64*
N	*Understanding & continuous management of risk; visibility of risk register*	*0.91*	*1.13*
O	*Project Manager & PM systems matched to project complexity, and culturally aligned*	*0.91*	*1.13*
P	*Effective means of learning from experience and continuous improvement environment*	*0.66*	*0.78*
Q	*Full understanding, and early engagement, of host government environment and institutional requirements*	*0.66*	*0.78*
R	*Right-sized systems engineering; managing and procuring in right sized project 'chunks'*	*0.51*	*0.78*

KEY FINDINGS

The ranked project success drivers in Table 2 reveal some valuable general conclusions for the project practitioner.

First, a relatively small (though not trivial) number of key project topics and indicators are demonstrated to impact significantly on the chances of success. Most significantly, implementation of excellent project control systems and processes, and a clearly defined project mission are shown to be twice as important as the next ranked driver. These considerations are important throughout the project but it is clearly necessary to test the intent, robustness, and understanding of these factors at the conceptual/approval stage.

Second, the rankings show the importance of ‘softer’ indicators such as social capability and expectation management that may not have been previously obvious. Selecting and appointing the right project management team is clearly vital, taking account of factors such as motivation, cultural sensitivity, and instilling the right amount of urgency. Moreover, recent studies highlight the need (some following negative events) to invest in effective project information control, both internally and externally.

Third, some factors that may be intuitively expected to rank highly e.g. risk management and system engineering process (as opposed to the application of systems design as part of goal setting etc.), appear low in the table, ranking 14^{th} & 18^{th} respectively. At face value, this indicates that while important, these may not be the make-or-break factors that alone determine project success or failure. For risk especially, this was counter-intuitive to contemporary experience and is worthy of further enquiry to separate the management science approach (the probabilistic future) described as *decisioneering* (Miller & Lessard, 2000), and the more applied managerial approach (the uncertain future) that continually matches risks with strategies.The topic of risk is revisited later.

Lastly, it will be noticed that, following the analysis, both general and high-tech columns rank the success drivers in the same order, albeit with differing importance. The variations, although minor, may reflect the character of high-tech projects (often involving R & D) where definitions and scope are often less defined, making top level support and baseline information more necessary. Similarly, management of risk, complexity and systems engineering process require slightly more emphasis. Overall though, high-tech projects clearly rely on the same key success drivers as most other projects.

As mentioned, the author was able to discuss the topics listed in Table 2 with ten experienced high-tech project professionals (Appendix B). Interview case notes show expert commentaries are clearly consistent with this study’s findings.

The combined analysis offers more insight for high-tech project practitioners than contained in the 'headline' rankings alone. Below is a closer examination of the top ranking drivers, followed by a brief discussion of several others.

Project Management System

The extent of a formal project control environment is largely a decision taken by the project management, in light of organisational policies and practice, type/size of project, and to some extent, project leadership style. Observations by the author revealed the application of ‘lite’ systems (e.g. MS Project running on a single machine), various tailored project management systems (in some instances designed to align with published ISO Standard type quality systems), and large corporate management information systems (MIS) such as MRP and SAP. Findings from this meta-study show that, although the project control environment must be well matched to the task in terms of complexity, culture, and maintenance, no one system or product stood out. The key point is that a system of some type must be in place.

The importance of standardisation in projects is highlighted by Milosevic & Patanakul (2005) in their survey of project managers who collectively concluded that "*having standardized project management tools helps with project success, more punctual schedules, more satisfied customers, better cost-effectiveness, and higher quality accomplishments.*" An empirical analysis of the relationship between project planning and project success by Dvir et al., (2003) concluded that "*A minimum level of planning tools and procedure use is also important but what kind of tools is of no importance.*" A very frank report from the Gemini telescope Lessons Learned Workshop (National Research Council Canada, 1999) contains at least five quotations from team members lamenting the lack of, or lateness, of effective project management control.

Atkinson et al., (2006) supports project tools but with a caution, "*tools and techniques…are very useful in the right place. However they [can bring] a focus on operations…with consequent lack of attention to strategic issues*". Erno-Kjolhede (2000) also qualifies in remarks about project management theory applied to research projects when writing "*project management tools for scheduling and planning are helpful in research projects – but also potentially misleading. Thus they should be used as flexible tools that are continuously adjusted to fit current project reality. They should not be regarded as a blueprint for the research project.*"

Ninin & Vanden Eynden (1997) investigated the application of project based management for high-tech activities at CERN, referencing a 1997 inquiry showing that 100% of staff involved supported the concept. They concluded that "*project-based management has been experienced recently for several controls projects and has proven its success from the human, organisational and managerial points of view.*"

Project Mission, Definition & Goal

Pinto & Slevin (1989) in their compelling report containing 10 critical project success factors posit that the project mission, while apparently obvious, is *the* most important factor across all project phases and argue that if forgotten or unclear, the project will likely fail. Clearly the early stakeholders must not only know and agree the purpose of the project, but also ensure that it is defined in the form of a documented and socialised scope containing technical objectives and goals, supported if appropriate by a business case.

Hartman & Ashrafi (2004) in their paper on SMART project planning recommend the establishment and agreement of success criteria at the outset, claiming this to be the single most important contributor to project success. Similarly, in '*Taming Giant Projects'* Grün (2004) argues that goal formulation is one of four success factors that (inter alia) influences the causes of [project] failure.

Not all large high-tech projects (except perhaps IT) are able to have their mission, requirements, scope and goals precisely defined, especially in the early stages. In looking back over 30 years of project management, Winch (1996) discusses the difficulty of looking over the cognitive horizon, and how the political, economic and regulatory environment may result in project trade-offs. He nevertheless advises early resolution as far better than proceeding with unresolved aims.

Project Communication

Competent information management throughout the project was found to be crucial (Clarke, 1999) to effective execution in two principal domains. The first area concerns communication with parties external to the project team, for example; users/customers, advisory committees, arms-length sponsors, political masters, suppliers, and the general public. Casework consistently reports the dangers of unofficial pathways for project information which may be interpreted (at best) incorrectly or (at worst) cause upset, or even financial or commercial strife, through premature announcements. The solution lies in the establishment of a project communications position early, and implement firm policies for information approval and distribution, especially in relation to problems, procurement, or discoveries.

The second area concerns internal communications, with examples of commonly reported deficiencies conveniently summarised within a Report on Project Management by the Mars Climate Orbiter Investigation Board (NASA, 2000). Under the general finding of inadequate communications between project elements during its development and operations phases, they list specific inadequacies as contributing causes of programming errors leading to mission failure:

- inadequate communications between project elements led to a lack of cross discipline knowledge among team members;
- a lack of early and constant involvement of all project elements throughout the project life cycle (e.g. inadequate communications between the development and operations teams);
- project management did not develop an environment of open communications within the operations team; and
- inadequate communication between the project system elements and the technical line divisions at the partnering research institution.

The weaknesses in the above example offer good lessons and reflect typical project interfaces at which communications breakdowns inhibit or prevent project success.

Top Level Support & Commitment

Appearing as the fourth most important in high-tech project success, this driver is relevant to most business endeavours. Pinto & Slevin (1989) echo other writers when they identify the responsibility of top management to support and resource a project once authority for expenditure has been approved, and also mention top management's ability to either help or hinder a project. Indeed, several authors (Hayfield, 1985; Baker, Murphy & Fisher, 1988; Rubenstein et al., 1976; Procaccino, 2002) give some emphasis to the negative effects of *too much* management, citing 'interference' and 'meddling'. Procaccino adds that removal of a project sponsor has more detrimental effect on success than starting without one.

Despite the dangers of interference, casework research demonstrates the powerful benefit of committed and concerned senior level interest in a project's execution, and of a readiness to act supportively when needed. This is validated through the often referenced Apollo project studied by Seamans and Ordway (1977) who table as one of their lessons from Apollo *"In the final analysis, the presence or absence of [top level] support is the single, most crucial element that spells success or failure"*. We conclude that top level commitment is vital for success, but note there is an important distinction between 'support' and 'interference'.

Project Baseline, Phasing & Performance Monitoring

The purpose and importance of a project baseline is threefold; (a) as a basis for cost and schedule estimation for project approval, (b) to establish a performance measurement reference, and (c) to establish appropriate expectations of project management and team prior to project initiation. Carried out in the context of project scope and budget, the baseline supports the project launch decision and the inevitable trade-off decisions by project management during the project. Surprisingly, a documented baseline such as this is frequently missing from projects (Shenhar & Wideman, 1996).

Cost and schedule estimation is held as part science, part art, and is notorious for poor assumptions and inaccuracies, especially in IT projects where optimism bias drives underestimations. Project estimators must be prepared and equipped to allow for project based and external events on an historical probabilistic basis, and to allow for calculated contingency that Butts and Linton's casework (2000) shows is so often understated.

Breaking large projects into phases and sub-projects, and the defining of work packages, is reported by Clarke (1999) as one of the most important tasks in new or development projects. Her study cites benefits including greater ownership by project teams; spread of responsibilities and accountability across a greater number of people; and easier delegation, objective monitoring, communication, problem identification and change management. This idea was developed further by de Wit (1988) in calling for specific objectives for different project phases, such that project success can be more usefully monitored and determined on phase performance.

The benefits of periodic project reporting is a common finding in studies of project success as Turner (2004) found when defining reporting as a critical condition of project success, and its absence as a route to failure. Kerzner (1998) similarly lists 'uniform status/monitoring reporting' as a critical success factor, especially in the growth stage of projects. Reporting systems should be internally consistent and 'fit for purpose' in that they should contain only sufficient, clearly presented data (supporting the modern 'dashboard' approach), avoid duplication and, where possible, be automated.

Project Leadership & Management

It is of course people who deliver projects, not processes and systems. Without competent, intelligent, and dedicated teams and individuals it is difficult to imagine any project finishing successfully. However, having the talent is not enough, and projects require both leadership (of people) and management (of processes and systems); these two attributes may not always reside in the same individual (Crosby, 2006).

Muller & Turner's (2007) large study of project managers and their influence on success, point out positive correlations between project success and older, more experienced managers, and also warn against assigning managers to projects below their capabilities. Project managers should be appointed early, lead the project through to the commissioning stage, and ideally work in their own culture. No performance difference was detected between male and female managers.

Individual leadership qualities and their effect on projects are less tangible. Thompson (Ashby & Miles, 2002) sets out three basic skills as predictors for success – capacity (knowledge and basic intellect, or innate ability), authenticity (the genuine article), and motivation (eloquently coined as "*influence many, control few*"). In a project with a history of problems, a weariness of change and lack of commitment, Clarke (1999) found that an absence of these qualities contributed to a general lack of motivation in people, especially to be a part of project changes. Clarke cites management example as one of the best ways to raise confidence and awareness of what can be achieved. As awareness increases of what is happening in their organisation, people become more involved and committed, and as a consequence, better motivated.

In the high-tech area smaller teams may work more effectively than in general projects, as Moody & Dodgson (2006) argue in their study of a complex aerospace project. They describe a single small, committed team with overlapping and complementary skills, made up of a proportionately large number of systems engineers with specialist knowledge across blurred project phases. This flexibility of implementation phases - which they suggest can only be done with a small team that can be across everything – is presented as a key to success.

Recruitment and nurturing of individuals cannot be ignored, as Rubenstein et al., (1976) show in their studies on influencing innovation success. Fieldwork indicated that certain people had played (often informal) roles in successful project initiation, progress, and outcomes.

Project managers and leaders have plenty of responsibilities and their selection can be pivotal to project success. However many high-tech research projects are cross-institutionalised and the project manager has only very little formal authority over project participants who are essentially peers, and who may only have a part-time commitment to the project. Erno-Kjolhede (2000) examines what ‘power’ to lead remains in such circumstances. He concludes that whilst accountability, commitment, information, influence, network control, and personal powers are attainable, formal authority must give way to persuasion and negotiation flair. He further argues that in high-tech projects, this is not necessarily a drawback. This approach to effective leadership and project success is more associated with knowledge, commitment, team-building, vision, and treating people as peers than it is with authority, subordination and issuing orders.

Gratton & Erickson’s study (2007) of 55 collaborative teams isolated eight HR practices leading to project success, highlighting the benefits of capitalising on the trust residing in skilfully managed ‘heritage’ teams. Their research indicates that when 20% - 40% of the team members are already connected through past associations, strong collaboration was evident at the start.

There are indications from the research that project manager profile, especially more subtle traits, has a significant effect on project outcomes. Further research is warranted on this topic.

OTHER DRIVERS

Following the most consistently highest ranked project success drivers, there are other strategic project dimensions in which early attention can materially influence success. Some of these areas, e.g. project manager competence, client/user expectations, and adequate resourcing, are well documented elsewhere. Other drivers have more subtle aspects reflecting specific research and are discussed below.

Urgency

Taking into account the caution concerning the potential harmful effects of urgency from Morris & Hough’s (1986) thorough study into precursors of success, the weight of evidence from more recent casework is that time pressure is a crucial variable for project success or, at least for avoiding project disasters. In this vein Grün (2004, introduction) alerts us to the *“inherent silent power of time”*. Pinto & Slevin (1989) also emphasise urgency as having important implications for success in R & D projects, encouraging the project manager to instil a sense of pace into the team, on the basis that urgent projects demonstrate a greater ability to secure resources than projects viewed as routine, or even dull. However, it is possible to go too far, as the NASA investigation into project management of the failed Mars Climate Orbiter (NASA, 2000) showed. At the time, a ‘faster, better, cheaper’ (FBC) strategy pervaded NASA’s space projects, however the tipping point where increasing scope met downward driven schedules and costs was unforeseen, to the extent that unmanaged project risk was dramatically increased, ultimately inducing failure.

Client/Supplier Involvement

Customers (often described as ‘users’ for high-tech facilities) can have a profound influence on project outcomes, as described in Procaccino’s study (2002) showing that success is directly related to the level of customer confidence in the project management and development team. Grün (2004) addresses the same point, describing it as the *“worst case”* when no permanent users are nominated to be involved in the planning phase, resulting in the operation and maintenance phases being “*left to chance*”. In studies of R&D projects (Pinto & Mantel, 1990) and IT projects (Taimour, 2005), client participation is clearly identified as a leading success indicator.

Supplier engagement through the procurement process is similarly important, beginning with the industry engagement strategy (Schill, 1979) and implementation of a project contracting policy (Morris & Hough, 1986; MPA, 2009). In high-tech mega-projects involving R&D, pre-contractual relationships are both common and essential, and can pose a problem known as ‘lock-out’ which could mean exclusion of precisely those organisations that have specific relevant knowledge or skills from the early stages of a project (Hall & Kahn, 2006). Such situations require expert management to avoid impediments to successful project delivery.

Change Control

Findings from this study elevate the subject of change management from a project tool to a strategic success driver. Both the literature casework and study fieldwork demonstrate that handling of deviations found through testing, failures, or inspection must not only be tackled systematically, but also be properly managed through corrective and preventive processes linked to configuration control systems. When discussing design changes in manned space programs (where the impact can be potentially counted in lives) at NASA's 2010 Project Challenge conference, one speaker expressed the view that 'there's no such thing as a small change'. Robust change management not only avoids repetitive errors: it is a foundation for continuous improvement through problem tracking and recording via a lessons learned system and is thus a vital component of the project management system.

Risk

The topic of risk management has become ubiquitous in our society and the world of project management. It is standard practice for projects of all kinds to create or adopt a risk management plan, evaluate project risk(s) and establish some form of risk register to document the results. Fieldwork interviews reveal that this process at least helps identify and categorise risk (albeit often subjectively), as well as encourage risk mitigation techniques and/or controls (including the shifting of risk along the value chain). In the better examples, effort is made to plot the risk in terms of phases and value, thereby enabling risk retirement (or 'burn') to be tracked. Studies show that this pays off, as in the work by Voetsch et al., (2005) who concluded that 53% of the respondents who reported their projects conduct risk reviews "*Almost Always*" report completing projects on time. Voetsch adds "*there is a statistically significant relationship between… the presence of a project risk management process…and reported project success rate of an organisation.*"

Given these strong correlations, why does risk management rank relatively low among key success drivers? Fieldwork evidence suggests two reasons. First, whilst project practitioners agree that risk identification and management is a requirement, too often it is seen as "busy work", pulled together largely to fulfil project funding or audits, and rarely consulted as a tool-at-hand to assist monitoring the project's exposure to failure. The second reason is simply that risk management is seen as part of the project fabric, something that the project manager practises subconsciously in daily decision-making, and does not report as an explicit success factor. Both explanations indicate a lack of serious and active risk assessment, at least partly explained by Butts & Linton (2009) in their insightful report concerning project estimation failures in NASA:

> *"Often it is not what we know will get us. It isn't even what we don't know that bodes trouble. It is what we don't know that we don't know that hoses (sic) things up. This is a cognitive blindspot created by the fundamental nature of knowledge that has not yet been encountered."*

It is therefore the very nature of risk that, despite the difficulty in identification and quantification, should drive project proponents and managers to more diligently assess significant threats, their potential impact, contingency, and mitigation.

External environment

Projects are not always self-contained: big high-tech projects in particular can require large physical spaces for development or deployment, involve regulatory standards, require public funding and/or political support, and may rely on social approval before proceeding. Belasi & Tukel (1996), when grouping factors for project success, identified this external framework of political, economic, and social factors, including marketplace forces. They point out the potential for early project termination should such factors be judged too risky or influential. Other factors, addressed by the RAND study of 52 mega-projects (Merrow, 1988) stress the potential conflicts between projects and institutional problems associated with environmental regulations, health and safety rules, labour practices and procurement controls. Fieldwork showed none of this has since diminished.

System Engineering

Finally, the concept of system engineering (SE) and its value, especially to complex projects, is often raised at the development stage of high-tech projects. Prevalent in defence, and large engineering projects, the aim of SE is essentially to apply influence at the design phase to enable easier and faster integration and test, ensure interface compatibility, and reduce risk, time and cost. SE is a discipline in itself, and where the approach is applicable, it is fundamental to project lifecycle management. A detailed study (Honour, 2004) of 42 projects and SE practice shows consistent correlations between investment in SE and project success, (especially regarding over-runs, cost and effective risk retirement) as well as subjective rises in output quality. However a one-size fits all approach to SE is not indicated and care is needed to avoid over-driving the project with SE. Honour's work (2004) determined that in terms of person-effort, the optimum is 15-20%, a figure he found corroborated in prior works by NASA and by Kludze, and confirmed by the UK VISTA ₤35 million infra-red telescope project. Similarly, when describing the large and complex Gemini telescope project, Engineering Leader Dick Kurz believes that "*it takes… professional SE to really carry it off*" enabling the project to stay on budget and close to schedule (Michaud, 2009).

IMPLICATIONS FOR PROJECT MANAGEMENT

Once the key success drivers are derived and ranked, attention can turn to exploiting the knowledge across the project life-cycle. A full treatise on establishing the project organisation, environment, and toolset, is beyond the scope of this paper. However, assigning the identified success drivers (referenced to Table 2 rankings) to early phase project strategies ensures that the key concepts may be embedded at a productive point.

Conceptual Planning

This is the time for clarifying the project definition, scope and goals, and if required, the business case [B]. Sponsor commitment must be in place, and client/user expectations agreed [D, G].

Post Concept Approval

Strategies are now developed for dealing with operations in the host environment [Q], key resources are identified and secured [I] (including management [O]) and a detailed risk review undertaken [N].

Project Approval

Strategies are implemented for project policies [A], systems engineering, site acquisition, procurement [Q], information management (including outreach and Public Relations) [C], and staffing.

Project Commencement

Planning, execution, and review systems, operating procedures, and document controls [A] are now instigated. Project baselines and phases are defined [E]. Change management, continuous improvement [P], and configuration control [M] is established. Strategic relationships are commenced with key suppliers [R].

Project team governance is asserted early through the project manager's approach to leadership, motivation, and social competence [F]. Especially important now is the assignment of accountabilities [L], aligning staff perceptions of goals and success, and instilling a sense of project momentum [J].

Lessons Learned – Post-Project Reviews

Given clear evidence that, despite the collected experience from general and high-tech projects, failures continue to happen, the question begs – why do we fail to learn from them?

One reason suggested from this study is the frequent absence of any formal post-project review or project history session (Atkinson et al., 2006; Verna & Cerpa, 2005) by the majority of the documented or visited cases. Such reviews are recommended in the Project Management Institute's literature, and endorsed by Williams (2008), who emphasizes the social process and the usefulness of story transmission. Anbari et al., (2008) stresses that regular collection of lessons learned in projects, their careful storage, and meaningful utilization in subsequent projects are critical elements of project success. Current practices evaluated by the author indicate an understandable focus on achieving the project deliverables, with many time-poor practitioners unwilling or unable to find and digest the experience of one or more cases relevant to their own project.

The formal conduct of a post-project review involving at least the core execution team is essential and could be viewed as a post-project success driver. In at least one major high-tech organisation (NASA) the costly failure to learn from past mistakes has been addressed through an Agency-wide 'lessons-learned' case study initiative (NASA, 2008).

CONCLUSION AND FUTURE RESEARCH

The failure of notable projects, whether they involve high-tech engineering, IT, or science endeavours, reinforces the patchy performance of mega-project management. Moreover, the project success statistics have not improved for decades despite the literature being profuse with project management theory, research and advice.

Drawing on case study work, research from the previous four decades, and contemporary experience, the present study augments the literature by presenting a contemporary evidence-based ranking of key success drivers, with particular application to large, high-tech projects.

Analysis shows that project management control and execution systems, and a clear project definition and goal set, are by far the most important drivers of project success. Mature information management systems rank third in importance, followed by 15 other significantly important factors shown to markedly improve project outcomes.

The limitations of the present research are acknowledged. More tightly defined success headings, and weighting of sample studies (e.g. complexity), would no doubt improve analysis rigour. Article length precludes a deeper (possibly numeric) exploration of how different success dimensions might sway the rankings.

The study findings imply further research to benchmark the performance of large engineering and science projects against the reported strategic drivers to further our knowledge of causal factors for project success. This could also drill deeper to compare success drivers in more specific areas e.g. IT projects. Further investigations of the impact of project manager traits are also recommended.

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APPENDIX A

Method and calculations supporting ranking of success drivers derived from the study.

The process of ranking success drivers uses the mathematics and calculation techniques developed by Saaty (Coyle, 2004) and are described within the generic Analytical Hierarchy Process (AHP). This is one approach to multi-criteria decision-making (MCDM) that can involve qualitative data. The method employs a reciprocal decision matrix obtained by pair-wise comparisons introduced by Fechner and developed by Thurstone (Alonso & Lamata, 2006). In the AHP, the input can be actual values, or scores from subjective opinion such as preference, judgement etc. and the approach has unique advantages when elements of the decision are difficult to quantity or compare. Decision situations to which the AHP can be usefully applied include choice, prioritisation, and ranking by importance (Teknomo, 2007).

Input data were drawn from examination of success factors from 29 general studies of project management encompassing 2,820 cases, as well as two success factor summaries drawn from cited papers within those general studies. These sources are listed in Table 1 of this paper, with numbers of individual case studies shown for both general and high-tech cases.

From each study, the listed or described success factors (derived from questionnaires, statistical analyses, or both) were grouped into common headings. This process resulted in the most common occurring findings being captured under 18 pragmatically themed success drivers which were given designators A through R. These were then tabulated by occurrence for all projects, and the sub-set high-tech projects, as shown in Table 3 below. (For convenience, they are sorted by occurrence frequency for 'all projects'.)

A pair-wise comparison process was then carried out for both 'all' and high-tech data by constructing a matrix for each with dimensions n=18, reflecting the number of success driver headings. Calculations for high-tech data are shown in Figure 1. For each of the 153 possible pair-wise success factor comparisons, a value was inserted in the matrix corresponding to the difference in the number of occurrences reported*. This value reflects either more or less support of one success driver over another. The lower triangle of each matrix was then populated with the reciprocal value.

Having completed the upper matrix, approximations of the Eigen vectors were then computed. This was achieved by dividing each element of the upper matrix by the sum of its own column, thus normalising the relative weights which are then correspondingly displayed in the lower matrix. The normalised Eigen vectors showing relative 'weights' are obtained by averaging across the rows. From this data, ranking is clearly indicated, as well as the relative importance of each success driver.

The consistency of the original data was then tested. $A\omega$ (the 18 element vector) is obtained by summing the products of each input value (by row) with its associated Eigen vector (by column). Since AHP theory says that $A\omega = \lambda max^{\omega}$, close approximations for λmax (the principal Eigen value) are derived by dividing each result by the corresponding Eigen vector value. The mean of these values gives an estimated λmax with which to calculate consistency as shown in Figure 1.

Saaty argues that a consistency ratio of >10% indicates unreliability (with a CR >90% close to randomness). In this study, the consistency ratios for 'all' data and high-tech data are 7.28% and 4.99% respectively, and are therefore consistent.

** Since a score of one (1) must equate to zero difference in occurrences, the entered value is actually the value + 1. This is not required to be an absolute value, merely a consistent scale.*

TABLE 3 – Success drivers tabled by occurrence within the study population literature

Success Driver	Designator	Occurrences -all projects	Occurrences-high-tech projects
Project management (PM) control & execution systems in place, with robust policies, planning, procedures, document control, audit, etc	*A*	*20*	*15*
Clear project definition, requirements, goals, objectives, scope, and project mission; sound business case	*B*	*20*	*14*
Mature project communication, information systems; effective public relations management	*C*	*15*	*11*
(Top) management (or sponsor) support with sustained commitment, appropriately engaged	*D*	*13*	*10*
Project baseline, estimates accuracy, project phasing, effective project performance (reviews) and measurement	*E*	*13*	*10*
Leadership skills, PM experience & stability; motivating & socially capable PM	*F*	*11*	*8*
Agreed realistic customer / user expectations; frequent customer contact	*G*	*9*	*6*
PM/Organisational understanding & competence in project management	*H*	*9*	*6*
Adequate resourcing of the project	*I*	*8*	*5*
Aligned perceptions of project goals & success - management and team; sense of urgency instilled	*J*	*8*	*5*
Effective stakeholder engagement / partnership (e.g. client, contractors, etc)	*K*	*8*	*5*
Organisational responsibilities assigned to right-sized capable team	*L*	*7*	*4*
Mature, effective project management change control process; effective deviations handling & configuration control	*M*	*7*	*4*
Understanding & continuous management of risk;	*N*	*5*	*3*

visibility of risk register			
Project Manager & PM systems matched to project complexity, and culturally aligned	*O*	*5*	*3*
Effective means of learning from experience and continuous improvement environment	*P*	*4*	*2*
Full understanding, and early engagement, of host government environment and institutional requirements	*Q*	*4*	*2*
Right-sized systems engineering; managing and procuring in right sized project 'chunks'	*R*	*3*	*2*

Figure 1– Pair-wise analysis for high-tech projects in the study

Designator	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
Occurances	15	14	11	10	10	8	6	6	5	5	5	4	4	3	3	2	2	2
A	1.00	2	5	6	6	8	10	10	11	11	11	12	12	13	13	14	14	14
B	0.50	1.00	4	5	5	7	9	9	10	10	10	11	11	12	12	13	13	13
C	0.20	0.25	1.00	2	2	4	6	6	7	7	7	8	8	9	9	10	10	10
D	0.17	0.20	0.50	1.00	1	3	5	5	6	6	6	7	7	8	8	9	9	9
E	0.17	0.20	0.50	1.00	1.00	3	5	5	6	6	6	7	7	8	8	9	9	9
F	0.13	0.14	0.25	0.33	0.33	1.00	3	3	4	4	4	5	5	6	6	7	7	7
G	0.10	0.11	0.17	0.20	0.20	0.33	1.00	1	2	2	2	3	3	4	4	5	5	5
H	0.10	0.11	0.17	0.20	0.20	0.33	1.00	1.00	2	2	2	3	3	4	4	5	5	5
I	0.09	0.10	0.14	0.17	0.17	0.25	0.50	0.50	1.00	1	1	2	2	3	3	4	4	4
J	0.09	0.10	0.14	0.17	0.17	0.25	0.50	0.50	1.00	1.00	1	2	2	3	3	4	4	4
K	0.09	0.10	0.14	0.17	0.17	0.25	0.50	0.50	1.00	1.00	1.00	2	2	3	3	4	4	4
L	0.08	0.09	0.13	0.14	0.14	0.20	0.33	0.33	0.50	0.50	0.50	1.00	1	2	2	3	3	3
M	0.08	0.09	0.13	0.14	0.14	0.20	0.33	0.33	0.50	0.50	0.50	1.00	1.00	2	2	3	3	3
N	0.08	0.08	0.11	0.13	0.13	0.17	0.25	0.25	0.33	0.33	0.33	0.50	0.50	1.00	1	2	2	2
O	0.08	0.08	0.11	0.13	0.13	0.17	0.25	0.25	0.33	0.33	0.33	0.50	0.50	1.00	1.00	2	2	2
P	0.07	0.08	0.10	0.11	0.11	0.14	0.20	0.20	0.25	0.25	0.25	0.33	0.33	0.50	0.50	1.00	1	1
Q	0.07	0.08	0.10	0.11	0.11	0.14	0.20	0.20	0.25	0.25	0.25	0.33	0.33	0.50	0.50	1.00	1.00	1
R	0.07	0.08	0.10	0.11	0.11	0.11	0.20	0.20	0.25	0.25	0.25	0.33	0.33	0.50	0.50	1.00	1.00	1.00
Sum	3.17	4.89	12.78	17.10	17.10	28.55	43.27	43.27	53.42	53.42	53.42	66.00	66.00	80.50	80.50	97.00	97.00	97.00

Pairwise Comparisons,
AHP method & calculations
Sources: Coyle 2004, Teknomo 2007

	A	B	C	D	E	F	G	H	I	J	K
A	0.31587	0.4086358	0.39111	0.3508283	0.3508283	0.2802413	0.2311248	0.2311248	0.2059282	0.2059282	0.2059282
B	0.157935	0.2043179	0.312888	0.292357	0.292357	0.2452112	0.2080123	0.2080123	0.1872075	0.1872075	0.1872075
C	0.063174	0.0510795	0.078222	0.1169428	0.1169428	0.1401207	0.1386749	0.1386749	0.1310452	0.1310452	0.1310452
D	0.052645	0.0408636	0.039111	0.0584714	0.0584714	0.1050905	0.1155624	0.1155624	0.1123245	0.1123245	0.1123245
E	0.052645	0.0408636	0.039111	0.0584714	0.0584714	0.1050905	0.1155624	0.1155624	0.1123245	0.1123245	0.1123245
F	0.0394838	0.0291883	0.0195555	0.0194905	0.0194905	0.0350302	0.0693374	0.0693374	0.074883	0.074883	0.074883
G	0.031587	0.022702	0.013037	0.0116943	0.0116943	0.0116767	0.0231125	0.0231125	0.0374415	0.0374415	0.0374415
H	0.031587	0.022702	0.013037	0.0116943	0.0116943	0.0116767	0.0231125	0.0231125	0.0374415	0.0374415	0.0374415
I	0.0287155	0.0204318	0.0111746	0.0097452	0.0097452	0.0087575	0.0115562	0.0115562	0.0187207	0.0187207	0.0187207
J	0.0287155	0.0204318	0.0111746	0.0097452	0.0097452	0.0087575	0.0115562	0.0115562	0.0187207	0.0187207	0.0187207
K	0.0287155	0.0204318	0.0111746	0.0097452	0.0097452	0.0087575	0.0115562	0.0115562	0.0187207	0.0187207	0.0187207
L	0.0263225	0.0185744	0.0097778	0.0083531	0.0083531	0.007006	0.0077042	0.0077042	0.0093604	0.0093604	0.0093604
M	0.0263225	0.0185744	0.0097778	0.0083531	0.0083531	0.007006	0.0077042	0.0077042	0.0093604	0.0093604	0.0093604
N	0.0242977	0.0170265	0.0086913	0.0073089	0.0073089	0.0058384	0.0057781	0.0057781	0.0062402	0.0062402	0.0062402
O	0.0242977	0.0170265	0.0086913	0.0073089	0.0073089	0.0058384	0.0057781	0.0057781	0.0062402	0.0062402	0.0062402
P	0.0225621	0.0157168	0.0078222	0.0064968	0.0064968	0.0050043	0.0046225	0.0046225	0.0046802	0.0046802	0.0046802
Q	0.0225621	0.0157168	0.0078222	0.0064968	0.0064968	0.0050043	0.0046225	0.0046225	0.0046802	0.0046802	0.0046802
R	0.0225621	0.0157168	0.0078222	0.0064968	0.0064968	0.0038922	0.0046225	0.0046225	0.0046802	0.0046802	0.0046802

	L	M	N	O	P	Q	R	Normalised Eigenvector	%	Aω	Approx λmax
A	0.1818182	0.1818182	0.1614907	0.1614907	0.1443299	0.1443299	0.1443299	0.238730867	**23.87**	5.19516856	21.76161221
B	0.1666667	0.1666667	0.1490683	0.1490683	0.1340206	0.1340206	0.1340206	0.195346941	**19.53**	4.314533994	22.0865193
C	0.1212121	0.1212121	0.1118012	0.1118012	0.1030928	0.1030928	0.1030928	0.111792904	**11.18**	2.398637954	21.45608406
D	0.1060606	0.1060606	0.0993789	0.0993789	0.0927835	0.0927835	0.0927835	0.08955448	**8.96**	1.870887172	20.89105057
E	0.1060606	0.1060606	0.0993789	0.0993789	0.0927835	0.0927835	0.0927835	0.08955448	**8.96**	1.870887172	20.89105057
F	0.0757576	0.0757576	0.0745342	0.0745342	0.0721649	0.0721649	0.0721649	0.057924489	**5.79**	1.152382518	19.89456498
G	0.0454545	0.0454545	0.0496894	0.0496894	0.0515464	0.0515464	0.0515464	0.033659326	**3.37**	0.634207486	18.84195422
H	0.0454545	0.0454545	0.0496894	0.0496894	0.0515464	0.0515464	0.0515464	0.033659326	**3.37**	0.634207486	18.84195422
I	0.030303	0.030303	0.0372671	0.0372671	0.0412371	0.0412371	0.0412371	0.02370534	**2.37**	0.432971097	18.26470758
J	0.030303	0.030303	0.0372671	0.0372671	0.0412371	0.0412371	0.0412371	0.02370534	**2.37**	0.432971097	18.26470758
K	0.030303	0.030303	0.0372671	0.0372671	0.0412371	0.0412371	0.0412371	0.02370534	**2.37**	0.432971097	18.26470758
L	0.0151515	0.0151515	0.0248447	0.0248447	0.0309278	0.0309278	0.0309278	0.016369565	**1.64**	0.294790673	18.00846083
M	0.0151515	0.0151515	0.0248447	0.0248447	0.0309278	0.0309278	0.0309278	0.016369565	**1.64**	0.294790673	18.00846083
N	0.0075758	0.0075758	0.0124224	0.0124224	0.0206186	0.0206186	0.0206186	0.01125559	**1.13**	0.205344418	18.24377168
O	0.0075758	0.0075758	0.0124224	0.0124224	0.0206186	0.0206186	0.0206186	0.01125559	**1.13**	0.205344418	18.24377168
P	0.0050505	0.0050505	0.0062112	0.0062112	0.0103093	0.0103093	0.0103093	0.007824212	**0.78**	0.148256329	18.94840362
Q	0.0050505	0.0050505	0.0062112	0.0062112	0.0103093	0.0103093	0.0103093	0.007824212	**0.78**	0.148256329	18.94840362
R	0.0050505	0.0050505	0.0062112	0.0062112	0.0103093	0.0103093	0.0103093	0.007762431	**0.78**	0.146417457	18.86232104
										Estimate λmax	**19.37347257**

Consistency Index = $\frac{(\lambda max-n)}{(n-1)}=$ 0.0807925

Random Consistency Index= 1.6181 (Source: Alonso & Lamata, 2006)
(for n=18)

Consistency Ratio (CI/RCI)= **0.0499305**
CR= 4.99% (Test for CR<10%=reliable)

APPENDIX B

Fieldwork Interviewees (principal contact)

- *AAD, Dr. Andrew Klekociuk, Leader -Antarctic LIDAR project. Discussion on science program management and logistics. Personal communications, Antarctica, December, 2004 and Australia, 16 January, 2009*
- *ALMA, Dr. Tony Beasley, ex-Project Manager ALMA radio-telescope project. Discussions on mega-project management and risk. Personal communications, Chile, 19-22 November, 2007*
- *ANSTO, Dr. Ross Miller, Project Manager OPAL nuclear reactor project. Discussion on approach to project governance. Personal communications, Australia, 8 Oct, 2009*
- *ASTRON, Dr. Marco de Vos, Head R&D ASTRON/LOFAR mega-array. Discussion on science project characteristics. Personal communications, The Netherlands, 23 July, 2009*
- *Australian SYNCHROTRON, Dr. Dean Morris, Head of Operations - Aust Synchrotron. Discussion on mega-project management. Personal communications, Australia, 4 March 2009*
- *CERN, Dr. Lyndon Evans, Project Manager - Large Hadron Collider. Discussion on characteristics of mega-projects. Personal communications, Switzerland, 23 July, 2009*
- *CSIRO-ATNF, Dr. Ron Ekers, ex-Director Aust. Telescope. Discussion on major project success factors. Personal communication, Australia, 12 March, 2008*
- *CSIRO-ATNF, Dr. Dave DeBoer, former Project Director - ASKAP telescope. Discussion on project management. Frequent personal communications during 2007-2009*
- *DESY, Dr. Wilhelm Bialowons, ILC Global Design Effort member - Deutsches Elektronen-Synchrotron (DESY). Discussions concerning science project structures. Personal communications, Germany, 19 July, 2009*
- *ITER, Mr. Peter Swinson, Head of Project Office -ITER Facility. Discussion on major project management. Personal communications, France, 20 July, 2009*

AUTHOR BIO

Phil Crosby* works at the SKA Program Development Office, UK. He was seconded from CSIRO's Astronomy and Space Science Division, Australia, where he manages strategic science planning, industry engagement, and the Project Review Board. Philip trained with ICL and BT, before operating his own medical and industrial electronics firm. Then followed 12 years with NATA in technical management standards; leading major field assessments including reviews of Antarctic science impacts, and ANSTO's operations. During 2005, Philip worked in Boeing Australia managing Industrial Participation. Apart from technical qualifications, he holds a BA (Business Administration), and is pursuing a PhD in mega-science project management.

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Characteristics and techniques of successful high-technology project managers

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Abstract: Despite a plethora of tools, technology and software, successful management of big science and engineering projects remains problematic, with many imperfect project outcomes. While much research focuses on management processes, characteristics of high-tech mega-project managers themselves are less well explored. What are the personal and professional attributes, skills and exemplar initiatives that are ingredients in project success? In this paper literature from the last 30 years is consulted alongside fieldwork results from several current, large, engineering and science projects in Europe and Australia. In particular, high-tech project manager success traits and initiatives are examined and discussed. Beyond personal traits - some obvious, some not - positive correlations of success are apparent around project and team management attributes, including the use of task forces, information management, a mission assurance mindset, and approaches to project complexity. The role of codified knowledge (the PMBOK® Guide) is examined, and suggestions offered for practical application of the study outcomes.

Keywords: project success, project management, mega-project, taskforce, project structure, collaborative, trust, urgency, mission assurance, complexity

Biographical Notes: Phil Crosby works at the SKA Program Development Office, UK. He was seconded from CSIRO's Astronomy and Space Science Division, Australia, where he manages strategic science planning, industry engagement, and the Project Review Board. Philip trained with ICL and BT, before operating his own medical and industrial electronics firm. Then followed 12 years with NATA in technical management standards; leading major field assessments including reviews of Antarctic science impacts, and ANSTO's operations. During 2005, Phil worked in Boeing Australia managing Industrial Participation. Apart from technical qualifications, he holds a BA (Business Administration), and is pursuing a PhD in mega-science project management.

1.0 Introduction

The management of big, high-technology (high-tech) projects has been repeatedly investigated but is not well understood (Cook-Davies, 2010), especially in terms of the personal characteristics and applied techniques of the project manager. This paper looks beyond the obvious skills and qualities of high-tech mega-project managers, and seeks to reveal the less obvious characteristics, traits, and initiatives that lead to project success. In short, what are the personal and professional attributes, skills and exemplar initiatives that are ingredients in project success?

In this paper, large high-tech mega-projects are defined as those involving research and development and/or application of technology, having a substantial infrastructure requirement and multi-million or even billion dollar budgets, and time-frames measured in at least years. The project manager is the person charged with ultimate delivery of the outcomes.

Post-WW2 years have seen a notable change in the mode of mega-project funding, approval, and leadership style. The first half of the 20th century saw ambitious undertakings in science and engineering usually championed by visionaries (Miller & Lessard, 2000) recognised for their personal knowledge, discoveries, and influence. The latter half of the 1900's saw increased complexity of machines and the project structures to build them. Such projects increasingly depended on formal organisation, plans, and budgets, and began to be more often identified with the host institute (e.g. NASA, CERN) than a single champion.

This development in management is epitomised by the case of the giant Mount Palomar telescope opened in 1949. Its undoubted driving force was George Hale whose style reflects the age of the 'Great Man' projects, as Florence (1994, p92) notes;

> *"a round of handshakes was enough to inaugurate the largest scientific project ever undertaken"*, and *"the committees met from time to time, but most of the decisions...emerged in notes and memoranda from Hale...[who] kept his fingers in every pie"*.

However Florence notes that even superb project champions have their limit (p91);

> *"Not even Hale at the peak of his abilities had the energy to manage this project alone. The two-hundred inch telescope was one of the first ventures into big science. No one had tried to research so many aspects of technology simultaneously, except perhaps [in wartime]."*

Systematic management of projects emerged in missile projects in the 1950s such as ATLAS and Polaris, and continued to proliferate into defence and civil works through the 1960s and 1970s. By 1990, project management was effectively professionalised and great science and engineering endeavours in the realm of physics research, computing, aerospace, and communications became established within modern organisational structures, along with their attending bureaucracies, 'stakeholders', and various forms of review committees.

Contemporary high-tech project managers are typically required to work in a number of dimensions including project leadership, research supervision, technical realisation (sometimes amid a daunting range of deliverables), financial accountability, planning and schedule responsibilities, project communications, and the challenging art of people management. For those whose forte is essentially project execution, the project formulative period especially can present bewildering problems requiring quite different skills and characteristics (Sykes, 1990). Adding to the challenge is the complexity and seemingly intractable nature of mega-projects. Even where authors have devised success 'roadmaps', the number of pathways and inter-relationships are daunting (Murphy et al. 1974; Grun, 2004).

The quest for a definitive set of managerial characteristics is a thoroughly researched topic with early reliance on *trait theory* (inherent personal qualities), and later recognising training potential as underpinning a situational or *contingency theory* of management. The 1980s popularized the *visionary* approach focusing on organisational change, followed by a move towards the soft leadership factors of the *emotional intelligence* school, and more recently the development of the *competence* school (Müller & Turner, 2010). Nonetheless, a discriminatory set of managerial qualities remains elusive (Gadeken, 1986).

This paper examines the characteristics of project managers that point to high-tech project success through examples drawn from the literature, and evidence from recent and current cases of large science-based projects. While recruitment processes are typically diligent when considering experience, background, and training of candidate project managers, this study identifies more subtle and deeper level characteristics of project managers that might be of practical use for improved selection of candidates for future projects.

2.0 Data & Research Method

The present study confines itself to data related to large high-tech projects, and published from the mid 1970s to the present. This period offers rich experience from peer reviewed research papers, relevant case studies, and articles from the professional management domain.

Many of the notable writers on the subject of project success consider the traits of the project manager, and the impacts these have on the overall success of the project (Baker et al, 1988; Cooke-Davies, 2000; Disterer, 2001; Gratton et al., 2007; Grün, 2004; Morris & Hough, 1986; Shenhar & Dvir, 2007; Smith & Winter, 2010). Several authors have looked specifically at the topic over a wide range of project types (Clarke, 1999; Erno-Kjolhede, 2000; Geoghegan & Dulewicz, 2008; Laufer & Hoffman, 2000; Müller & Turner, 2007; Verner & Evanco, 2005), again linking behaviour and competence to project success outcomes. Müller & Turner (2010) looked deeply into leadership competencies of successful project managers using a global questionnaire, while Keegan et al. (2004) examined transformational leadership.

The present research also canvassed the popular 'bodies of knowledge' (the PMBOK® Guide, the APM's Project Management BoK, and IPMA's Competency Baseline), as well as published accounts of specific big science and engineering projects (Florence, 1994; Robertson, 1992; Seamans & Ordway, 1977).

An important initiative from the literature was the UK research activity called Rethinking Project Management (Maylor, 2006) where a number of leading project management academics and senior practitioners from industry purposely set out to question mainstream ideas. Of particular note from this work was the need for increased recognition of human issues, the social nature of projects, and resulting challenges for management. Interestingly, the same topics received high visibility at the 2010 NASA Project Management Challenge, an event focusing on best practice in high-tech environments.

Despite the breadth of work around the topic, there remains a knowledge gap relating to specific characteristics of managers with high-tech project success. To help bridge the gap by the use of contemporary field data, the author conducted a series of investigations at several large scientific facilities in Europe and Australia (Appendix A, Exhibit 1). The chosen sites each satisfied the criteria of having substantial and specialised infrastructure, > US$100 million budget (except the Antarctic LIDAR), and a science goal concerned with astro, particle, or nuclear physics. Visits of 2-3 days were pre-planned to ensure access to key project management representatives. Formal interviews were conducted, each typically lasting 3-5 hours. Use of a question list ensured a systematic approach and consistency of topic coverage; however interviewees were free to amplify their responses as necessary. These meetings revealed, amongst other research outcomes, commonalities and application of traits and techniques with a focus on the effects of managerial approaches and behaviours.

The validation of published material through field casework is advanced by Flyvbjerg in his seminal paper 'Five Misunderstandings About Case Study Research'. When arguing in support of this phronetic approach (Flyvbjerg, 2006, p221) says;

> *"the case study produces the type of context-dependent knowledge that research on learning shows to be necessary to allow people to develop from rule-based beginners to virtuoso experts"*

Flyvbjerg explains the richness of information in the case narrative, and its ability to describe realities which are hard to reveal or define in scientific parlance (Flyvbjerg, 2001). This qualitative methodology is aligned with the 8ed Theory (GT) approach – the systematic generation of theory from data that contains both inductive and deductive thinking (Georgieva & Allen, 2008). The gathered data are coded and grouped into similar concepts in order to make them more workable. From these concepts, categories are formed, which are later developed into topic headings for ease of reference. GT studies are considered as qualitative since statistical methods are not used, and are often presented without figures.

In this study and in accordance with GT methodology, a variety of data sources are valid for inclusion, not just theoretical research and planned observations. Field notes made from formal and informal interviews, general observations from experience in the workplace, and expert group meetings all supplemented the research. The combined methodologies of literature research validated through fieldwork, though by its nature must be incomplete, enabled the extraction of several recurring topics, each presented as findings in sections 3.0 and 4.0, and summarised in section 6.0.

3.0 Project Manager characteristics leading to success

Processes to recruit, interview and appoint the necessary outstanding individual to manage a scientific and/or engineering project are generally adept at attracting candidates with the required qualifications, project management exposure, and general experience. This study posits that the successful management of high-tech mega-projects especially, as distinct from large projects (Sykes, 1990), is a particular and highly challenging task, requiring a special portfolio of attributes beyond those commonly identified at interview.

These attributes or traits are presented in this section as pre-cursors of high-tech project success.

3.1 The uncertain nature of mega-projects

A commonality between definitions of a project is that of a broadly definable task, and therefore necessarily a *temporary* endeavour. Mega-projects surviving the often precarious ‘approval for expenditure’ stage and lasting up to a decade or more may strike hurdles, or even get truncated, before reaching an operational phase. Those who run such projects have to know when to change course, when to proceed or pause, and above all, when to stop (Sykes, 1990). Thomas & Mengel (2008) suggest complex projects present ambivalence and ambiguity of the not-yet-known, with emerging situations that crucially shape meaning, interpretation, and social significance. When describing project shapers, Smith & Winter (2010) add to this the scanning of project boundaries for unwelcome ‘messengers’, and alert us to peripety; the arrival of events that reframe understanding of all that has gone before. Moreover, in developing the concept of *ProjectCraft*, Smith (2007) warns of social uncertainties in the form of unknown agendas, and emergent and divergent strategies. Fieldwork on this topic within the case studies (AAD, 2009; ITER, 2009; ALMA, 2007) confirm a fundamental attribute of the successful project manager – the ability to deal with uncertainty, and the personal career impacts, within an enterprise of undefined duration.

3.2 Authenticity

When asked about characteristics that underpin the respect and loyalty accorded to project managers, a common response across most project teams personally interviewed can be summarised as “authenticity’ (AAD, 2009; ITER, 2009; CERN, 2009; Samuel, 2009; Kendra & Taplin, 2004). Phrases such as “*he’s done this before and draws on that experience*”, “*a dogged, quiet achiever*”, and “*he leaves the flag-flying to others and just helps us get on with it*”, provide useful insight to attributes that are anecdotally linked to successful project execution.

In a Project Management 'complete reader', Graham and Englund conclude that; "*Any lapses by upper managers in the authenticity and integrity of their dealing…are likely to have a severe impact on the achievement of project goals.*" They go on to say; "*It is a recurring theme in our experience…that authenticity and integrity link the head and the heart, the words and the action; they separate belief from disbelief, and often make the difference between success and failure*" (Verzuh, 2003, p27-30). When discussing leadership, Thompson similarly identifies authenticity (the 'genuine article') among the three basic skills as predictors for success (Ashby & Miles, 2002).

The broad appreciation for the success associated with project managers who demonstrate authenticity and genuine talent should not be confused with, or offset by, charismatic charm, despite its reported benefits within transformational leadership. Morris and Hough's (1986, p219) seminal study of project success and failure notes that "*not all leaders are charismatic personalities...this in no way diminishes the significance of their leadership*". When considering charisma in his 5-year study of leadership, Collins (Ashby & Miles, 2002) found that truly successful managers tended to be modest, humble, and reserved, but enormously wilful personalities. Another author writes, "*You become a leader not primarily because of your natural charisma, but because others believe you to be a leader*" (Smith, 2007, p83).

Whilst a Major Projects Seminar (MPA, 2007) concluded that project manager domain knowledge increased the chances of success, the attribute of authenticity does not necessarily require deep knowledge of the project's science/engineering technologies and goals (Verner & Cerpa, 2005). Moreover, while technical ability does provide increased credibility in a high-tech environment, it should not be an overriding indicator of the effective project manager (Blanchard, 1990; Graham & Englund, 1997). In the case of Australia's nuclear research reactor, OPAL, the three project managers spanning the construction phase had no specific nuclear experience, but all were judged by team members as being competent technical project practitioners, and well matched to the task.

3.3 Collaborative approach

A feature of modern giant scientific and engineering programs is their global involvement. Whereas projects such as CERN's Large Hadron Collider (LHC), and the coming Square Kilometre Array (SKA), physically span country borders, almost all 'high tech' mega-projects are international collaborations regardless of their host location. To share know-how, risk and cost, resources may be pooled in the areas of research and development, project planning, and funding. However, as the preparatory SKA work has shown, this is not to say that there is always shared agreement of the goals of the collaborative partners.

The project manager, faced with the complexities of international collaborative working, requires a sound understanding of mechanisms for cross-cultural, multi-disciplinary groups – something only achieved by practical experience. The project manager is likely to be central to any high level strategic collaborations and competency is crucial for project success.

Collaborations with external parties also call for experience and skill. Goldratt (1997, p173) addresses this point in connection with project vendors saying; "*Persuading people to collaborate is always necessary. The time when you could dictate [to suppliers] is over. If you want people to think, to take initiative, you cannot dictate*".

In a contemporary UK study (Samuel, 2009), the practical coordination of collaborations in mega-science is described as particularly difficult, with limitations imposed by time zones and travel budgets, this having implications for who is seen as the overall leader, and who is accountable and responsible for successfully delivering the project. Project directorates need to be very sure that the Project Manager can meet this key challenge.

3.4 Balancing leadership with management

Critical observation against modern theory shows that managers do not always transform into good leaders, or vice versa. Management is largely about coping with complexity and good managers bring order and consistency through processes, plans and structure, and by monitoring results. In contrast, leadership is concerned with directing change and aligning people by communicating an inspirational vision, and then helping them overcome hurdles (Crosby, 2006). To achieve success, both roles obviously require some capability of the other.

Laufer and Hoffman (2000, p xxi) write, "*most project management writings stress the managerial aspects of projects, failing to recognise the significance of leadership*", and conclude that project managers have to assume *both* leadership and managerial roles.

Müller & Turner's (2010) research into leadership competencies by industry type revealed strong correlations between successful high-tech managers, and *critical thinking* (intellectual [IQ]); *team development* (managerial [MQ]); and *influence / motivation / conscientiousness* (Emotional [EQ]).

The supervisory demands of high-tech mega-projects, characterised by creative people operating in environments of minimal formal structure and reporting relationships resonates well with the 'transformational leadership' (TL) style. First introduced by Burns and added to by Bass (Hötzel, 2004), TL describes a leadership approach that transforms followers into leaders, inspires extraordinary performance, and exemplifies coaching, mentoring and intellectual stimulation. Whereas transactional management reflects a cost-benefit exchange (plan, negotiate, and reward), transformational leaders articulate an attractive vision (excite, inspire, and support). (Stewart, 2006; Keegan et al. 2004).

The effectiveness of TL within the project world was investigated by Keegan et al. (2004) who concluded that, while project managers are not dissimilar to line managers in terms of TL behaviour, the positive effects may be less pronounced in the temporary project environment. Early results point to a weakening of effect due to "*the multiple and temporary leader-follower relationships, shifting alliances, and overlapping social relationships* [seen in projects, meaning that] *project managers are unable to make the promises or exercise the same influence over career paths"* (Keegan et al. 2004, p615). However, the nature of complex, multi-disciplinary high-tech projects suggests that a TL approach should elicit increased performance levels and success, and further research may usefully examine new leadership theories and forms of organising project teams to fully realise these gains.

Whilst the literature is replete with examples of *leadership* qualities, there is little commentary concerning the characteristics of project *managers* relating to project success. Practical handbooks tend to skim over the topic, confining advice to the need for general management proficiency, adding characteristics such as knowledge of project management, performance accomplishment, and personal traits surrounding attitude, personality, team guidance, and driving project objectives while balancing constraints (PMBOK® Guide, 2008).

Case study interviews (CSIRO, 2008; CERN, 2009; ASTRON, 2009; ITER, 2009) offer richer data revealing commonality of views concerning project manager traits as a combination of transformational leadership and management skills including;

- Qualified, and experienced, in complex technical projects

- Knowledgeable and functional in the popular project management applications (e.g. PRIMA VERA, MS Project)
- Obsessively mindful of the critical path, and always driving forward
- Effective delegator, but not afraid to 'get hands dirty' when needed
- Ready and able to do 'what it takes' to remove roadblocks
- Sets the example in terms of ethics, behaviour, and standards
- Maintains an intellectually demanding environment
- Maintains a systems engineering view, but is not stuck at that level
- Knows what to communicate, to whom, and when.

3.4 Persuading and negotiating

Interviewees underlined that, high-tech projects are characterised by design challenges including technology changes e.g. ASKAP (CSIRO, 2009), contractual and construction delays and amendments e.g. OPAL (ANSTO, 2009), commissioning problems e.g. LHC (CERN, 2009), internal differences of opinion, and a host of external environmental challenges (Merrow, 1988; Eden et al. 2005). In the case of multinational science endeavours, it is not unusual for partner contributions to be 'in-kind' further complicating the authority hierarchy. More than one interviewee likened people management in high-tech projects to 'cat herding'.

A key skill then for the successful high-tech mega-project manager is the ability to foresee, mitigate, and manage these problems through skilled and sensitive persuasion and negotiation.

When reviewing large, dispersed collaborative projects Erno-Kjolhede (2000) explored what 'power' to manage exists in such circumstances. He concludes that whilst accountability, commitment, information management, influence and control, and personal powers are attainable, formal authority must give way to persuasion and negotiation flair. However he argues that in research (high-tech) projects, this is not necessarily a drawback. Mega-project managers will require the confidence that comes with experience and maturity to strategically influence outcomes, and understand the advantages of transformational management.

Project Management Institute (PMI) documentation describes several project execution scenarios where the project managers' negotiation skills must be adept (PMBOK® Guide, 2008). These are borne out by fieldwork cases and include the highly demanding task of managing stakeholder expectations in terms of likelihood of project acceptance, proactively anticipating concerns, and resolving identified issues. "*Managing expectations helps to increase the probability of project success by ensuring that the stakeholders understand the project benefits and risks*", (PMI PMBOK® Guide, 2008, p262).

Mega-project procurement, commonly assigned to a specialist department, will likely have some accountability to the project manager, especially when involving any major, strategic, or critical path acquisitions. Such activities draw on persuasion and negotiating skills as a key characteristic for successful contract execution and procurement logistics.

3.6 Trust, culture and diversity

Trust is a key ingredient (Sauer, 2008) in forming and maintaining collaborative social relationships, and several interviewees implied its importance unprompted. Samuel's research (2009, p28) draws on Politis, Chowdhury, and Ross when establishing that; *"trust is an important condition within any team since teamwork is dependent on knowledge sharing, and knowledge sharing is influenced by the degree of trust that exists between people"*. Samuel continues, "*It is difficult to build trust...and whilst this is true of any team, the challenges imposed by geographical and* *cultural dispersion becomes particularly important for managing global teams."*

The challenge to build trust within global multi-cultural projects necessarily tests the capability of the project manager in dimensions rarely discussed at the project outset. Kendra & Taplin (2004) address the subject of project success within different cultural frameworks and identify the need to recognise the differing values and the task of developing shared value sets to underpin the building of strong project management. Riordan (2001) echoes the argument for scientific and engineering cultures within mega-science projects; while Aronson et al. (2010) in their study of project sprit and success, suggest that the project manager has responsibility for demonstrating a set of values which nurture the unique culture of high-tech successful projects.

In discussing knowledge transfer barriers, Disterer (2001, p4) asserts that "*Trust results in common expectations of reliability, consistency, and plausibility. Trust reduces the fear that others will act opportunistically. Likewise…management must act as peers to give an example in knowledge sharing"*.

Perhaps when the stakes are highest, issues of trust and harmonisation of diversity become most valued, yet conversely most testing. Following the Apollo program, NASA commissioned a 'lessons for management' report to identify key success characteristics that arose from this most complex technical endeavour (Seamans & Ordway, 1977, p294). In relation to dealing with diversity, the report found,

> *"NASA was dealing…with all sorts of people from all kinds of disciplines. Many of them were not used to working together, much less in the exposed environment characteristic of the Apollo program, In addition to engineers, technicians, and construction workers, [we had] theoretical scientists, legislators from Congress, lawyers, businessmen – a whole gamut of individuals. NASA's goals, problems, failings, had to be explained to all, in a language they could understand. [We] had to encourage all to work in an open, time-constrained, team-oriented, and stressful environment that was new and puzzling to many."*

Again from the space engineering sector, Thomas Coughlin (Leader – NEAR asteroid orbiter project) ties trust to the successful delivery of a spacecraft within 27 months and US$4 million under budget. He explains the one-off launch window meant, *"I had to let all the people involved, including me, do their job, and only their job. This involved a lot of trust"*. (Laufer & Hoffman, 2000, p193).

Finally, Graham & Englund (1997), when identifying environments for successful projects, are clear on the need for unprecedented levels of trust and openness, and caution that managers may have difficulties when coming from a less trusting organisation. Certainly, team leader candidates at large European projects (CERN, 2009; ITER, 2009) are questioned closely regarding their skills in nurturing diverse, cohesive teams.

3.7 Personal profile

While contemporary recruitment practices in science and engineering are clear regarding non-discrimination by way of age, gender, or ethnic background (e.g. CSIRO, 2010), it is useful to look at what the literature and current experience says about profiles and delivery of project success. Müller & Turner's (2007) large empirical study of project managers and the influence of their profiles (e.g. age range, experience, gender, nationality) on success, point out many useful implications when matching project managers to roles.

First, in terms of the importance of project success factors, the study reported that more complex and challenging projects increases the awareness of success factors generally, and that project managers should not be assigned to projects below their management capabilities. Some nationalistic variation was detected, with European project managers rating success factors as averagely important, significantly lower than other parts of the world (although peaking in middle age). No differences appeared in performance based on gender.

Müller & Turner looked further at differences by nationality. They point to Wang and Huang's work showing that project success may be determined differently than in the mainstream project management literature. Contrary to an emphasis on time, cost, and quality, Chinese project managers emphasise relationships as the main criterion for overall success. Research cited on the Indian IT industry (by Agarwal and Rathod) identified functionality within scope as the foremost success criteria. Overall, project managers with greater experience emphasise the importance and influence of team satisfaction on success.

There are also differences in rating of success criteria, and performance against them by age, reflecting a growing of confidence with experience. Older project managers assign higher importance to teambuilding, and research in the military acquisition environment (Gadeken, 1995) strongly links competencies to experience. Müller and Turner (2007) found this well supported by Lee-Kelley & Leong, Loong, Prabhakar & Dolfi, and Andrews, all of whom found a significant correlation between project manager experience and project success.

Second, project managers that are capable and responsible for the wider project life cycle (not just planning, execution and close-out) tend to be more successful. Project managers should therefore be assigned at the earliest stages and ideally lead their project up to the commissioning stage (supported by Murphy et al. 1974).

Third, Müller and Turner (2007) found that project managers working in their own culture tend to be more successful than expatriates, implying improved outcomes from local site candidates, mentored (if needed) by a more senior manager who may come from abroad.

Gadeken (1986, p41) surveyed the profiles and career progression of 1300 engineers and scientists and found *"that manager-engineers exhibit the same preference for leadership roles that [other] managers do, but do not possess the same level of social poise nor enjoyment of human interaction"*. Gadeken's (p44) advice that *"engineers and scientists need more interpersonal development to improve both their selection opportunity and success"* remains a valid pointer for today's recruiters.

Finally, an intrinsic quality of the mega-project manager is the intellectual maturity and discipline to manage beyond *"the rational, objective, and universal representations of 'the project' with a phronetic analysis of the ambiguous, fragmented and political reality of project situations"* (Cicmil et al. 2006, p679). For high-tech IT projects, Souer & Reich (2008) couple these qualities with the need to exhibit emotional intelligence that reflects deep personal identification with project goals. The foregoing notions imply a 'super-manager' with vast experience, and delivering success in the face of great uncertainty, while expertly tackling the challenges of the wider economic, geo-political, diplomacy, and social aspects of the project (Blanchard, 1990). The present study found it is precisely this rare mix of intelligent gravitas, technical awareness, social proficiency, and political confidence that sets outstanding mega-project managers apart.

3.8 A sense of mission and urgency

Ultimately a key characteristic of mega-project managers is the enthusiasm and determination to keep driving the project forward, and to effectively communicate this 'sense of mission' throughout the team (Graham & Englund, 1997; ITER, 2009). Mega high-tech enterprises have voracious appetites for funds, even during quiescent periods, and maintaining progress on all possible fronts is crucial.

NASA manager, Jerry Madden (Laufer & Hoffman, 2000) argues that a critical characteristic for projects managers is the application of judgement to position stress levels between lethargy and team fatigue. This is perhaps most obvious when unplanned deviations occur. The skill to juggle resources, quickly re-plan, and restore the critical pathway requires a special, multi-dimensional intellect and the ability to maintain a balance between unproductive stress and pressure, and motivating urgency. George Morrow, NASA's Director of Flight Projects concurs with Madden, adding "*If we managed the early phase of projects with the same sense of urgency as systems integration and test, we'd be a lot more efficient in the overall life cycle*" (NASA, 2009).

From the literature, Grün concurs while tackling a different aspect in 'Taming Giant Projects' (Grün, 2004, p31). He argues that in order to achieve success, the project manager must be prepared to limit goals so as to counterbalance the tendency to expand the technical scope of mega-projects. Such forces are often hard to oppose in high-tech projects and "*therefore it is essential to have, or to create time pressure for the project.*" Specifically in the software project area, a sense of urgency was strongly linked to regular project checks, and listed third in Boettcher's work on IT project success factors (Attarzadeh & Ow, 2008).

When looking to create positive, and diminish negative, determinants of success, extensive research by Murphy et al. (1974) asserts that the project manager should develop commitment and a sense of participation and mission among project team members from the outset. Seamans & Ordway (1977 p275) recount from their Apollo project study that *'To marshall our resources and order our course is a task of the greatest delicacy which must be accomplished under the most relentless urgency'.*

Finally, fieldwork from the present study revealed a tangible sense of proprietorship at the ranks of senior management, and this was cited among many project teams as important in driving the project mission in terms of direction and maintaining pace. (CSIRO, 2009; CSIRO, 2008; CERN, 2009; ANSTO, 2009)

4.0 Managing Project Initiatives and Environment

4.1 Project Structures and Teams

The effectiveness of a project to achieve its goals is dependent on the shape and functionality of the project structure and operating environment (Graham & Englund, 1997). Miller and Lessard (2000) go further, arguing that institutional arrangements and strategic systems are greater determinants of success of large engineering projects than project engineering and management.

Management structures, and especially the relationship between management and stakeholders in large high-tech projects, commonly generate tensions for the project. As one recent European study (Katsanevas et al. 2009, p56) found;

> *"the existing successful projects demonstrate that a certain degree of structure and management is not only necessary, but can also support the success of the science project itself. The balancing between enough regulation or structure and too much has to be done in a way satisfying both the researchers and the funding agencies"*

Collaborations can also present demands on project structures, especially in the case of equal partners. The 50:50 division of the ALMA radio telescope project between European and American partners (ESO and NRAO respectively), each having a project manager operating under a joint Board, naturally slows down and complicates any decision making. (ALMA, 2007).

The Australian OPAL nuclear project commenced without a formal project manager, favouring instead a Management Board drawn from other parts of the ANSTO organisation (ANSTO, 2009). However this was soon found ineffective and a 'traditional' project manager role was then established, successfully taking the project through to completion.

Experience from the successful Auger project, operated under the auspices of Fermilab, show that even in loose structures, some rules are needed, and responsibilities need to be clear.

A noted feature of Auger's success was the project manager's proclination to frequently visit the many partners, facilitate exchange of information, and address problems promptly and visibly (Katsanevas et al. 2009)

The ability to effectively manage team-based structures applies equally in the commercial environment. In a report on the success of the 343MW Huntstown CCGT power station in Ireland (Garnett & Hatfield, undated, p5) the authors concluded *"Open teamwork [between contractors and staff] proved to be a definite benefit to the project. With the complexity of construction, there will be no shortage of [failures and mistakes] to overcome without having an institutional adversarial blood stream running through the project"*.

Interestingly, Samuel's study (2009) concurred with this study's fieldwork, and commentary from the Auger project, that in mega-science teams and particularly academic circles, the need for team building activities was considered to be inappropriate and largely unnecessary, as association with a project having a grand science ambition is sufficient basis for a robust common passion.

In the high-tech area smaller teams may work more effectively as Moody & Dodgson (2006) argue in their study of a complex aerospace project. They describe a single small, committed team with overlapping and complementary skills, made up of a proportionately large number of systems engineers with specialist knowledge across blurred project phases. This flexibility of implementation phases - which they suggest can only be done with a small team that can be across everything – is presented as a key to success.

A study by Gratton et al. (2007) of 55 collaborative teams isolated eight HR practices leading to project success, highlighting the benefits of capitalising on the trust residing in skilfully managed 'heritage' teams. Their research indicates that when 20-40% of the team members have past associations, strong collaboration was evident at the start. The success rate of 'heritage' teams points to an interesting area of future research.

The present study found that setting up a standard project management structure within the organisation should not absolve the project manager and/or Directorate from reviewing its effectiveness, and instigating change where necessary. Germany's XFEL x-ray laser project commenced under a thorough, well documented governance structure, yet was later compelled to recommend a taskforce review to deal with the orthogonal nature of external entities (DESY, 2009). Projects managers need to be ready to embrace such change.

In summary, when selecting potential managers for scientific and engineering projects, Directorates should not overlook the matching of characteristics to the operating environment and structure. A manager may appear to have failed at one assignment, yet could perform well at another with different organisational and team conditions. Organisational structure, control, systems, and processes are not on their own sufficient for successful innovation, and there is overwhelming evidence that the right individual is a necessary condition for project success (Rubenstein, 1976)

4.2 Task Forces

Despite considerable planning, risk assessment and capable management, it would be most unusual for a major scientific and engineering project to proceed to conclusion without a significant problem appearing. Occasionally a 'wicked problem' may emerge that defeats normal problem-solving approaches (Partridge, 1981). One study found that, on average, projects met five unexpected events during execution, and some had twelve (Miller & Lessard, 2000). The handling of problems that threaten the critical path is a key test of capability for the project manager, and any recruitment process should carefully review the candidate's approach, experience and performance in relation to major problem solving.

The recognition of the need for immediate assistance, convening of specialist personnel (physically or virtually), managing the process to solve the issue, and transferring the outcomes to the project team(s) are all vital functions, requiring leadership, mature judgement and coordination skills of project managers. Each of the case studies for this paper employed the task force (or' Tiger Team') concept, an ad-hoc group operating heuristically to deal with a crisis, critical deviation or roadblock (Pavlak, 2004).

To further explore this aspect, the author surveyed experienced leaders of large scientific and engineering projects (Appendix A, Exhibit 2) to better understand the operative nature of task forces, and the challenges they pose for high-tech project managers. The conclusions of the research focus group were gathered under three aspects:

Membership & Support

The ideal team size is between six and ten members. Other than support staff, all members must be professional scientists/engineers offering a fair representation of skill and opinion. As in other project groups, it helps if members know each other and can bond quickly. A mixed gender membership from the same or close generation is suggested. An expense budget should be set, and if secretarial support is required, this function should be managed only by the leader.

Authority & Scope

The task force must be given a clear mandate in the form of a task statement and deadline. The problem to solve must be clearly scoped, and any terms of reference should be brief and non-restrictive, other than having task depth and boundaries defined. Often, the task force itself will not be given authority to make actual decisions, however any authority awarded must match the responsibility/accountability required.

Success factors for task forces

- Task forces operate best when tackling (a) emergent program level challenges to enable an effective technical way forward, and (b) addressing deficient organizational practices to improve the program.
- There is a will amongst stakeholders for a situation to be un-stalled, or solved.
- A deadline or other imperative exists.
- The task force members are able to "roll their sleeves up", leave their egos at the door, and become totally objective. "A 'burn' on the problem by a small group can often break the impasse."
- The group is co-located, appropriately isolated, and really taken 'offline'. The group is given management and organisational support, and is relieved of other duties and distractions.
- Frequent meetings and reports to the project manager or sponsor are used to keep on track.
- The format of the outcome is defined, and the 'end conditions' built-in so that closure is effective.
- The results must be capable of being actioned/implemented.
- The taskforce leader must have technical expertise and a systems perspective, be experienced in the domain, and have the ability to synthesise the outcomes. The team leader needs to be smart, objective, build confidence and trust, and be a respected 'dictator'.

The survey indicated that task forces were effective in quickly tackling 'showstopper' events, bringing focus to wide-ranging discussions (e.g. technology options), simplifying complex problems, and are useful to reset the existing pathway to an outcome. As such, the timely assembly and deployment of a task force in response to project stress offers a useful interview topic for candidate managers.

4.3 Project information management

It is one thing to create or shape a project structure, and another to make this effective through communications and information management. high-tech projects have an inherent need to convey large amounts of complicated information across a range of domains and levels both inside and outside the organisation.

Fieldwork for this study revealed two important areas beyond functional document control processes that draw on the characteristics of the project manager – that of managing information exchange (the delivery dimension), and managing information dissemination (the content dimension).

Technical data, designs, system descriptions, and other evolving documents normally require iterations within and outside the project and need careful consideration by management in terms of their distribution, especially among collaborative groups. The project manager must display firmness in approving circulation lists and meeting participants, yet be ready to modify according to circumstances. Case interviews verified that the project manager is unable to be involved in every information exchange; therefore clear protocols must be implemented that reflect the project needs and management style, as well as the expectations of stakeholders (CSIRO, 2008; ANSTO, 2009; SYNCHROTRON, 2009). Moreover, science and engineering projects tend to generate valuable intellectual property (IP), and project management must establish and demonstrate standards in compliance with IP policies.

Managers also declare their character through the quantity, quality, and detail of the information they disseminate, and to whom. This especially applies to reports, meeting outcomes, and funding matters where the attributes of judgement and discretion must be keenest. Case study interviewees agreed that project managers releasing information through messages to sub-groups and teams (especially from headquarters to sites); need to strike an appropriate tone of leadership rather than officialdom. Trust issues were evident here also, and the experienced project manager is expected to display care concerning delicate and confidential matters.

In a study using success factors to improve project management, Clarke (1999) identified communication throughout the project as critical, in particular its influence on the acceptance of change. Her research strongly links effective communication with interpersonal skills.

Lastly, Clarke (1999) emphasises the importance of communicating within the final stages in a project as opportunities to convey achievement and project learning. She also proposes that one of the best ways to motivate people and make them more confident of what can be achieved is through more effective communication. A practical example is NASA's annual Project Management Challenge that includes a formal awards ceremony where group and individual achievement is recognised through motivating project story information.

4.5 Mission Assurance

A particular characteristic of project managers drawn from fieldwork combines leadership with the traits of being 'resolute' and 'fastidious', and is displayed as an unwavering sense of purpose in making mission success the highest priority at all levels of the project.

This single-minded (though not tunnel-vision) approach becomes very apparent during deeper investigations of project system management, where integration of technical domains often reveals both technical and philosophical inconsistencies at the interfaces. The resolution of these tensions can easily lead to outcomes that can potentially compromise the sustainability of the project, and it is imperative that the project manager applies fortitude and leadership to maintain project focus, and as highlighted in the fieldwork, is supported by the Project Directorate in doing so (ITER, 2009; CERN, 2009; CSIRO, 2009).

The adoption of a mission assurance approach is captured most compellingly within NASA reports. Following a review of NASA's 'Faster, Better, Cheaper' (FBC) approach to space missions in light of a growing failure rate (Spear, 2000), certain flaws began to emerge concerning cost cap challenges, taking shortcuts under pressure, and risk conflicts for project managers However the recommendations largely missed the root cause. Meanwhile NASA's Mars Climate Orbiter Mishap Investigation Board (MIB) independently concluded that *"[FBC] has failed to instil sufficient rigor in risk management throughout the mission cycle"* (NASA 2000, p6), and recommended the implementation of a new paradigm, termed Mission Success First. The MIB went further to describe how the Mission Assurance function should operate within projects, its rigorous oversight of testing and verification, and most importantly, interfacing with project management in driving mission success criteria.

In NASA's model (NASA, 2000), mission assurance requires that institutional line management become more engaged in the execution of the project, and be held accountable for mission success. This means project managers asking the right questions at meetings and reviews, getting the right people to those reviews to fearlessly uncover mission critical issues early in the program, and pursuing their resolution. Given the obvious tensions arising between mission assurance and project deliverables, these are clearly key responsibilities requiring valiant project management.

The legacy of past methodologies applied to high-tech/long lifetime projects can remain to challenge contemporary project managers, as in the case of FBC and the Space Shuttle navigation units (Goodman, 2002), and NASA's Genesis spacecraft program (NASA, 2005). Project managers joining existing science and engineering enterprises need to be capable and ready to build latent risk into their mission assurance programs.

4.6 Project Complexity

Scientific and engineering mega-projects are typically characterised by multiple components, multiple functions, and requiring the involvement of multiple organisations (Milosevic & Patanakul, 2005; Grün, 2004). They are information rich (Thomas, 1997), and cannot be designed or communicated by a single expert (Moody & Dodgson, 2006). The management of complicated (intricate, of many parts), and complex (interwoven, interdependent), projects demands exceptional skills, described succinctly by Shenhar & Devir (2007, p115);

> *"Managing successful [complex] projects is a serious challenge. Not only must project leaders cope with poor communication among managers, designers, and customers, but also they are strongly dependent on a complex web of external suppliers, complicated procurement systems, and lengthy, detailed contracts … and other collaborators."*

Cavanagh (2009, p4) captures both the range and essence of what complex project management demands of the project manager as;

> *"vision and motivation; empathy; attention to relationship building, in order that trust may be mutually awarded and maintained through difficult periods; the ability to take a holistic view; consummate communications skills; practical application of experientially-derived wisdom; and perhaps most of all, courage – the courage to be able to speak the truth (and hear it!), and to take good risk".*

In dealing with project performance in large engineering projects, Miller & Lessard (2000, p19) note that, *"Their technical difficulties do not condemn them to failure; far more troublesome, however, are the difficulties arising from their complexity, irreversibility, and dynamic instability."* Such complexity and dynamism leads to unpredictability with new risks emerging correspondingly with project length.

Commenting on the success of the Gemini telescope project, Dick Kurz tells how the job of building such a complex scientific instrument required a new kind of partnership, incorporating multiple countries and expert project management. "*[It was recognized] that a project of this magnitude takes…professional management and professional system engineering to really carry it off*" (Michaud, 2009, p34)

In a recurring theme in this study, mega-project complexity is not restricted to technical design, interfacing, and execution; it extends to structural, social, and exogenous factors that will severely test the less experienced manager. Schein and Kanter highlight the interplay between individuals, teams, and management that can work positively and negatively in a context of personal ambitions, confluences and conflicts, and project goals (Levine, 2002).

Cooke-Davies and Teague (2009, p7) elegantly summarise the aptitude required of project managers when they write;

> "*delivering a complex project is not so much…knowing what to do and designing a system and processes to do it, as a matter of skillfully navigating the tides, storms, and cross-currents of human beings, with all their desires, motivations, quirks, and behaviours, while constructively engaging with them to achieve desirable outcomes*"

5.0 Practice Guides and Success Attributes

Since the 1970s, project management institutions have formed around the world, offering their membership the benefits (inter alia) of shared information and professional certification, based on published 'Bodies of Knowledge' (BoKs) largely developed through practice rather than research. The attractiveness of formal recognition is indicated by Project Management Institute (PMI) data showing that in 2006 almost 86% of its 210,000 members were certified as Project Management Professionals (PMP). (Morris et al. 2006). Other BoKs are offered by the UK's Association of Project Management (APM), the International Project Management Association (IPMA) whose Competency Baseline is an amalgam of European BoKs, and the Engineering Advancement Association of Japan (ENAA).

The role and effectiveness of the BoKs was deeply researched by the UK Rethinking Project Management group in 2006, who found that while clearly useful, there are flaws in their development. Project front-end management in particular, with its human, structural, and external issues so influential on project outcome, is cited as being especially deficient in BoKs (Morris et al. 2006). This general view is echoed in a recent Position Paper from the International Centre for Complex Project Management which stated;

> *"we have a bagful of well-developed methods and tools, and a reasonably comprehensive project management body of knowledge. Ironically, these things…aren't enough, and relying on them alone won't work"* (Cavanagh 2009 p2).

Nevertheless, while project management certification against the BoKs principles alone does not guarantee good project management execution, a track record of well run projects plus certification is a very strong indicator of a high performing project manager (Müller & Turner, 2007).

The PMI is strongest in terms of spread and influence, and their guide (PMBOK® Guide, 2008) is the most widely recognised and accepted Book of Knowledge (Crawford, 2000), being promoted as a foundation reference in the area of "knowledge, processes, skills, tools, and techniques that can have a significant impact on project success." Although not purporting to go beyond the status of practice handbook, it is useful to review the PMBOK in terms of alignment with the ideas presented in this study, and test for any epistemic value supporting the practical application of the research outcomes; refer to Table 1.

Table 1 – Showing alignment between the concepts in this study, and the PMBOK® Guide

Characteristic/Attribute/Skill	**PMBOK® Guide 2008**	**Alignment**
Authenticity	Generally implied only in sections 1.6, 2, 4.3, and 9.3	Weak
Collaborative Approach	Touched on in Section 9 and Appendix G	Weak
Leadership and Management Capability	References in sections 1.6, 2, 9, with 'soft skills' addressed in Appendix G	Moderate
Persuasion and Negotiation	Referenced in sections 9, 10, 12 and Appendix G	Strong
Trust and Diversity	References in section 9 and Appendix G	Moderate
Personal Profile	Not addressed	Weak
Sense of mission and urgency	Urgency only addressed in terms of risk in section 11	Moderate
Project structures	Referenced in section 2, 4, and 9	Strong
Task Forces	Implied references in sections 5, and 10	Weak
Information Management	Referenced throughout	Strong
Mission Assurance	Implied in section 8, 11 in terms of quality and risk only	Weak
Project Complexity	Scattered mentions in various sections	Weak

The conclusions indicate, perhaps unsurprisingly, that the PMBOK® is intended much more as a practicing project manager's handbook than a project personnel assessment or development tool. Whilst 'good practice' is captured in terms of knowledge, processes, tools, and techniques, the publication is less informative concerning the more subtle (e.g. interpersonal) characteristics required of project managers that can significantly impact on project success, and currently falls short of being strategically useful in this regard. Nevertheless, the latest (4th) update begins to address some of the characteristics dealt with in this paper, largely listing these in a new appendix (PMBOK® Guide, Appendix G – Interpersonal Skills). This is suggestive of recent acknowledgement of the importance of these types of factors and offers potential for future expansion.

6.0 Summary and Conclusions

This paper set out to look beyond the 'standard' set of skills and qualities attributable to managers of high-tech mega-projects, and sought to add new knowledge by exploring the less obvious key characteristics of project managers that lead to project success.

Data were sourced from the published literature spanning the last 30 years, together with extensive fieldwork from nine mega-science facilities, and the personal experiences of a selected group in relation to task forces. The data were examined using a grounded theory approach, gathering supporting arguments, and drawing compelling and practical inferences.

The limitations of the methodology are acknowledged, and adding a temporal dimension with numerical analysis to show management trends would likely yield further conclusions. The study also reveals an incomplete understanding of the application of transformational management in high-tech projects, and the relationship between charisma and success, and further research is warranted.

Whilst a definitive set of personal qualities is idealistic, the research shows that eight personal characteristics, traits, or skills are strongly indicated as subtle, though significant, factors in driving success within scientific and engineering mega-projects. These are:

- The ability to deal with the temporary and uncertain nature of mega-projects;
- Having and demonstrating personal authenticity;
- Applying skill in the management of collaborations;
- Having an appropriate balance of management and leadership talent;
- Motivating strategic influence through persuasion, encouragement, and negotiation;
- Building trust in a diverse cultural environment;
- Having a personal profile well matched to the project; and
- Driving a clear sense of project urgency.

These factors are interrelated and careful consideration is required in the selection of someone with the right mix of traits (Nicholas, 2004). A further five factors were shown to be positively related to project success in the context of creating, managing successful project structures. These are:

- Establishment of an appropriate project and team structure;
- Deployment of effective project task forces;
- Effective information management;
- Application of a mission assurance approach; and
- Competent management of complexity.

The success drivers described could usefully supplement the discussion agenda at the project manager interview stage by exploring the candidate's approach and experience in these subtle, yet vital, pre-cursors of mega-project success.

Acknowledgments

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Appendix

EXHIBIT 1: Fieldwork Studies (Principal contact identified only)

- *AAD, Dr. Andrew Klekociuk, Antarctic LIDAR project. Discussion on science program management and logistics. Personal Communications, Antarctica, December, 2004 and Australia, 16 January, 2009)*
- *ALMA, Dr. Tony Beasley, ex-Project Manager ALMA radio-telescope project. Discussions on mega-project management and risk. Personal communications, Chile, 19-22 November, 2007)*
- *ANSTO, Dr. Ross Miller, Project Manager OPAL nuclear reactor project. Discussion on approach to project governance. Personal communications, Australia, 8 Oct, 2009)*
- *ASTRON, Dr. Marco de Vos, Director Research & Development, Netherlands Institute for Radio Astronomy. Discussion on mega-project management. Personal Communications, The Netherlands, 18 July 2009*
- *Australian SYNCHROTRON, Dr. Dean Morris, Head of Operations - Aust Synchrotron. Discussion on mega-project management. Personal communications, Australia, 4 March 2009*
- *CERN, Dr. Lyndon Evans, Project Manager - Large Hadron Collider. Discussion on characteristics of mega-projects. Personal communications, Switzerland, 23 July, 2009)*
- *CSIRO-ATNF, Dr. Ron Ekers, ex-Director Aust. Telescope, Discussion on major project success factors. Personal communication, Australia, 12 March, 2008)*
- *CSIRO-ATNF, Dr. Dave DeBoer, Project Director - ASKAP telescope. Discussion on project management. Frequent personal communications during 2007-2009)*
- *DESY, Mr. Wilhelm Bialowons, ILC Global Design Effort member - Deutsches Elektronen-Synchrotron (DESY). Discussions concerning science project structures, Personal communications, Germany, 19 July, 2009)*
- *ITER, Mr. Peter Swinson, Head of Project Office -ITER Facility, Discussion on major project management. Personal communications, France, 20 July, 2009)*

EXHIBIT 2: Research Focus Group on task forces

- *Mr R. Sharp - Senior Director - Strategy and Technology, NXP Semiconductors (formerly Philips Semiconductors), Southampton, UK (retired)*
- *Mr B. Biddington – Space Team Leader, ASIAPAC, Cisco Systems Inc*
- *Prof. R. Schilizzi – Director, Square Kilometre Array Program Development Office, UK*
- *Dr. A. Paull - Research Leader, Applied Hypersonics, Air Vehicles Division, DSTO, Australia*
- *Dr. J. Bradfield-Moody - Executive Director, Development, CSIRO, Australia*
- *Prof. P. Hall - Director, Engineering and Industry Collaboration, Curtin Institute of Radio Astronomy, and ICRAR Deputy Director, Engineering and Technology*
- *Mr Charles O. Adler – Senior Systems Engineer, The Boeing Company, USA.*
- *Ms Dawn Schaible – Manager, Systems Engineering Office, NASA Engineering & Safety Centre (comments reported in ASK Journal, NASA, Fall 2009).*

Memo 129

Procurement strategies enabling success in high-technology mega-projects: Preparatory work for the SKA

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Procurement strategies enabling success in high-technology mega-projects: Preparatory work for the SKA

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Abstract

The procurement of goods and services for projects is traditionally seen as a largely administrative or operational task rather than having strategic importance. Modern high-technology mega-projects are dependent on mutual and enduring industry collaborations and demand a strategic management approach. Effective procurement for giant science/engineering projects has thus become a necessary prerequisite to overall project success. This paper presents a review of the literature and contemporary cases related to high-tech mega-project procurement, and references various legislative and operational environments. Nine acquisition strategies are presented as newly distilled planning topics that are important to procurement success. The study proposes that by addressing these key strategies, large scale 'high-tech' projects can improve the effectiveness of the procurement processes, and enable a more productive and open relationship with suppliers.

Keywords: project success, procurement, mega-project, supplier evaluation, contractor, risk

Contents

1. Introduction

The procurement of goods and services for projects was traditionally seen as largely administrative or operational rather than having strategic importance (Virolainen, 1998; Schill, 1979). However project complexity is driving a more strategic approach (Jaakkola, 2004), and recognition of forces other than purely transactional, show a maturing approach to the contracting problem (Winch & Gil, 2010). Within the world of science and engineering mega-projects, the breadth and pace of technology advance, and demands for cost control, bring new importance to professional management of procurement including technology identification and access, supply channels, and industrial relationships (Schill, 1979).

This paper presents a study of large scale procurement practices relating to big science and engineering projects, and is particularly relevant to the Square Kilometre Array project (see Appendix A) – a €1.5 million global enterprise to design and construct the largest radio telescope yet built, and to be located either in Australasia or Southern Africa (SKA 2010). This paper aims to distil key acquisition strategies relevant to success in high-technology (high-tech) mega-projects.

'Mega' or 'giant' projects are defined as those endeavours typically having multi-million or even billion dollar budgets; time-frames measured in years, and attracting a high level of public or political attention. High-tech projects are inherently complex, and involve research and development (R&D) and/or novel application of science/engineering technologies, and require substantial infrastructure. The term 'procurement' is used in its wider sense to cover the process ranging from establishing the requirements, global sourcing, placing of the contract, overseeing execution, and in some cases dealing with through-life support (Hall & Khan, 2006).

Modern procurement management in the high-tech environment is more reliant on buyer-seller partnerships than a traditional adversarial approach. These relationships tend to be longer term, ongoing, and risk-sharing, and strive for win-win outcomes at lower cost (Virolainen, 1998). Within procurement, the key task of contract management itself can be broadly grouped into three areas: service delivery management, relationship management, and contract administration. *"All three areas must be managed successfully if the arrangement is to be a success [and] good preparation and the right contract are essential foundations for good contract management"* (OGC, 2002, p5). Contract execution, administration and specific documentation are of course vital to procurement outcomes, though beyond the scope of this study. Suffice to say that the *"light legal touch"* suggested by Hall & Khan (2006, p22) is consistent with the general thesis of key, yet simple principles offered in this paper.

2. Scope, data sources and study method.

This study addresses the institutional (publicly funded) procurement environment, contracting models, procurement specifications and terms, contracting instruments and value, tender evaluations, supplier relations, planning, and risk. To extract best practice and subject wisdom, input is drawn from published research papers, generic project management texts, and articles from the popular literature. Complementary and supportive experience is taken from recent and current international 'high-tech' projects so as to offer relevant learnings for the SKA.

The collected findings are presented within nine topic headings in section 5.0. For each topic, a 'key strategy' is presented as both a success driver, and as a suggested topic heading within the structure of any 'high-tech' mega-project procurement plan.

3. The extant literature

Although there is a great deal of written material concerning general purchasing strategy and approaches there is little that focuses on procurement for high-tech mega-projects *per se*. Much of the literature resides in management texts and guides, and is centred on the transaction. Several authors (Jaakkola, 2004; Morris & Hough, 1986; Blanchard, 1990) offer solid advice regarding strategic contract policy and procurement management, linking contract management success to project and business performance. Winch and Gil (2010) go further by considering theories for complex project contracting strategies and present approaches to deal with the dual problems of contractor selection, and motivation. Tender evaluation criteria and contractor selection is an area deeply researched by Watt et al. (2010), and Zeydan et al. (2010) who offer a mathematical model. Supplier selection is described in detailed practical terms by Blanchard (1990). Both the UK National Audit Office (NAO), and the Office of Government Commerce (OGC) publish a range of business guides including the NAO's Improving Procurement manual (2004), and OCG's Contract Management Guidelines (2002), both containing much practical advice.

More specifically, contract design and execution in the engineering field is tackled by Nicholas (2004). The published proceedings of the UK's Major Projects Association offer relevant case material. Virolainen (1998) undertake a theoretical study of procurement strategy for industrial firms, emphasising the importance of the buyer-supplier relationship over a mix of approaches. Schill's (1979) examination of the topic in advanced technology organisations acknowledges the growing strategic and entrepreneurial importance of high-tech procurement. Carnegie Mellon's Software Engineering Institute issues the CMMI for Acquisition Technical Report (2007) – a collection of best-practices for high-tech acquisition.

Finally, this paper is generally informed by institutional and project based material e.g. CERN's research into technological learning through project procurement (Autio et al., 2003), SKA Memo 80 on industry liaison (SKA, 2006), and the NEON organisation Project Acquisition Plan (Ashley, 2009).

4. Framing procurement as a precursor to project success

Acknowledging the strategic nature of procurement means giving proper and early attention at the project preparatory stage to policies, processes, and resources. Jaakkola (2004) points out that the process of establishing contract management in an organisation can take years, and should be viewed as an on-going process designed to generate cost savings. By documenting the process, the steps and interactions may be clarified. A proposed process flow for the SKA is shown in Appendix B.

In considering modern procurement challenges, A Major Projects Association seminar concluded that the following questions can help organisations decide on a procurement approach through better understanding of the determining factors (adapted from MPA, 2009);

- What is vital for success?
- What is the funding [and how secure is it]?
- What are the possible risks to success, and what risk must be managed by the organisation?
- How will those risks change, or how can they be mitigated over time?
- What experience requirements are needed for other parties to manage risk, and what reward/commitment incentives can be put in place?

The legislative environment

'High-tech' mega-project procurement will almost certainly be a global endeavour, and aside from the giant aerospace/defence contractors, is likely to occur in the institutional (or public) domain.

Public funding for such science / engineering projects or programs requires that procurement complies with regulations e.g. the European Procurement Directives, the World Trade Organisation rules, and national legislation (Hall & Kahn, 2006). In the USA, public purchasing is enshrined within FAR Part 12 (NASA, 2009a). A full description of the various global trade environments is beyond the scope of this paper, suffice to say that the technicalities, procedures (especially related to maintaining open competition) demand expert attention.

The self-contained treaty organisations adopt strict procurement rules. In CERN's case the FIDIC Conditions of Contract are embraced, incorporating an industrial return coefficient for member states. The legislative impact, including its taxation status which impacts directly on procurement instruments, will depend upon the legal identity of the project.

The legal structure for the SKA has yet to be decided and will require expert advice to review options for appropriateness. However useful experience comes from contemporary examples. Treaty organisations (e.g. CERN, ESO) are generally satisfactory entities although bureaucratic and take a long time to establish. The ITER treaty model with a supervisory Council appears less effective. Similarly, the European Research Infrastructure Consortium (ERIC) entity takes a long time-to incorporate (at least nine months), and being a relatively new construction, has some uncertainties and likely difficulties for an SKA (Chance, 2010).

Formalised collaborations under an MoU (e.g. AUGER, HESS) are simpler and succeed in an environment of goodwill. Commercial-like structures such as LOFAR (formed as a special limited partnership under Dutch law) and XFEL (established as a German limited liability Company) enable a legal trading entity to be quickly created. Research by ASPERA concluded that 'high-tech' collaborations are complicated and lengthy to realise, and linking between unequal partners is intrinsically difficult; it may be more cost effective to link to an existing organisation (ASPERA, 2009). One independent (commercial-in-confidence) study concluded that *(i)* a Dutch foundation (*stichting*), *(ii)* a UK company limited by guarantee, or *(iii)* a US not-for-profit corporation in Delaware, are equally suitable for the purposes of effectively executing the SKA Project (Chance, 2010).

Global sourcing

Schill (1979) points out the strategic liaison role played by procurement to ensure that suppliers remain competitive and at the forefront of technology, as well as realise better cost and product performance. Moreover, he assigns strategic responsibility for materials and technology identification both to the buyer, and the market – an important tactic identified in the SKA Capability Assessment Model (Crosby, 2010). This approach addresses the concept of 'scaling up' in terms of industry capability, where science-based mega-projects may demand hundreds or thousands of an item previously produced only as a speciality part. Even so, there may be no ongoing commercial market.

The strategic identification, stimulus, and utilisation of global capability (Virolainen, 1998) may be 'kick-started' by a formal scouting process which may itself be coupled to preliminary vendor screening; the focus being on determining which suppliers are (actually or potentially) qualified, and have the capacity and/or talent to perform the work (Blanchard, 1990). The NEON organisation identifies this phase as 'pre-solicitation/evaluation' in their technology procurement plans.

Internal-external procurement

In 'high-tech' projects many of the outcomes are entirely dependent on new technologies that must be demonstrated to 'proof of concept' level (e.g. the SKA Pathfinders) before production quantities can be considered. Even then, commercial restrictions may limit procurement choices. If a "make" or a "buy" decision is feasible, a lifecycle cost/benefit analysis should be conducted between the alternatives and/or competitive offers to determine the best option for specified performance at least cost, without jeopardising other project interests or resource priorities. Due consideration must be given to intellectual property ownership, as well as the long term capital and cost-benefit impacts of 'high-tech' outsourcing.

In NASA's case, most of its funding is spent on contracts; however its strategic plan outlines the need to maintain institutional capacity and core competencies through having its workforce perform some of the hands-on work. The advantages and disadvantages between in-house and contracted work was recently reviewed for the MMS spacecraft project, with the conclusion that both approaches have significant strengths and weaknesses, while acknowledging clear benefits in maintaining a level of in-house competency (NASA, 2009b).

5. Strategies for procurement, with applicability for the SKA

The SKA project, a global collaboration currently in its preparatory stage (PrepSKA), is expected to commence a detailed design period in 2012/13 and begin phase one construction in 2015/16. Given the 50 year lifetime of the instrument, strategies necessarily enacted early may have long term ramifications, and are clearly important to get right. The following topics describe key areas where prevailing wisdom and lessons learned can help shape strategies for procurement success.

5.1 The procurement office

Given the lead times involved with 'high-tech' mega-projects, the establishment of a functional procurement team should be considered early. Underpinning the strategic arrangements, Jaakkola, (2004) states *"The first step is simply to get the basic contract management operations established. These include…a centralised contract repository, appointment of person(s) responsible…a contract management handbook, contract templates"*. The procurement system, in terms of software tools and processes integrated to the project management, also require early and careful selection and management.

Roles and responsibilities require definition and approvals assigned, ideally with an individual assigned as focal for each major contract. As the UK Office of Government Commerce (OCG, 2002, p7) advises *"The importance of contract administration to the success of the contract, and to the relationship between customer and provider, should not be underestimated"*. The American styled Integrated Project Teams (IPTs) model has showed functional success in procurement.

Successful management of any enterprise relies on effective communication and no less so in procurement, especially between the procurement office and design team during early phases. The conveyance of information concerning emerging technologies, forecast changes, financial analyses of upfront costs and investments, and cash flow risks, when added to the more traditional price and delivery schedule data, ensure strategic value for the project.

Key Strategy #1: Early establishment of procurement office structure, resources, processes, roles and responsibilities, and information management systems.

5.2 Procurement policies and planning

The overall approach to the 'high-tech' acquisition program is captured in the procurement plan; itself linked to the project master plan/system timeline. The procurement plan sets out top level policies for sourcing, tender management, contract evaluation and approvals, *juste retour,* as well as the regulatory environment, responsibilities and authorities, procurement strategies, and pointers to detailed procedures and guidance. The procurement plan may be in the form of a public document (Crosby, 2008a), enabling industry and other stakeholders to understand and prepare for project opportunities, and possibly an internal version created for the project (Hall & Kahn, 2006).

Strategic planning of mega-project procurement will include research and monitoring of lead times of major system components (Appendix C), and relating this information to the project timeline (Appendix D). This is crucial for all stakeholders understanding. Procurement plans may be complemented by national or international industry participation plans describing the intent of procurement policies in relation to fair competition, strategic capacity building (regional development), and indigenous involvement (Crosby, 2008b).

Such plans need not be large documents, a current example being the NEON Project Acquisition Plan, covering references and scope, procurement strategy, functional responsibilities, and procurement plans succinctly within its nine pages (Ashley, 2009). LOFAR's plan covers similar topics in 11 pages (de Geus & Kahn, 2002). Plans for specific type acquisitions can be referenced and separate, as can general institutional purchasing manuals, regional rules, and Conditions of Contracts.

Key Strategy #2: Formally approve procurement policies, strategies, and plans, and document these within a concise approved Project Procurement Plan.

5.3 Informed contracting with industry

The level and method of industry interfaces will vary according to the stage of the project e.g. preparatory and construction phases, through to operations. In the early stages, there are four ways in which industry may be engaged (Perna et al. 2009, p21);

- *High level engagement, at the concept level, to discover new technologies or industrial information and skills*
- *R & D contracts for prototyping & design*
- *Global price enquiries for COTS requirements*
- *'In-kind' contributions of personnel, tools, technical services, or other resources*

These engagement options, and later construction phase activities, will normally lead to selection, approval, and a contract using instruments such as a collaboration agreement, Request for Information (RFI), Request for Quotation (RFQ), or Request for Tender (RFT). These processes build on, and are informed by, the global industry 'scouting' process which takes account of the regional/country capabilities to the appropriate extent. Mega-projects may choose to be more proactive; ITER for example, pre-announces each year's intended procurements for next 24 months.

Although RFTs may be restricted to project member states, open RFTs are most common for science/engineering supply acquisitions (as used in ESO). This more likely guarantees both the largest number of industry enquiries, and a fair approach in gathering industrial information, and supply offers. Price enquiries and R&D contracts performed via open tenders provide the following advantages:

- guarantee of full access to a worldwide market to identify the best available technologies, free from any geographical boundary restrictions;
- continuous monitoring by project stakeholders for fairness in the industrial involvement.
- the ability to look strategically at regional capability for possible 'chunking', bundling or split of contracts, or to address *juste retour* issues. (Not permissible under some US Funding rules).

The contents of RFTs and other issued documents are normally closely scripted by institutional templates validated by legal professionals. However care should be taken to ensure that standardised language and text does not mask or generalise either the specific need or overriding objectives of the procurement. Blanchard (1990) identifies several issues for which tender documentation should solicit an expanded response from the contractor;

- A detailed plan of execution (to ensure the scope is understood)
- An overall staffing chart, and project schedule with critical path defined
- A 'manpower' load chart indicating committed and available resources
- Resumes of key staff with at least one alternative each
- A choice of contractor's project manager

- An estimate of the number of engineering plans to be supplied

Whilst open requests for information or offers have advantages, and are usually a legislated requirement in public procurement for 'high-tech' mega-projects, some experts point to the benefits of a more direct approach. Partnership sourcing, where the buyer and supplier develop a close and long term relationship resulting in lower total costs, can enhance dependability and overall supplier quality (Virolaonen, 1998). The arrangement encourages early strategic supplier engagement and recognises distinctive value. Blanchard (1990) too promotes direct negotiation through the question, "*When a company is seeking to convert a concept or idea into a reality...why not get the best [firm] that is available?*". Once that vendor(s) is known, discussions can begin early, and eliminate much of the time and cost of the competitive bidding process. Blanchard continues "*administrative niceties have crept into the execution of projects...and are indicative that we may have lost sight of the real objective – to convert a concept...into a reality and to begin returning the investment as rapidly as possible"*. Whichever mode is selected for supplier contracting, it should be subject to cost/benefit analysis, and risk of long term innovation and costs being sacrificed for expediency.

Terms & Conditions

Contractual terms and conditions (T&C) will largely be set by the governance model adopted, and with advice from project funding agencies. Nevertheless guidance can be drawn from documented experience generally, and also from many of the major contemporary science and engineering facility projects. Some of the applicable terms and conditions that warrant particular discussion are listed below, and have relevance for the SKA project.

Penalties – Whilst penalties are commonly applied to contracts at the general level, or against specific deliverables, some care is required with their construction. The nature of mega-science programs usually entails both design modifications and unexpected events that can cause delays which may (even inadvertently) trigger penalty clauses invoking liquidating damages within supply chains. Expert legal advisers are needed to draw up such clauses so as to reflect the collaborative nature of the contract, yet ensure retention of power to act in circumstances of supplier failure. Notably, T&Cs for the OPAL project required that disputes are not permitted to delay delivery of contracted goods or services.

Delivery Timing – Procurement programs will be based on project master plans that will almost certainly be amended over time. Contractual documents will therefore need to incorporate some avenue to adjust schedules of procured goods and services (particularly within 'Just-in-Time' arrangements). Failure to do this may lead to delivery of goods at incorrect project phases, causing delays or requiring storage, and resulting in cash flow problems from unsynchronised contractor billing.

Payment – Extended contracts will usually incorporate payment milestones. Payments should only be made against measurable, and tangible deliverables, or otherwise verifiable 'earned value'. Clawing back over-payments is a very management intensive task, and leads to breakdown of goodwill across the supplier base.

International Pricing – To facilitate proper competitive procurement, and ensure fair evaluation, contracts should require price offers to be in a single, universal currency. To enable this, a foreign exchange (FX) conversion methodology will be required, and directions given regarding the application of duties and tariffs.

Guarantee – Contracts stating or requiring guarantees against goods or services performance, delivery dates, or compliance need to be very explicit regarding the extent of the warranty issued, and remedies for failing to meet it. Compensation must not only include rectification of the fault or breakdown, but also any costs or associated effort on the part of the buyer's organisation to restore performance. In the case of the SKA, systems and components may well approach or exceed their advertised warranty period prior to entering service. Procurement contracts should seek to delay the commencement of the warranty period until the goods are operational, or extending the period to cover any such delay.

Ethical standards – Not all countries and regions have equivalent ethical standards. These should be overtly stated in contractual documents and made clear in all dealings. This is especially important concerning hospitality, gift giving, and passing of information. It is not suggested that such policies should prohibit social customs or observance of business courtesies, merely that these customs be conducted openly, be of an acceptable scale, and transacted without prejudice.

Environmental awareness – The project may consider taking an official position on global warming impacts and incorporate a 'green' policy (as per GEMINI) into its procurement function. This could take the form of addressing issues such as packaging, shipping-miles, favouring firms employing sustainable systems, and using fully electronic purchasing systems.

Subcontractor conditions – Contracts must address the topic of subcontracting, stating clearly the conditions and approvals required. (E.g. ESO's contractors require authorisation before subcontracting). Ideally, any subcontracts will be 'back-to-back' with the prime contract for all terms and conditions, and be especially clear on the requirement to mirror quality assurance and performance requirements fully down the supply chain (as per CERN practice). Subcontractors must be identified within tender offers, and their credentials verified.

Intellectual Property (IP) – The management and treatment of foreground, background, and project generated IP and copyright material should be addressed through an IP policy, and must be known, practiced, and conveyed to suppliers through the procurement process, especially where 'open sourcing' is applied. A vital feature of the SKA procurement function is the requirement for the project to have 'freedom of use' for all such IP. Where this is not possible or acceptable, the SKA will require clear understanding of royalty/licence costs.

Key Strategy #3: Obtain full understanding of global capability scouting information, and employ appropriate approaches and instruments with terms and conditions supporting project goals.

5.4 Contracting models

Various contracting arrangements are possible for SKA-like projects, and several models are shown in Appendix E, Figs 1-6 (adapted from Morris & Hough, 1986). The actual structural links between the project organisation and suppliers may vary over project phases, and in accordance with contract size, geographic spread of members, funding shares, and the legal entity structure.

Contractual relationships are unlikely to remain stable over the entire project, being subject to company buy-outs, change of key personnel, and even change of business focus. Procurement documentation needs to be contractually robust to ensure continuation of supply.

The prime contractor–subcontractor relationships shown in Appendix E also embrace the concept of supply chains, where suppliers can usefully engage with SMEs to exploit niche capability.

Key Strategy #4: Establish the contracting model, aligned with the legal entity. Develop relationships with principal contractors and the supply chain.

5.5 Ensuring competitiveness

'High-tech' mega-project acquisition both enables and benefits from market competitiveness framed by the strategic approaches described previously, and driven through project procurement policies and initiatives, as described below.

Pricing

The offered price for any good or service reflects the contractual risk involved, and is therefore to some extent influenced by the buyer's policy. "*If the risk is large (say more than about 10%) the price becomes unnecessarily high, especially if there is no real competition*", say Hall & Kahn (2006, p20). They further explain that if the risk is under-estimated, cost-cutting can ensue, thus working in a highly detrimental way for complex scientific projects, and most dangerous when the contract was won with an artificially low bid. These concerns are also voiced by Nicholas (2004) who describes 'fixed price with determination' to counter the tendencies described above. Blanchard (1990) posits that risk and contingency for uncertainty should not exceed 5% of the total expected cost for fixed price contracts.

Even under a 'best value for money' procurement approach, price remains a key discriminator among tender offers. This is true whether a competitive contract is 'cost-plus reimbursable', a fixed price basis, or somewhere in-between. Since bidders will build contingency in their offers commensurate with their perception of the risk, each offered price will contain a combination of costs, profit margin, and 'risk money'. It is not uncommon in aerospace projects for early contracts to be on a cost-reimbursable basis, and later production orders to be firm price contracts – the latter requiring much lower procurement management effort.

Fixed price contracts are most common in mega-projects (ESO, VLT, and LOFAR) generally, though Morris & Hough (1986, p217) argue they are *"clearly inappropriate in high risk situations,"* Contracts may incorporate financial incentives for achieving or exceeding defined project objectives e.g. delivery date, performance, etc. Damages may apply for failed performance, but as shown in the VISTA project, and in MoD reports, are not always effective (UK Ministry of Defence, 2009). Buyer-driven changes in scope can be accommodated, but generally at a cost, with a premium value attached for any contract variations.

Cost reimbursable contracts involve payment to the contractor for legitimate expenses for completed work, plus a profit margin. Financial incentives may be applied. This type of contract is useful for flexibility in directing the contractor when the precise scope of work cannot be defined at the start, and may well be applicable to the SKA environment. Moreover, some price certainty is possible with cost caps in place. Simplified cost reimbursable contracts are often useful for R & D work and are conducted on a 'time and materials' reimbursable basis using a pre-agreed schedule of fees.

Economic price adjustments, tied to a reliable financial index, are commonly applied to large project procurements spanning a period of years. A special provision is included allowing for pre-defined changes to the contract price due to changed conditions e.g. inflation, exchange rate variation, or less commonly, specified commodities.

A novel approach taken by some large scale technical integrators (e.g. cell-phone assemblers) is to take the stance of price-setter rather than price taker. In this case the tender documents will include either (a) fixed price per item, or (b) a variable price per item based on quantities offered, or (c) a price cap representing the maximum price that will be paid, encouraging competition beneath that figure.

Split buying

For procurement of high quantity parts, split-buying offers the advantage of spreading the production risk over two or more suppliers. This can be appropriate in cases where each supplier indicates an individual production capability beneath that required by the project, and especially where sharing of tooling is practical. Apart from raising competitiveness, split-buying is also appropriate where the purchaser has a policy preference of not becoming the dominant or exclusive customer of the supplier. Counter to this, spreading a quantity order over too many suppliers will reduce any economies of scale.

COTS Purchasing

Another way to encourage competitiveness is to specify Commercial-off-the-Shelf (COTS) products (where possible) within tender documents. The GEMINI telescope project experience tells us that COTS products are always cheaper to acquire, support and upgrade, and are often available from several sources, sometimes via global channels.

Industry Consortia

To better understand and potentially service the needs of major high-technology projects, local or global industry consortia may be formed, either as regional (possibly government) initiatives, or encouraged by the project itself. Such teaming arrangements are usually beneficial in allowing industry to more efficiently work together to address mega-project needs, as well as spawn 'spin-off' collaborations or opportunities to service adjacent markets.

Mega-projects should be alert to the formation of cartels, especially where there are restricted numbers of bidders. A cartel is a formal organisation of suppliers that agree to coordinate prices, marketing and production, and are anti-competitive. The EU's competition law explicitly forbids cartels and related practices in its article 81 of the Treaty of Rome. Long Term Partnering Arrangements (LPTAs) with key vendors offer strategic pathways for global procurement.

Broader Outcomes

Overlying project acquisition strategies for capability deployment, and application of *juste retour*, may modify price-based decisions in terms of allowing for the non-financial benefits of technology transfer and exploitation, and regional capacity building. The importance of this latter item is recognised for the SKA project, and explored and reported through a recent COST initiative (COST, 2010).

Value for money (VfM) comes from the effective, efficient and economic use of resources. Getting value for money means optimising the ratio between value and cost, and may be numerically or subjectively quantified (OGC, 2002). A VfM bid assessment not only provides lower overall cost benefits, but also the common ground for very different offers to be compared. The simplistic 'lowest price' criterion is unable to grant neither the lowest total cost of ownership (costs over the whole life cycle) nor project life performance. The VfM decision criteria must consider project quality and performance, in relation with other requirements including economic value, reliability, supportability, purchase risk, and price (Perna et al. 2009).

Key Strategy #5: Ensure competitiveness in contracting, through carefully planned pricing strategies, and a 'value for money' approach.

5.6 Procurement Specifications

The purchase of products, materials, software, tooling, systems, and other tangible needs for complex high value projects requires focused attention on defining the specification. This can be done through (a) documented designs (blueprints), controlled engineering drawings and notes, prototype examples, and supplemented by part numbers; or (b) a detailed performance specification where the inputs, outputs, design constraints and tolerances are stated, but not the precise physical design. Both approaches are validated with test plans against performance criteria. In the former, the contractor will be expected to deliver an exact version in every respect to the designs provided. In the latter, the contractor has some latitude to develop and construct/create the item(s) as long as the performance criteria and design constraints are met. It is not uncommon for both approaches to exist within 'high-tech' mega-projects.

Linked to this concept is the notion of manufacturability (or 'design for manufacture'). It is essential that designs intended for large scale production are developed with input from industrial experts so that contracts can be issued with the benefit of knowledge from practical production techniques and limitations. The procurement office has an important role in this. Another vital consideration is 'upgradeability' – the application of production expertise to ensure that future production runs can be modified to accommodate improvements in the design at low cost. A relatively small increase in the initial procurement cost may lead to great savings later. A procurement policy is also required to cover the specification requirements of professional services.

Contemporary cases offer useful advice for the SKA. CERN commend flexibility and innovation in procurement, and suggest that procuring initial sets of spares as part of the construction procurement avoids potential commissioning delays. Australia's OPAL program mostly used a performance specification, and noted that a pre-solicitation 'scouting' process reduced cost and time overall. LOFAR experience from The Netherlands warns of underestimating the specification difficulties of mass production and systems integration. A general recommendation was that the combination of processes forming the leanest model that meets the requirements of the project is best adopted.

Key Strategy #6: Apply purchasing specifications that are appropriate to the goods or services required, are flexible for optimal outcomes, and developed with input from industry.

5.7 Procurement risk

The procurement process and fulfilment of the contract may be endangered by several kinds of risk as listed below, only some of which are within the provider's control (adapted from OGC, 2002, p13);

- Poorly drafted contracts
- Inadequate resources assigned to contract management
- Customer team not matched to the supplier team in terms of either skills or experience (or both)
- Wrong people put in place, leading to personality clashes
- Context, complexities and dependencies of contracts not well understood
- Failure to check supplier assumptions
- Unclear authorities or responsibilities relating to commercial decisions
- Lack of performance measurement or benchmarking by the buyer
- Focus on current arrangements rather than what is possible or the potential for improvement
- Failure to monitor and manage retained risks (statutory, political and commercial)
- Lack of supplier capacity, or scope creep beyond ability.
- Loss of supplier's key staff
- Change of supplier's business focus
- Financial insecurity, and *force majeure*

Risks are heightened by procurement itself, with a dependency on one or more external providers, leaving the buyer with reduced ability to command and manage variables (Schill, 1979). Even when a risk is notionally subrogated to the supplier it cannot be dismissed, "*transferred risks…cannot be forgotten about simply because the contract obliges the provider to deal with them. A key point is that business risk can never be transferred to the provider*" (OGC, 2002, p25)

In discussing advanced technology organisations, Schill (1979) specifies nine specific risk areas; concluding that 'high-tech' procurement is especially prone to a wide risk front when requiring development of new materials, components, or equipment. He cites time overruns of some 180% and cost overruns of 200-300% on Government contracts.

Risk of Pre-competitive relationships (lock-out)(adapted from Hall & Khan, 2006)

As a general principle, potential bidders should not be given foreknowledge of contractual requirements and it is good practice to avoid direct contact between contracting personnel and potential bidders once a purchase action has commenced. In 'high-tech' mega-projects, this is not always easy, as there is often contact between project personnel and industry; nevertheless policies must be observed and a culture of internal discipline is required. Such a policy poses major problems for large scale, long term projects with considerable R&D, since public procurement rules are not always in sympathy with the specific needs of such projects.

An example is where a company is involved in an early (and vital) stage of the project there is a risk that the (potential) bidding firm might be excluded from subsequent participation precisely because of its prior knowledge (also known as 'lock-out'). This could mean exclusion of precisely those organisations that have specific relevant knowledge or skills from the early stages of a project. This situation creates difficulties for the strategic engagement potential for early involvement in multi-million Euro 'high-technology' projects (such as the SKA).

Another extreme example is when one of a number of potential bidders for a contract has already been given a contract for a prior phase of the work. The advantages are obvious and include a better understanding of what will be needed, reduced costs through familiarity of system interfaces, and the possibility of customer developed hardware.

However, it *is* possible to operate properly within the rules and still do what is technically and scientifically necessary (as shown by 'real world' examples) but it does require a lot of care, forethought and advance preparation regarding the procurement scheme.

In practice, the LOFAR project found success with software correlator development largely because of effective nurturing and management of industry collaboration with IBM. The ALMA radio telescope also features pre-competitive engagement with industry mostly via conventional contracts.

Some of the approaches that projects can take include:

- Crafting the legal entity, so that specialist contractors can be legally engaged.
- When placing a study or technology development contract, do this on the basis of a competition, thus providing a justification for continuing relations with the contractor.

- Assign the study or R & D work with provision for the results to be made available to all potential bidders for the main contract.
- Employ parallel competitive studies. These can sometimes produce better results, as well as justifying the further selection of one contractor, though cause added expense.
- Seek contractors for early stage work who do not have the capacity or desire to engage in large scale manufacture. A contractual condition can be that the contractor agrees to be available as a potential sub-contractor to any future potential main bidder.
- In extreme circumstances a developed technology that is regarded as vital can be treated either as customer furnished equipment or as an imposed sub-contract. This has the disadvantage that it entails considerable customer responsibility for the results.

Key Strategy #7: Understand and actively manage procurement risk, including the critical early stage engagement phases.

5.8 Tender evaluations and contractor selection

The evaluation of potential contractors for public, 'high-tech' mega-projects demands close attention, especially for high value prime contracts. Blanchard (1990) favours a two-stage process, pointing out that tendering imposes costs on all parties, and limiting the 'full and final' offers to a few qualified firms narrows the choice and lifts the quality, though possibly results in higher prices. He suggests the compromise is to restrict tender invitations to four or five for very large projects, but no less than three.

Practitioners agree that effective contractor evaluation requires an approved, transparent procedure, and should be conducted against pre-determined criteria (Hall & Kahn, 2006). The application of the ISO 9000 Quality Management Systems has seen useful standardisation in this. However while supporting the principle, Crosby (1996) calls for sensible application of such standards, particularly in the area of approved supplier lists, where completion of a questionnaire often falls well short of the intended diligence. Project Directorates should ensure that funding is allocated for an appropriate level of quality audit as well as technical compliance checking for each major procurement contract, and that this 'mission assurance' aspect is documented within tenders and acknowledged by bidding firms.

Contractor selection

A study undertaken by Watt et al. (2010, p59) contributes interesting data from 222 engineering project cases concerning the relative importance of tender selection criteria. Their research shows that "*past project performance and technical expertise were of almost equal importance, but twice that of tendered cost. These, coupled with project management expertise contributed to a combined importance >85%"* of the nine measured criteria. Blanchard (1990, p47) concurs, saying "*Nothing can replace the experience with suppliers as a determinant of the probability of on-time delivery"*. Experience from the GEMINI project recommends active checking of past work and competency, not simply relying on contractor assertions.

Key Strategy #8: Evaluate and select project contractors using a fair and balanced process, executed against standardised procedures, and focussed on criteria weighted in favour of mission success parameters.

5.9 The purchaser-supplier relationship

A close partnership style relationship is crucial for publicly funded science/engineering procurement where economic benefits flowing to the community through contracts are viewed as equal success indicators to project outcomes. Nonetheless, the procurement activity must be impartial, formal, and transparent, and with the expectations of each party clear and actively managed.

In long term mega-project contracts, where interdependency between buyer and provider is inevitable, both parties have an interest in a fruitful relationship, though the profit motive must not be overlooked. The three key factors for success are trust, recognition of mutual aims, and communication. In discussing information flows in procurement, the UK Office of Government Commerce argue strongly for a change of paradigm in information sharing and suggest that fear of exposing the buyer's thinking, position, or concerns should be modified by adopting *"a realistic balance between openness and reserving negotiating positions"* (OGC, 2002, p30).

The relationship between some suppliers and the project often begins at the project inception and early R&D phase where technologies and niche capabilities are being investigated, products tested, and experiments conducted. Companies (particularly large ones) are sometimes open to (or volunteer) early stage collaborations or other strategic synergies such as personnel exchanges, expert advice, or free/loaned tools and technology. The procurement office needs to be aware of these pre-contract arrangements to ensure that 'lock-out' situations don't develop (see section 5.7), and that such opportunities are agreed to fairly and are transparent to the industrial community.

Once contracts are awarded in the construction phase, the relationship between suppliers and the project must be formalised under a contractual framework that maintains this positive interaction and openness. This is especially vital concerning inspections and acceptance of work which lessons learned from major 'high-tech' projects suggests can be a defining point in procurement success. ESO asserts the right to inspect and verify goods anytime, whereas both ITER and CERN undertake planned inspections of work at suppliers. OPAL participates in witnessing of hold points defined in test plans, and collaborates in commissioning. LOFAR emphasise close relations with suppliers; using the process to guarantee quality. Their procedures include installing inspectors in supplier's factories. CERN go further, swapping inspectors between suppliers and choosing not to rely on ISO 9001 certification or supplier's QA records. However close and positive the relationship, the VISTA project found that contractors always need help regardless of any contract conditions.

Another important aspect to supplier relationships is the amount of dependency involved, and a project policy decision is required regarding limitations to the size of order in respect to any given company's size or turnover. This decision will take account of the balance between desired level of reliance of the firm on the contract, and the buyer risk attached to highly geared contracts. CERN takes the standpoint of preferring not to be >20% of the supplier's business, while NASA promotes multiple suppliers as both a risk mitigation strategy and competition driver.

A point made strongly by the UK's National Audit Office report 'Improving Procurement' (NAO, 2004) is the need for sound client capability, particularly senior management leadership skills, and paying particular attention to enhancing key aspects of procurement capability. These are:

- raising commercial awareness, having better, more up to date management information particularly on current market prices
- more joint purchasing between departments, and more proactive management of suppliers
- managing the risk of relying on too small a number of suppliers for key commodities, and
- developing procurement expertise and better targeting of value-for-money improvements.

Key Strategy #9: Implement fair and transparent procurement processes, and exploit open strategic partnerships while allowing for evidence based supplier inspections.

6.0. Summary and conclusions

Procurement is vital to the success of mega-projects, being both shaped, and the shaper of, the 'high-tech' environment, and influencing how much R&D vendors do. Schill notes US Air Force Commander Schriever's comment *"The pacing factor in acquiring technologically-based modern aerospace systems is management, not science and technology"* (Schill, 1979, p299).

In fast changing technological situations, effective acquisition strategies can help decrease risk, shorten lead times, reduce investments, and improved response to project needs (Virolainen, 1998). This paper has shown that an informed, holistic approach to procurement can improve the effectiveness of the process, and underpin more productive and open relationships with suppliers. In particular, nine key strategies are suggested as being necessary to address in order to position the procurement function as a precursor for 'high-tech' project success. These are shown listed in Appendix F, together with potential management implications for the SKA project.

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Glossary

ALMA	Atacama Large Millimeter/submillimeter Array http://www.almaobservatory.org/
AUGER	Pierre Auger Cosmic Ray Observatory http://www.auger.org/
CERN	European Organization for Nuclear Research http://public.web.cern.ch/public/
COTS	Commercial off-the-shelf (readily available from industry)
ESO	European Organisation for Astronomical Research http://www.eso.org/public/
GEMINI	The Gemini Observatory http://www.gemini.edu/
HESS	High Energy Stereoscopic System http://www.mpi-hd.mpg.de/hfm/HESS/
IBM	International Business Machines Corporation
Integrated Project Team (IPT)	A multi-disciplinary team led by a project manager responsible and accountable for planning, budgeting, procurement and life-cycle management of the investment to achieve its cost, schedule and performance goals. Team skills include: budgetary, financial, capital planning, procurement, user, program, architecture, earned value management, security, and other staff as appropriate
ITER	International Thermonuclear Experimental Reactor http://www.iter.org/
LOFAR	(ASTRON) Low Frequency Array http://www.lofar.org/
MMS	Magnetospheric Multiscale Project http://science.nasa.gov/missions/mms/
NASA	National aeronautics and space administration
NEON	National Ecological Observatory Network http://www.neoninc.org/
OPAL	Open Pool Australian Light-water reactor http://www.ansto.gov.au/discovering_ansto/anstos_research_reactor
PrepSKA	Preparatory phase for the SKA project
SKA Pathfinders	Generic title given to projects where prototype technologies are developed and deployed as testing facilities for proposed SKA technologies. Includes the two precursor instruments in Australia and South Africa
SME	Small and Medium Enterprises
subrogated	substituted (one person or body) for another with reference to a claim or right
VISTA	Visible and Infrared Survey Telescope http://www.vista.ac.uk/
VLT	Very Large Telescope http://www.eso.org/public/teles-instr/vlt.html
XFEL	X-ray free-electron laser http://xfel.desy.de/

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APPENDIX A

About the Square Kilometre Array

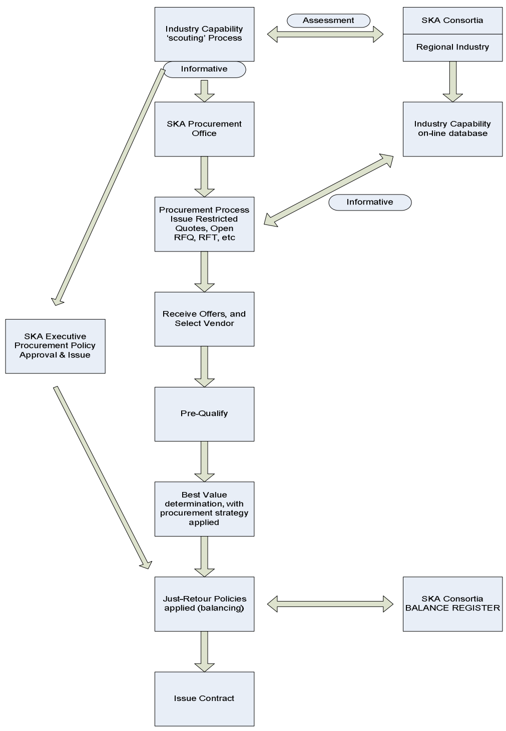
The Square Kilometre Array (SKA) will be a revolutionary international radio telescope for the 21st Century designed to address fundamental unanswered questions about our Universe.

The total collecting area will be approximately one square kilometre giving 50 times the sensitivity, and 10,000 times the survey speed, of the best current-day telescopes. With receptors extending out to distances of 3,000 km from the centre of the telescope, the SKA project stretches the limits and risk profiles of several leading edge technologies.

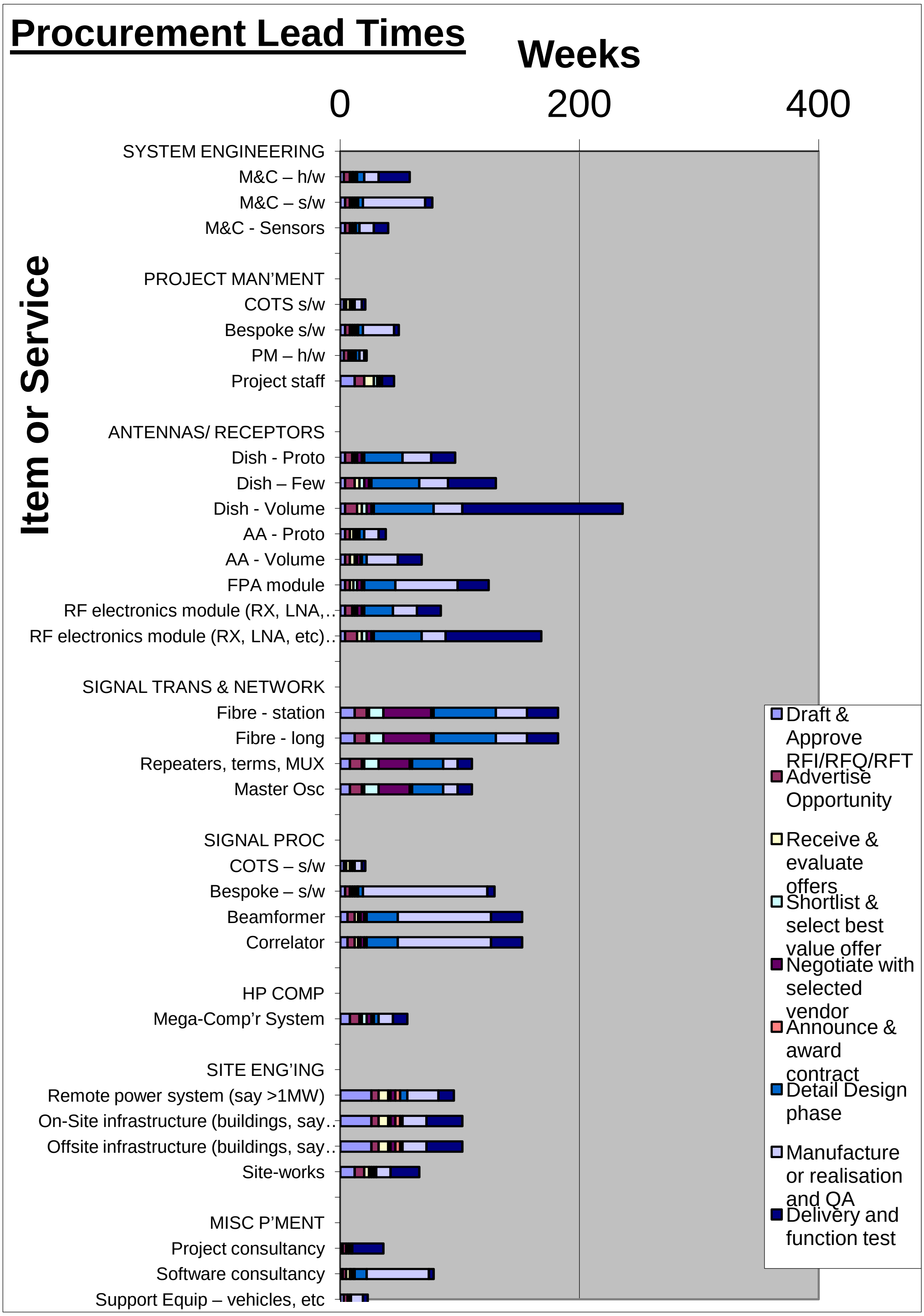
More than 70 institutes in 20 countries, together with industry partners, are participating in the scientific and technical design of the SKA telescope which will be located in either Australia – New Zealand or Southern Africa extending to the Indian Ocean Islands. The target construction cost is €1,500 million, with preconstruction planned to commence following the host site decision in 2012.

APPENDIX B

Procurement process flow (proposed) for SKA Project

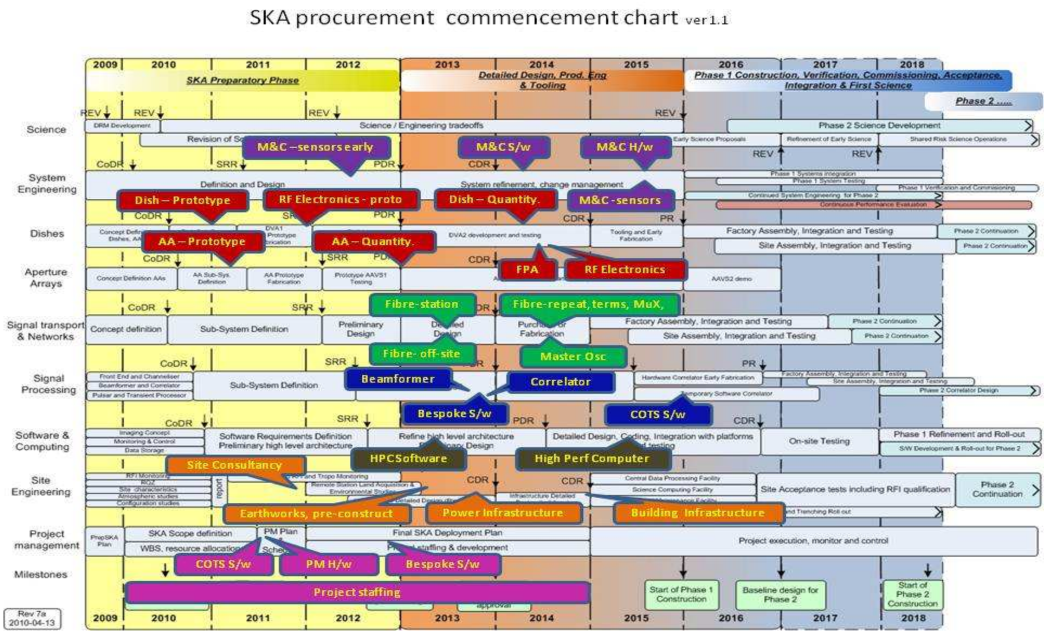


Procurement Lead Times Chart for SKA



APPENDIX D

Example procurement commencement for the SKA



APPENDIX E

<u>*Contracting Models for the SKA*</u>

Fig 1: Owner Organisation Managed - Single Contractor. The Owner organisation has direct contact with a prime Contractor.

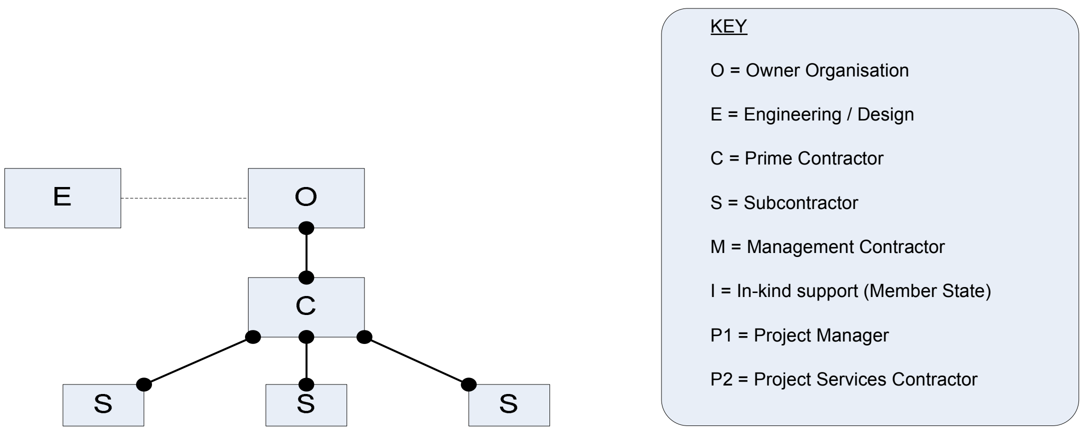


Fig 2: Owner Organisation Managed – Multiple Contractors. The Owner organisation has direct contact with several main Contractors; Contractors may have many subcontractors.

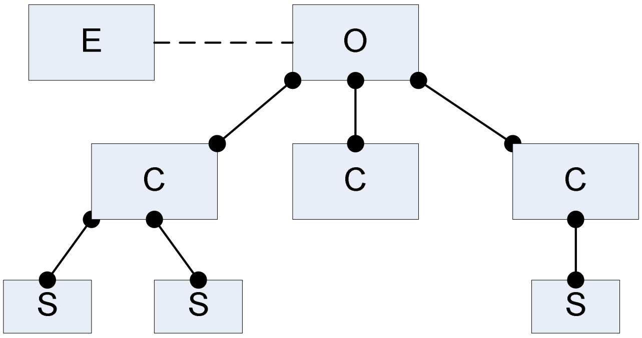


Fig 3: Management Contractors. Owner organisation engages a Management Contractor (MC) to assist planning, supervise work, and check performance. The MC may direct contractors, but contracts are between the Owner and Contractors.

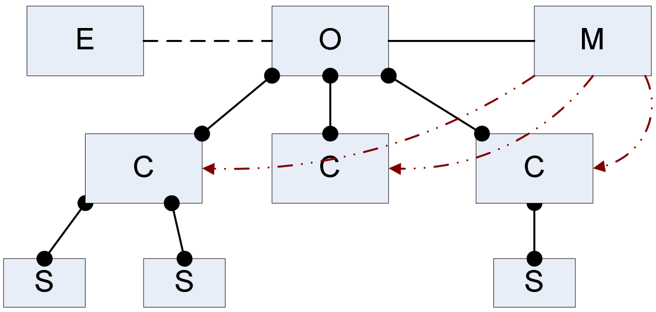


Fig 4: Project Manager. Owner organisation engages a Project Manager (PM) to coordinate and supervise the work. The PM has some project performance accountability, and contracts are between the PM and Contractors. Highly successful in the case of the OPAL Research Reactor, Australia.

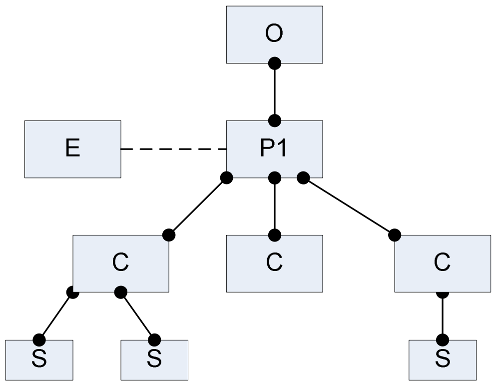


Fig 5: Project Services Contractor. The Project Services Contractor joins the Owner organisation project management team. Staff from the two groups work jointly, but contracts are between the Owner and Contractors, with potential loss of contract knowledge.

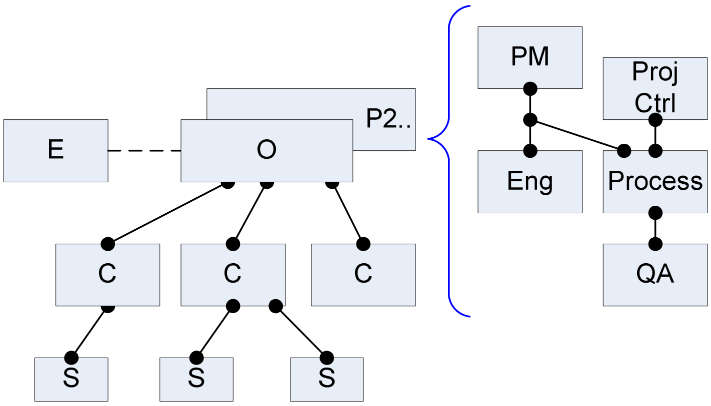
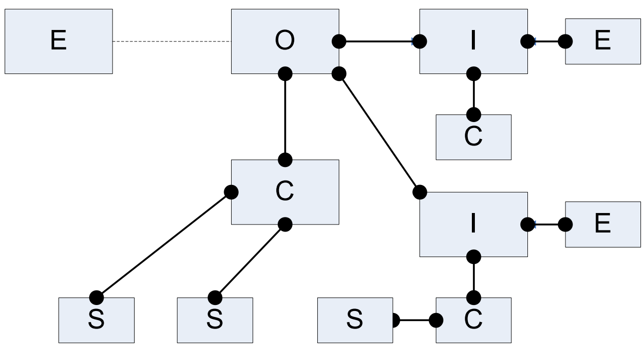


Fig 6: The Owner organisation shares the contractual responsibility with member States who have agreed to manage 'in-kind' contributions (refer ITER model). Responsibility for cost/schedule variations requires clarity between the parties.



Most important key strategies for procurement success, and implications for the SKA project

Key Strategy	Descriptor	Management Implications for the SKA Project
1	*Early establishment of procurement office structure, resources, processes, roles and responsibilities, and information management systems.*	Begin consideration of staffing and other resource requirements for the SKA procurement office, including a capital and operating estimate for early approval. Commence recruitment.
2	*Formally approve procurement policies, strategies, and plans, and document these within a concise approved Project Procurement Plan.*	Drawing on the work of PrepSKA Work Package 5, approve and implement an SKA procurement policy and associated strategy, responsibilities and authorities, and operating procedures.
3	*Obtain full understanding of global capability scouting information, and employ appropriate approaches and instruments with terms and conditions supporting project goals.*	Ensure the global industry capability assessment process is completed, and reports available to procurement personnel. Develop, review and approve procurement instruments.
4	*Establish the contracting model, aligned with the legal entity. Develop relationships with principle contractors and the supply chain.*	Work with SKA governance board to align the SKA legal entity with the adopted models for contractual relationships with suppliers.
5	*Ensure competitiveness in contracting, through carefully planned pricing strategies, and a 'value for money' approach.*	Procurement management to devise acquisition strategies that ensure value for money, and respect *juste retour* agreements.
6	*Apply purchasing specifications that are appropriate to the goods or services required, are flexible for optimal outcomes, and developed with input from industry.*	Procurement management to devise and apply purchasing approaches that match required goods and services. Consult with strategic industry partners to the SKA (e.g. SoMI signatories).
7	*Understand and actively manage procurement risk, including the critical early stage engagement phases.*	Devise and implement an active system for identifying and tracking procurement risk. Consider contingency reserves.
8	*Evaluate and select project contractors using a fair and balanced process, executed against standardised procedures, and focussed on criteria weighted in favour of mission success parameters.*	Ensure that a competent system and team is established to undertake formal assessment of SKA supplier offers. Implement sound and defensible assessment criteria, and records management.
9	*Implement fair and transparent procurement processes, and exploit open strategic partnerships while allowing for evidence based supplier inspections.*	Procurement management to work with legal advisers in preparation of specific and generic contracts documentation. Establish processes and resources for supplier-based inspections.

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Building Resilience in Large High-Technology Projects: Front End Conditioning for Success

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ABSTRACT

Success in mega-projects is frequently discussed among project theoreticians and practitioners. This research focuses on high-technology projects and draws on recent literature and fieldwork at ten contemporary mega-science projects in Chile, Australia, and Europe. This study concludes that project success is not random, and that early adoption of certain approaches, activities, and launch conditions will position a project for success and resilience. Nine resilience factors (beyond *a priori* programmatical artefacts) are grouped into three ‘attitudinal’ factors, and six ‘conditioning’ factors. These are then examined in detail against three case study projects. The study conclusions show that attitudinal factors remain a challenge, especially within institutional type high-tech projects, and launch conditioning shows mixed levels of application. Through the nine factors, this paper offers newly consolidated insights for high-tech project start-ups. It presents the case for co-application of contingency funding and ‘proto’ task forces in response to unknown risks, and advocates the establishment of more formal information ‘traffic’ management through an empowered centralised project information office.

Keywords: resilience; project success; mega-project; high-technology; optimism; lessons-learned; ambiguity; information management; risk; contingency

INTRODUCTION

Success and failure in projects is a frequent topic among both project theoreticians and practitioners. Mega-projects especially have received attention from academic authors and the popular press, often recounting performance failures and cost and time overruns, which sometimes lead to *fiascos* (Grün 2004). Less reported are the great successes where project goals were met, budgets contained, and most importantly, the customer or users were satisfied. Regardless of outcome, each case offers a learning opportunity providing the causal factors are investigated and the lessons applied.

This study posits that project success, unlike project planning (Flyvbjerg, Bruzelius, & Rothengatter, 2003) is not indeterminate by nature, and that undertaking certain activities, coupled with application of particular policies and launch conditions at the front end, positions a project for success and resilience. Evidence of continued high-tech project failure (e.g. Standish, 1995, Proccacino, Verner, Overmyer, & Darter, 2002) indicates that a specialist examination is warranted, with the aim of convincing project managers to focus harder in nine areas contributing to project robustness and resilience. In this paper, I aim to identify the early conditions required for high-tech mega-project success, beyond the basic 'givens' of project structure, funding, tools, and plans.

Resilience is defined here as being akin to robustness in the sense of building strength and the ability to recover from, or adjust easily to, misfortune or change. The parameters of mega-projects are not tightly specified here, except to note that these endeavours typically have hundreds of millions or even billion dollar budgets, time-frames usually measured in at least years, and often a high level of public or political attention. In this paper, high-tech projects are defined as those involving research and development (R&D), a significant information technology (IT) component, application of leading edge science/engineering technologies, and with substantial infrastructure requirements.

LITERATURE

Compared to the amount of project management practice guides, Books of Knowledge (BoKs), and 'how to do it' literature, written project management theory is less common and better described as a collection of techniques and best practice than a scientific treatment of the topic. In response to project management approach and attitudes, Erno-Kjolhede (2000) tackles the management of research projects, addressing the underlying concepts of complexity and uncertainty at the conceptualisation phase, and the balancing of risk-taking and failure. Difficulties with early stage risk assessment in relation to over-reliance amid uncertainty are examined by Bakker, Cambre, Korlaar, & Raab, (2010); Flyvberg et al. (2003); and Geraldi, & Kutsch, (2010). Project shaping as a management craft is investigated by Smith & Winter (2010) who show clear links to project success, while Miller and Olleros examine episodic style project shaping as a competitive advantage (Miller & Lessard, 2000). Blanchard (1990) and Cook-Davies (2002) discuss the 'people' aspects of new projects and the pivotal role of management as the first human resource, while new work by Jani (2010) asserts that self-efficacy enables resilience in IT project teams. Nonetheless, attitudinal factors for project shaping and context setting have yet to be set out in relation to high-tech projects specifically.

A number of early critical success factors (CSF) are proposed by Elenbaas (2000) who notes the crucial conditions and complex environments within project start-ups. Much referenced authors Shenhar & Dvir (2007) emphasise the need for early tailoring of project success measures and dimensions. In their examination of project peripety (an abrupt turn of events), Engwall & Westling (2001) explore assumptions around linear project processes and the limiting effects of articulating imperfect knowledge at project start-up. Lechler & Dvir (2010) offer recent work on linking project management structures to project success, arguing for serious attention to early organisational structure. Weston (2007), Fellows & Alexander (2010), and Fisher (2010) each touch on early stage risk of immature technologies and the gap in understanding between industry and institutions. While these (and other) authors address diverse facets of early stage project conditioning, there remains a gap in the literature for an empirically based summary of early stage conditioning factors concerning resilience within high-tech projects.

STUDY APPROACH & METHODOLOGY

This study draws from material largely published between 2000 and 2010. While peer-reviewed papers and books offer expert knowledge, reports from project publications revealed more practical experience. Discussions at relevant conferences and workshops gave further insights; in particular the topics of peripety, optimism, and mission assurance which were prominent at the 2010 NASA Project Management Challenge, an annual best practice networking event (NASA, 2010a).

This paper includes data from ten cases from a broader research assignment by the author into mega-science project management being conducting at 16 large scientific projects in Europe, Chile and

Australia. Each project is characterised by having specialised infrastructure, > US$100 million budget, a challenging IT and software requirement, and a science goal concerned with astro, particle, or nuclear physics. I observed planning and execution processes, and formal and ad-hoc meetings, both in the office and worksite. At each project, I undertook between five and ten formal interviews with project directors and managers, each typically lasting 3-5 hours, and loosely structured to permit the gathering of salient learning aspects from each case. The fieldwork study list is shown in Appendix A, Exhibit 1. The data gathered from casework is referenced in upper-case throughout this study and introduces the 'lived experiences' of project practitioners.

The value of field casework is advanced by Flyvbjerg (2006), who explains the richness of information in the case narrative, including single studies depending on the case and how it is chosen. He asserts that casework capability can describe realities which are hard to reveal or define in scientific parlance (Flyvbjerg, 2001). The case study as a research method is supported by Yin (2009), who describes the rigorous methodological approach required for conclusion validity, and usefulness when investigating complex phenomena. The present study applies pattern matching from complementary evidence (triangulation) to avoid reinforcement of preconceived ideas and strengthen validity in accordance with Yin's principles.

This research effort focuses on eliciting resilience factors beyond *a priori* programmatical processes, resources and artefacts (such as execution plans, project funding, Work Breakdown Structures, etc.). The findings are grouped into three 'attitudinal' factors, and six 'conditioning' factors described in the following sections and defined as 'special' factors to distinguish them from traditional programmatical factors. Attitudinal factors are those which require an intellectual stance or approach, whereas conditional factors are realised through purposeful activity. These 'special' resilience factors are then examined against three contemporary mega-science cases and the findings used to inform the study conclusions.

ATTITUDINAL PROJECT SHAPING

Balancing enthusiasm with realism.

A necessary component of any high-tech project funding bid is the enthusiastic belief by the protagonist(s) that it can be executed on time, on budget. This often leads to inaccurate estimates, most disappointing when over-selling is used to win favour with funders. Grün (2004) talks of project proponents, project managers, contractors, and planning experts who may form 'over-optimism-coalitions'. Grün further identifies over-optimism (p41) as the *"tendency to underestimate the difficulties of achieving the technical goals… the operation & maintenance costs, and the costs caused by the changing of technical goals."*

Evidence of optimism is not hard to find. A lessons-learned workshop from the Gemini telescope project revealed that the effects of science drivers on cost and schedule led to overly optimistic estimates, resulting in a 300% over-budget in one instrument (NRC, 1999). Observations in a radio astronomy technology White Paper describe overly optimistic cost and development time estimates as the most frequent cause of project de-scoping (Fisher, 2010). A UK defence report lamenting a £205 million cost increase over 20 projects admitted that *"on far too many projects, the Department is over-optimistic and sets unachievable cost, time and performance objectives"* (MoD, 2009). In the US, NASA officials, seeking to boost congressional support, sought to emphasise the Space Shuttle's apparent low development cost. Such optimism proved flawed, as the program encountered delays of three years and cost overruns of 60% prior to its first mission loss in 1986 (Shenhar & Dvir, 2007). When interviewed, NASA Director, George Morrow asserted *"a major pitfall is being overly* *optimistic early in the project lifecycle.”* (NASA, 2009)

The cost-schedule paradox is a formidable enemy. A US Defense Acquisition office investigation concluded that once past 15%, an over-budget program is ‘highly unlikely’ to recover original projections and the final overrun will get worse (Butts & Linton, 2009). Over-optimistic budget and schedule expectations are shown to inhibit project success, and are especially likely on projects with institutional difficulties (Murphy, Baker, & Fisher, 1974). IT projects appear to be especially vulnerable (Verner & Cerpa, 2005).

How then might we recalibrate our thinking without losing the all-important project enthusiasm? Blanchard (1990) claims objectivity may be the only defence against the snowballing effect of eagerness, and suggests that, as a balancing process, project proponents should also develop a case for *not* proceeding. Realistic estimates and plans (i.e. neither optimistic nor pessimistic) would seem a correct approach, but Erno-Kjolhede (2000) argues that this could lead to project participants failing to innovate, and result in second-best performance. He recommends a tone of ‘highly ambitious’, or ‘challenging’ planning, driving stretch goals underpinned by factual data. Flyvbjerg et al. (2003) strongly support cost estimates accompanied by a risk analysis of future cost regimes, thereby offering a realistic view to curb against ‘appraisal optimism’. The Acquisitions Defence RUSI Group offer practical advice to break the ‘conspiracy of optimism’ including transparency, realism, de-risk programs and interfaces, and ultimately consider cancelling programs (Weston, 2007).

Butts & Linton (2009) who investigated NASA’s cost estimation performance, conclude that undershooting cost and schedule projections is a well verified NASA phenomenon, being rooted in an historical practice of over-optimism. In response, their report introduces a hybrid model (the Joint Confidence Level - Probabilistic Calculator, JCL-PC) for accurately estimating cost and schedule reality in complex science and engineering environments where maturing technologies are present. The adoption of sophisticated cost tools (e.g. the Square Kilometre Array Cost Engine), managed by trained and experienced project personnel, perhaps heralds a maturing approach to cost realism that could be adopted by other projects.

Checking for relevant lessons learned

The value of recording lessons-learned from past projects, and the investigation of experiences from like-projects during early stage high-tech project planning, seems obvious. But casework reveals little effort is applied to these valuable activities. Many of the facilities investigated for the present study almost totally relied on the collective experiences of project staff and management rather than any formal survey of analogous projects, thereby failing to learn of other’s mistakes (ALMA, 2010; ASTRON, 2010; CSIRO, 2009).

Authors consistently promote the need to learn from project experience, and cite this as vital for continuous improvement as well as evidence of project management maturity (Cao & Hoffman, 2010; Verner & Cerpa, 2005; Cooke-Davies, 2002; Kerzner, 1998; Williams, 2004; PMI, 2008; Fisher, 2010). Nevertheless, Disterer (2002, p512) concludes “*only a few firms manage systematically to identify and transfer valuable knowledge from projects to following projects [so that people can] apply it to future tasks”*. Smith & Winter (2010) directly link ‘front-end’ management with project success and promote the idea of deliberately exploring insights and implications flowing from past project perspectives, and crafting appropriate action responses. Formal lessons learned capture mechanisms are needed to avoid ‘project amnesia’, including knowledge management systems. Schindler & Eppler (2003, p223) suggest methods for learning from experience and cite the Boeing approach of applying the results of past project investigations, thus delivering “*the most successful and error free market launches... accomplished in the history of Boeing”*.

Industry are more adept at systems to capture and retrieve previous learnings, experience put to great use in lowering costs in orbital satellite projects (TOPSAT, 2010).

Within organisations, project staff have opportunities to learn and reuse lessons (Davies & Hobday, 2005), and post-mortem results can be stored within knowledge systems, or communicated directly to other teams (Collier, DeMarco, & Fearey, 1996). Mapping techniques that show chains of causality are useful in transferring lessons-learned to other projects (Williams, 2004). For the high-tech planner in single project organisations effort is required to access and locate such learnings (CSIRO, 2009). Schalken, Brinkkemper, & van Vliet, (2006) address this problem with a (highly qualified) method based on Grounded Theory to deal with qualitative information from project reviews. An alternative is to access public databases such as NASA's Engineering Network (NASA, 2010b), and The Software Program Manager's Network (SPMN, 2010). Whatever method is used, lessons-learned and wisdom applied from analogous projects is concluded to be a vital, though largely underused, project success factor.

Embracing complexity, ambiguity and uncertainty

High-tech mega-projects are characterised by risk, complexity, ambiguity and uncertainty, not just related to technology, but introduced via multiple collaborative parties, and often a dispersed infrastructure. At start-up, uncertainty surrounds performance levels, objectives and motivations, capabilities, stakeholder expectations, and political environments.

High-tech mega-projects are always complicated, and almost always (by adding uncertainty) complex. Not only through the abundance of programmatic interfaces, but also because of the interactions between systems. Complex systems as understood in the contemporary sense are testing of management (Crosby, 2012a), and have an inherent level of unpredictability (Pavlak, 2004a; Miller & Lessard, 2000). Grasping this complexity, and preparing the project for it, demands early stage agile and adaptive management (Shenhar & Dvir, 2007). To respond strategically, project management will likely develop more than one (possibly several) management strategies (Crosby, 2006; Pich, Loch, & De Mayer, 2002), before down-selecting the final way forward. Beinhocker (1997 p8) supports this approach, saying "*In a complex adaptive system, a focused strategy…is necessary for day-to-day survival, but [is] not sufficient in the long run…strategies must be robust [and] perform well in a variety of possible future environments*". Thus project shaping is as much about keeping options open, as about trouble-proofing.

Traditional project management practice as outlined in the Project Management Bodies of Knowledge (PMBOKs) applies a rational probability-based approach to management, but is poorly equipped to deal with project uncertainty (Pender, 2001). Atkinson et al. (2006) characterise uncertainty as the incompleteness of information, a normal situation for early stage high-tech projects that requires tolerance from development teams, and may only be mitigated by trust in management.

The early stages of R&D (high-tech) projects are dominated by long periods of ambiguity where solutions (and even problems) are unclear, possibly conflicting, and where change is incremental. There follows a short period of peripety (Engwall & Westling (2001), where one solution (or a set of solutions) becomes the obvious candidate as the legitimate path forward. Peripety is a turn of events leading to cognitive transition from ambiguousness into a less daunting state of uncertainty, often recalled as a time when real achievement occurred. It is not simply a change of fortune, but a change of understanding of all that has gone before (Smith & Winter, 2010).

In dealing with uncertainty, Smith (2007) invokes the pragmatic skills of 'ProjectCraft' starting with uncertainty spotting, and alerts the project manager not to delegate this to risk managers. He suggests we pose the critical questions: are we confident in our assumptions, and if wrong, could the impact be serious? Moreover he supports uncertainty workshops, stating that (p134) *"we must spot the potential frauds, and shake the tree to find out what is not secure"*. However fieldwork suggests that such analysis is rare, and is absent from the ten cases investigated.

Based on the literature and casework, managers of high-tech projects can lift confidence by addressing ambiguity through preliminary studies and by using new knowledge to improve sense-making and thus refine the way forward. Uncertainty can only be reduced by acquiring necessary information through explicit questions (Engwall & Westling, 2001).

LAUNCH CONDITIONING

Project mission & success definition

While the setting of time and budget limits at project commencement is problematic (Bakker et al., 2010), no project should start without at least a broad objective(s) aligned to stakeholder expectations and priorities. The IPMA Project Manager's BoK (Caupin, Knoepfel, Koch, Pannenbacker, Peres-Polo, & Seabury, 2006) list objectives, mission, and project charter in its start-up guidance. However Atkinson, Crawford, & Ward, (2006) warn of 'premature definition' based on insufficiently defined specifications, especially in novel, one-off high-tech projects. Having a well-defined project mission was ranked #1 in the project definition stage by Hyvari (2006), and ranked #2 in a recent meta-study of high-tech project success drivers (Crosby, 2012b). When linking success to project types (including high-tech), Shenhar & Wideman (1996 p9) assert *"As part of every project's front-end planning...agreement should be reached on the project's principal success criteria having regard to its project type"*. In software projects, Verner & Cerpa (2005) found that the start of a project offers greatest chance of quality improvement through better requirements setting. O'Brochta (2002 p1) draws on CIA technical project experience to conclude that, *"the earliest phases of the project life cycle have the most dramatic impact upon the odds that projects will be viewed as successful"*. Clearly it makes sense for project success measures to be integrated with planning at project initiation, and possibly included within the project team's charter if it exists (Shenhar & Dvir, 2007).

Fieldwork findings for this research agreed that statements around the mission and science goals were often established early (driven by funding applications and collaboration approaches), but project success definitions were less obvious in early planning (ITER, 2009; CSIRO, 2008; VISTA, 2010), although in hindsight were considered useful by interviewees and incorporated earlier in future projects.

Reporting and decision-making policies and structure

A common characteristic of large high-tech projects is the distributed nature of the technical and governance committees. In the commercial world this is evident through strategically located research nodes (e.g. Boeing's virtual PhantomWorks) and global procurement management. Institutional mega-projects frequently assemble executive and technical committees from world-wide nominations, and from a third stakeholder group – the funding agencies which pay for, but do not benefit from, the project output (Khang & Moe, 2008). This coming together of diverse people and interests to achieve a common purpose requires perceived and actual distances to be overcome, and responsibility to be shared (Aronson, Shenhar, & Reilly, 2010). Ideally, all this happens in a spirit of effective communication and coordination, active participation, trust, and common expectations (Samuel, 2009; NRC, 1999).

Such challenges prove difficult to meet in practice. Fieldwork interviews exposed tensions where operative project managers felt frustrated by a lack of decision or feedback on project shaping proposals. Project staff also reported irritation when committees made pronouncements or aired concerns regarding matters considered outside their remit, especially when related to early stage technology selection. Several interviewees thought their committees were too large to work effectively.

Davies & Hobday (2005) write *"Different organisational cultures, problems in contractual relations and the need to integrate different domains of knowledge make collaborative projects very difficult to execute."* A recent ASPERA report addressing start-ups of science infrastructures (Katsanevas, Miller, Berghöfer, Metzger, Rülle, & Zickgraf, 2009) emphasises the need for clear decision-making processes with one body/person having final say, and reject a 50:50 sharing of decision-making (ALMA, 2007) as ineffective. Lessons learnt from the ASPERA report encourage early formation of a Management Board, supported by a core management group, interlocked to the researchers and administration through a clear (documented) decision-making and reporting hierarchy.

In establishing clear reporting and decision-making, top management can either help or hinder a project. Several authors (Hayfield, 1985; Baker, Murphy, & Fisher, 1988; Rubenstein, Chakrabarti, O'Keefe, Souder, & Young, 1976; Procaccino et al., 2002) give some emphasis to the negative effects too much management, citing 'interference' and 'meddling'. The last author adding that removal of a project sponsor has more detrimental effect on success than starting without one. Conversely, fieldwork revealed protracted decisions as the only real complaint of management efficacy, with only the (German) XFEL project identifying the need for total management restructure (DESY, 2009).

Project information control

Large projects generate a vast amount of information. Much of this, especially the formal project procedures, plans, and records, are usually organised within some form of centralised Project Management Information System (PMIS). Computer based PMIS not only store large amounts of data, but can intelligently handle, sort, back-up and report timely (sometimes predictive) information of immediate use to managers. Most importantly for high-tech mega-projects, modern packages will integrate complex data relationships between scheduling and network planning, resource management, budgeting, cost control and performance analysis, and risk burn (Nicholas, 2004). Clearly it makes sense to establish a PMIS of appropriate scale and capability early, and enforce its use.

However case investigations (CSIRO, 2008; CSIRO, 2009; ASTRON, 2009; DESY, 2009) show that the discipline required to create, register and link all relevant project documentation within a controlled environment is rarely maintained outside of externally audited (usually industrial) projects. Observations during fieldwork show a mixed attitude to centralising plans and data, with personal storage practices representing the highest risk.

Of at least equal significance to the successful project execution is the abundance of information exchanges that take place around the project, internally and externally, and often not recorded centrally. This information 'traffic' flow includes face-to-face meetings and conferences, telephone and video meetings, emails and presentations, all sometimes involving arms-length groups. As the project community grows through the conception stage through to execution, the risk of misalignment of working group effort, misunderstandings of priorities and changes, and misinformation to external parties grows accordingly. Moreover, exercising weak control over these 'satellite' information channels leaves aspects of the project imperfectly recorded, leading to inefficient external reviews and limiting the usefulness of central repositories as stores of lessons learned (CSIRO, 2009; ALMA, 2011; HIPER, 2010).

How should early phase project managers address this situation? Implementing a project management system based on an accepted professional guideline (e.g. PMBOK) may go some way to instilling the required practices. Implementing a certified (independently audited) management system (e.g. ISO 9001) will demand compliance with procedures designed to apply control of information flows, as well as instigate corrective and preventive action for process failures. However, the present study concludes that the most effective means of establishing an information controlled environment is to introduce it early, drive it through management example, and dedicate resources to maintaining it. The early phase UK HIPER project is already benefiting from a distinct Work Package entitled Public Relations and Communications. In its most mature form, this might involve a Project Information Office (PIO) as the repository of centralised information, documents and data; holding responsibility for arranging meetings, telecons, etc, and managing their inputs and outputs. The PIO would hold authority for approval and recognition of any satellite group information needs, including the use of project templates, branding, intellectual property (IP), and single point management media interfaces.

Experience from the Dutch LOFAR project suggests that extensive formalisation (PIO-style) early in the project was viewed unfavourably (ASTRON, 2010). However the increasing drive for industrial class high-tech mega-projects (as opposed to technical institution models) is demanding greater rigour. LOFAR's Dr. de Vos suggests that a balance might be struck by providing a Wiki-type environment where early stage documents and concepts from scientists and engineers can be assimilated less formally.

Risk & Contingency

High-tech projects have inherent risk as a consequence of their *raison d'être*, and higher risks must be consistent with higher contingency (Fisher, 2010). A standard method to deal with project execution risk is a register type tool using a rating system to score anticipated risk based on the likelihood and consequences of the defined event occurring. Management decisions are then taken to accept, mitigate, or remove those risks. This approach is reasonably effective at project start-up for the *known knowns*, but takes little account of the *unknown unknowns* – events, circumstances or results that are invisible to the project. Howell, Windahl, & Seidel, (2010) link 'consequences' to risk by reasoning that extreme uncertainty (chaos) equates to a 100% probability of an unexpected event.

The conventional approach is therefore problematic because of the perception that resilience has been instilled to deal with all unexpected events (Pender, 2001), whereas it is actually most reliant on experiential hindsight as a risk predictor. Geraldi et al. (2010 p548) contends that in projects *"it is not a question of* if *but* when *unexpected events will emerge"*. These may include transactional issues such as exchange rate fluctuations, market changes etc. (Nicholas, 2004). On average, projects encounter five unexpected events in the formative stages and some confront as many as twelve (Miller & Lessard, 2000). The ALMA telescope gas energy supply interruption being one example where an early assumption appeared fully reliable, only to be unexpectedly revoked (ALMA, 2007).

If the substantive risk to the project is unknown, how might we deal with it at the project formative stage? This study suggests a dual response: applied contingency, and threat readiness.

'Project contingency' (rather than specific threat contingency) includes those external factors or events that cannot yet be pinpointed but will seriously jeopardise the project when they materialise. However quantifying contingency is non-trivial. The PMBOK mentions reserves and contingency but not how they are computed or applied within the project (Pender, 2001). Nicholas (2004) offers a calculator as well as suggesting an overrun allowance in some circumstances. NASA has developed the

‘Joint Confidence Level – Probabilistic Calculator (JCL-PC) founded on the hypothesis that a project’s early phases hold many unknown risks (Butts & Linton, 2009). Many contemporary high-tech project reports recommend early budgeting for (cash) reserves around 20% - 25% (Fellows & Alexander, 2010; JPL, 2010).

Since the unknown cannot be planned in detail, an alternative method is to plan for everything; (the Napoleon approach) expecting that something will go wrong and that a solution will be needed as the challenge emerges. When referring to the aggressive, revolutionary high-tech F117 Stealth Fighter program, Nicholas (2004) writes*; “Expecting the unexpected is often better preparation for coping with risk than preparing extensive plans and believing that the unexpected has been eliminated.”*

General managerial alertness is clearly required to scan broadly for potential threats. Smith (2007) describes ‘uncertainty spotting’ skills; the early seeking out and challenging of threats and assumptions. Being watchful, and informed by timely and accurate trend-type data, is indicated as a key strategy for building resilience.

Coupled with this are task force response teams (aka ‘tiger’ or ‘cheetah’ teams) which are shown to operate effectively to contain and direct events (Crosby, 2012a). The strength of task forces lies in their combined expertise, detachment from the project, and freedom from project bureaucracy (CERN, 2009). Power is concentrated through limiting numbers and very careful participant selection (Pavlak, 2004b). However, task forces take time to establish and become effective, and this paper posits that one or more task force panels might be anticipated, assembled virtually during project start-up, and periodically offered a project ‘health’ report so that a dormant state of readiness is maintained. In the event of an unforeseen disruption, a panel of previously enrolled experts are far better placed begin problem solving than a bricolage type response.

In addition to applying contingency and maintaining a quiescent threat readiness, wise project managers will practice skilful early stage planning to try and avoid unplanned events. Activities including response training, stakeholder negotiation skills, avoidance of panic and over-reaction, and speedy approval processes, all serve to strengthen resilience (Geraldi et al., 2010).

Project environment

Whatever their size or structure, projects exists within a larger financial, geo-political, and governance framework (project environment) that can both enable and constrain the enterprise (Blanchard, 1990). The high-tech projects considered in the present study generally require physical space for infrastructure, often in underdeveloped (green-field) areas prone to host site sensitivities. Gaining approvals for large engineering facilities, often involving decades of operations, can be a slow process fraught with challenges. Merrow’s (1988 p vi) study of 52 mega-projects concludes:

> *“Cost growth and schedule slippage...are driven primarily by conflicts between the projects and host governments, i.e., institutional problems relating to environmental regulations and opposition, health and safety rules, labor(sic) practices, and procurement controls. The importance of institutional factors clearly distinguishes mega-projects from their smaller cousins.”*

Projects encumbered by excessive government restrictions or involvement showed a strong negative relationship to success in a study by Murphy et al. (1974), while Pinto & Mantel (1990 p274) add *“change in the project environment beyond the control of management”* as a cause of project failure.

There is advantage in establishing the project within known, coherent and mature institutional arrangements. Miller & Lessard (2000) write *“Projects shaped in incomplete* *and shifting arrangements have a hard time taking off: they require deals and agreements that may not stand for long"*. In the $3bn Accelerator Production of Tritium (APT) project, project management successfully adopted the concurrent engineering approach, integrating design, planning, and operations teams early on, and conducting up-front analysis driven by environmental (NEPA) requirements. Consideration of these early resulted in significant changes to design and operability of the plant (Laufer & Hoffman, 2000).

A proactive approach to government negotiations offers real benefits. By leveraging the infrastructure investment, the ALMA project not only won significant concessions, but also eased visa processes for foreign workers (ALMA, 2011). However, failure to fully understand regulatory compliance can be costly. For example, the Australian ASKAP radio telescope encountered unanticipated delays in achieving government approval for land use, requiring significant diplomacy and skilled effort from project personnel (CSIRO, 2009). Blanchard (1990) urges early attention to regulatory approvals, and argues that the cost of compliance with environmental and special interest groups needs must be factored into project cost estimates.

A 2007 report of major astronomy project surveys warns of changing political agendas, agency priorities, budget pressures, as well as unanticipated disasters, and scientific results. It recommends to *"start with a more realistic sense of agency budgetary and policy environments...so that [project] surveys can be more resilient"* (Fellows & Alexander, 2010 p3). The world beyond the project is neither benign nor complacent, and early stage investment into securing a legally compliant, socially acceptable, and affordable project deployment plan pays dividends.

Mission Assurance

Fieldwork undertaken by Crosby (2012a) reveals a particular characteristic of some high-tech project managers; an unwavering sense of purpose in making mission success the highest priority at all levels of the project. The adoption of this 'mission assurance' approach is captured compellingly within aerospace industry reports (e.g. NASA, 2000) which encourages institutional line management to become more engaged in the execution of the project and be held accountable for mission success. So important is this viewed at NASA, it now maintains specific safety and mission assurance functional offices.

The implementation of a mission assurance function (part auditor, part advisor, part 'devil's advocate') means placing this vital resource outside of mainstream project delivery, yet close enough to have ready participation in critical testing, meetings, and reviews, and with access to project management. The role is principally one of questioning and checking that activities, deviations and changes, particularly at project interfaces, pose no unrecoverable threat to execution and performance.

Created at project start-up, the mission assurance function is best placed to conduct a project audit after the definition stage but before execution begins. Graham & Englund (1997 p192) describe this as *"like a group of expert consultants...review the plans and proposals before the project team begins...and provide feedback on the technical and managerial feasibility of the plans...using their knowledge and experience to foresee problems."*

Several of the interviewees for this study claimed that external panels fulfilled the niche of mission assurance while conducting design reviews etc., but the temporary nature of these panels is never equivalent to a project-bound person or group. Moreover, rather than be created as part of the project execution and deployment team, this paper argues for a distinct mission assurance role to be assigned at project inception, and developed as a central (overhead) function necessary for driving project success.

BRIEF QUALITATIVE ASSESSMENT

Having drawn out the more subtle, though highly influential, attitudinal environmental and launch conditions shown to be important for project success, it is useful to examine how these nine factors are addressed in practice.

For this, I selected three large radio-astronomy projects from the fieldwork studies. Although similar in terms of being remotely located giant radio telescopes with large and complex information technology (IT) requirements, they are discriminated primarily by project budget, infrastructure size, and execution stage (see Appendix A, Exhibit 2).

In preparation for the comparative assessment, I examined the data collected during detailed on-site investigations, as described in the study approach & methodology. The data were sorted to expose relevant examples of situations or events that fell within the special factor categories identified in the present study. Against each factor, I describe a challenge that faced each of the three cases, and the method and extent of the response from each project. Appendix B shows this work tabulated to enable ready comparison and contrasting of challenges and responses between the case projects, and reveal commonalities.

Space limits preclude an in-depth data analysis here; however a summary presents useful insights. Cost, schedule and performance optimism was universal, and each project introduced constraints to meet budgets. Little effort was evident to learn from analogous high-tech projects. All three cases struggled at some point to deal with project ambiguities and uncertainties, though responses showed these challenges are surmountable. Some disconnect was apparent between lofty science goals and practical execution, later bridged through individual project initiatives. Both reporting and decision-making processes, and project information control, were competently managed, but with room for maturation to industry standards. Risk and contingency factors were handled only moderately well, exposing the ASKAP and SKA projects especially to the effects of unforeseen disasters. While the important external project landscape was managed well in all cases, the potential advantages of a formal mission assurance program have yet to be exploited.

CONCLUSIONS AND DISCUSSION

The present study illustrates that for most high-tech projects, both attitudinal and conditioning factors remain a challenge, no less so for large and complex IT projects.

Schedule and cost optimism especially is a well known phenomenon, yet it continues to be neglected. The issue results partly from failure to forecast project costs accurately (especially software) and partly through competitive funding environments where underestimates in time and/or cost have traditionally been tacitly accepted or even encouraged. Anecdotally, current global economic conditions indicate reducing tolerance to this approach in the face of stricter funding priorities (Matson, 2010). Use of lessons learned has been historically weak, and remains patchy. High-tech mega-projects especially should formally plan for at least a degree of up-front research to inform the major challenges and decisions ahead. Early ambiguity in projects can frustrate project groups used to a more industrial model, yet are overcome through trust building – itself dependent on effective and frequent project team communication.

Regarding launch conditions, the benefits of defining the project mission and success definitions early are strongly evident, as are clear and consistent structures for reporting and decision-making. The concept of a Project Information Office (PIO) is advanced with a remit covering not only information, documents and data, but also the broader responsibility for convening conferences, meetings, telecons, and managing / recording their ‘traffic’ flows. As such, the PIO would be the central coordinator of project community information needs, including project templates, branding, IP, and single point management media interfaces.

Risk management is typically dealt with programmatically and tends to see projects as a deterministic process, but this approach fails to fully consider *unknown unknowns*. To address this epistemic uncertainty in high-tech projects, a two-pronged approach is suggested: (i) estimating and establishing an identified contingency reserve, ideally integrated to dynamic risk 'burn', and (ii) the early appointment of one or more 'proto' task forces panels kept in dormant readiness to offer expert advice against unanticipated events.

The execution of large infrastructure projects carries compliance obligations involving national authorities. Even with State blessing, these external negotiations are rarely simple, and need careful and dedicated stewardship at (or before) project start-up. Lastly, this study supports the formation of a mission assurance function working alongside project management, supporting the project teams, and reporting at Director level. Integrated at the conceptual phase, the mission assurance specialist(s) brings experiential capability and intellectual rigour to project definition.

Management of the conceptualisation and planning phases is shown to have a pivotal effect on the ultimate success of projects. For international high-tech projects especially, the alignment of key activities with key players is crucial. It is people, with their talents, attitudes and experience, who ultimately deliver the initiatives (and thus the performance objectives) outlined in this study and sponsors should strive to hire the best staff available (Katsanevas et al., 2009). This underpinning aspect of projects is advanced by Cook-Davies (2002 p189) as "*people perform every process, and it is the people who ultimately determine the adequacy*".

SUMMARY

The paper has drawn together and deepened knowledge of how large high-tech projects may be conditioned (beyond *a priori* mechanistic attributes) to improve resilience in the face of inevitable set-backs and unexpected events. The new insights drawn have value for early stage mega-project planners to improved conditioning of projects for success. Recent literature was examined, complemented by relevant field casework. Nine resilience factors were grouped as:

(a) Attitudinal

- realistic, fact based
- a lessons-learned culture
- ambiguity/uncertainty tolerant

(b) Conditioning

- mission and success clearly defined
- clear reporting and decision structures
- strong information control
- risk preparedness
- external environmental awareness
- mission assurance role implemented

These factors were tested against three large high-tech (science /engineering/IT) projects to determine their relevance and value in framing early-stage adjustments to typical and contemporary high-tech mega-projects. Commonalities were reviewed, and these informed the general conclusions.

STUDY LIMITATIONS AND FURTHER RESEARCH.

This study has taken a case-study analytical approach by presenting data from selected literature research, validated by contemporary case experience, and presented this in explanatory form. The limitations of this qualitative methodology (without deep numerical analysis) are recognised, and the possible observer bias in study is acknowledged. The number of case studies could be widened and possibly broadened to introduce other stakeholders e.g. IT backbone providers, funding agencies, and land-owners. Interesting further research is indicated to correlate resilience factors between high-tech, and other project typologies (e.g. large civil), to reveal early stage initiatives beneficial to increasingly industrialised science mega-projects.

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EXHIBIT 1: Fieldwork Case Studies (Principal contact identified only)

- *ALMA, Dr. Tony Beasley, ex-Project Manager ALMA radio-telescope project. Discussions on mega-project management and risk. Personal communications, Chile, 19-22 November, 2007, 28 October, 2010, and 12 June 2011* http://www.almaobservatory.org/
- *ASTRON, Dr. Marco de Vos, Head R&D ASTRON/LOFAR mega-array. Discussion on science project characteristics. Personal communications, The Netherlands, 23 July, 2009 and UK, 28 September, 2010* http://www.lofar.org/
- *CERN, Dr. Lyndon Evans, Project Manager - Large Hadron Collider. Discussion on characteristics of mega-projects. Personal communications, Switzerland, 23 July, 2009 http://public.web.cern.ch/public/en/lhc/lhc-en.html*
- *CSIRO, Dr. Ron Ekers, ex-Director Aust. Telescope. Discussion on major project success factors. Personal communication, Australia, 12 March, 2008 http://www.narrabri.atnf.csiro.au/*
- *CSIRO, Dr. Dave DeBoer, ex-Project Director - ASKAP telescope. Discussion on project management. Many personal communications during 2007-2009 http://www.atnf.csiro.au/projects/askap/*
- *DESY, Dr. R Wichmann, XFEL Project, Deutsches Elektronen-Synchrotron (DESY). Discussions concerning project structures and systems. Personal communications, Germany, 19 July, 2009 http://xfel.desy.de/*
- *HIPER, Dr. C Edwards, HiPER Project Director, STFC Rutherford Appleton Laboratory. Discussion concerning project resilience in early stage high-tech projects, Personal Communications, Didcot, Oxfordshire, 15 November, 2010 http://www.hiper-laser.org/overview/hiperproject/managerstructure.asp*
- *ITER, Mr. Peter Swinson, Head of Project Office -ITER Facility. Discussion on major project management. Personal communications, France, 20 July, 2009* http://www.iter.org/
- *TOPSAT, Professor Richard Holdaway, Director of Space Science and Technology, STFC Rutherford Appleton Laboratory. Discussion concerning success factors in high-tech space related projects, Personal Communications, Didcot, Oxfordshire, 20 May, 2010 http://www.sstd.rl.ac.uk/Topsat/*
- *VISTA, Dr. Ian Bryson, Head of Strategic Development, UK Astronomy Technology Centre, Royal Observatory Edinburgh, VISTA Team discussion, 2 February, 2010 http://www.vista.ac.uk/*

EXHIBIT 2: Key Project Data – ALMA, ASKAP, and the SKA

Identifier	Budget	Infrastructure	Location	Stage
Atacama Large Millimetre Array (ALMA)	US$1.4 billion	50 dish high-frequency radio telescope array, plus command and processing centre	Andes Mountains, Chile	First stage commissioning
Australian SKA Pathfinder (ASKAP)	A$140 million	36 dish mid-frequency radio telescope array and data processing centre	Inland from Geraldton, West Australia	Construction of antennas and infrastructure

Factor	Project	ALMA (Chile)	ASKAP (Australia)	SKA (UK based)
Realism	***Challenge***	• Expectations of a networked 64 dish array in original (2001) budget. Bottom up costing revealed significant project costs overlooked	• Underestimates of cost and resources to develop receptor (PAF) technologies • Possible descope impact due to budget trade-offs. Stakeholder expectation issues	• Underestimates of cost, time and resources to meet software and computing requirements • Potential for severe and negative impact on the project
	Response	• Re-baselining exercise in 2005 triggered call for additional funding • Descope to 50 dishes pre-construction • Project now proceeding	• Consultation with industry regarding volume production costs • Revised plan / funding proposal developed to show viability with alternate project pathway	• Use existing code wherever possible • Top-down 'cost-cap' budget 'as a design constraint' approach to development • Use first order parametric estimating models for software estimating
Lessons Learned	***Challenge***	• Domain knowledge considered held within the partners (NSF, ESO, NAOJ) through specific capabilities. However weakness emerged for industrial integration capabilities	• Domain system engineering knowledge held tacitly by individuals. • No formal systems to codify, archive, or transfer lessons learned	• Domain system engineering knowledge held tacitly by individuals. No formal systems to codify, archive, or transfer lessons learned. The level of coordination and hence collaboration is negatively impacted
	Response	• Level of stakeholder investment meant major decisions not optimised • Therefore all decisions still not ideal or based on researched experience	• Currently no formal lessons learned mechanism evident	• Some effort made to consult developers and operators of like-projects, however highly sporadic, and communications of findings largely ineffective
Complexity, Ambiguity, and uncertainty	***Challenge***	• Deep technical domain knowledge for major system components and software, but project interfaces less defined and complex	• Push for technology break-throughs, especially in PAF's, computing, and 'green 'energy • These are complex, inter-related problems with unclear solutions	• Unfolding science goals and 'proof of concept' TRLs causing ambiguity • Complex Exascale computing capabilities do not yet exist, and may be unaffordable
	Response	• Large investment in system engineering resources to continually resolve interface issues • Project leadership instilled culture of 'relay-race' rather than 'marathon'	• Highly intensive and frequent technical and planning meetings held • There is some sense-making emerging, but peripety has yet to occur	• A more modest Phase1 SKA design released • Science ambitions scaled to computer power budget (flops and watts) • 'Moore's Law' uncertainty remains • Match contingency to complexity

Factor	Project	ALMA (Chile)	ASKAP (Australia)	SKA (UK based)
Mission & Goals	***Challenge***	• Science high-level goals considered fixed objective, with clear vision of project success. However re-baselining meant compromise	• The broad project goal is clear; however some divergence is apparent between long term and short term objectives	• Development of a mega-project mission within an international collaboration and funding framework. Scope creep
	Response	• Re-scoping of project largely maintains achievement of science objectives through adjusted operations	• A group is assigned to bring certainty to the long term purpose of ASKAP • Overcoming shorter term technical barriers is the present mission	• The SKA now has stated science goals against a top-down budget, a Design Reference Mission, and a Phase1 pre-construction Project Execution Plan
Reporting and Decision Structure	***Challenge***	• Need for strong and clear project reporting and execution structure, in face of 50/50 ownership • Decision structure and process must be consistent and workable	• ASKAP resides within a well defined project management structure. Reporting at the Integrated Project team (IPT) level is less consistent, though competent	• Reporting and decision-making structures are complex and variable, typifying the science community decision-making behaviour • Participation in committees and at decision meetings is inconsistent
	Response	• ALMA project structure well defined and implemented at work-site level • More prone to compromise and decision-delay at higher management levels • Third partner added (NAOJ) • Major decisions need lengthy discussion at Joint Alma Office (JAO) level	• Fine tuning the project structure to reflect the project team site location is in process. • Project reporting is enhanced through migration and automation of reporting processes to DAPTIV© platform	• Efforts to lift effectiveness and integration of meetings and decisions mostly unsuccessful • Task Forces work effectively • The planned move to a project office structure will ‘normalise’ reporting and decision-making to industrial model
Information Control	***Challenge***	• Project information control extremely important to maintain project control, and effective procurement systems	• Possible mismatch between ASKAP execution, industry, and large institutional framework • IP requires specialist management	• SKA design and cost data yet to be brought under a formal control system, and there is no formal PMIS in place.
	Response	• The JAO maintains strict controls on project technical data, procurement data, system engineering documents and Standards, and PR material • Major meetings administered centrally • Some reluctance by NAOJ to announce problems early	• ASKAP project information is under dispersed control. IPT leaders maintain technical data control • Industry consortium established • IP is periodically identified through active scan and appropriately managed	• Appointment of a Systems Engineer under a Project Manager is starting to create information discipline • The planned move to a project office structure offers opportunity to professionalise communications management

Factor	Project	ALMA (Chile)	ASKAP (Australia)	SKA (UK based)
Risk & Contingency	***Challenge***	• Need for full identification and tracking of project risk, despite differing risk and contingency culture within the major project owners	• Propensity to focus on tactical risks, and downplay need for contingency, despite evidence of significant likely cost-growth	• Propensity to focus on tactical risks, and downplay need for contingency reserves, despite past experience in mega-science
	Response	• American approach to risk adopted • Comprehensive risk register, risk 'burn' reports, and contingency established and tracked - 15.8%, later reduced to 9.2% • Task forces readily established (e.g. antennas specification problem)	• Little overt acknowledgement of, or pre-planning for, unknown risks • Recent moves to address project and corporate risk and contingency in new business plan	• Recent costing strategy foreshadows a contingency component • Growing awareness of importance to acknowledge *unknown* risks within the professional team, yet specific cash reserves remain unclear in costings
External Environment Aspects	***Challenge***	• Construction and operation of a mega-science facility in the Chilean Andes • The location is harsh and remote • Need for skilled and unskilled workers during construction phase	• ASKAP will be situated in remote Australia. There are indigenous people sensitivities, some environmental fragility, and competition from mining companies. Electrical quietness requires legislation	• Deployment of a large infrastructure project in sensitive geographic location requires lengthy and careful planning in conjunction with approval authorities • Requirement for a 'neutral' HQ site
	Response	• Substantial planning and site negotiation with Government at early stages • Landowner on ALMA Board • Specific 'Astronomy Site' legislation enacted • Tax-free 'diplomat' status for foreign project personnel. Project has sales tax-free status	• Substantial effort and cost is being applied to ensure compliance (in spirit and in fact) with land use policies • Radio-quietness is under legislation development • Negotiations are proceeding with mining interests	• There is Team awareness of project environmental aspects - mostly funding scenarios and site issues. These are dealt with by the Project development Work Packages, and overseen by the SKA Project Executive • Host site and HQ site investigations are underway
Mission Assurance (MA)	***Challenge***	• Requirement for project 'watchdog' role to ensure vigilance and prompt response against threats to mission goals	• Implementation of project 'watchdog' role to ensure vigilance and prompt response against threats to mission goals.	• Implementation of project 'watchdog' role to ensure vigilance and prompt response against threats to mission goals.
	Response	• ALMA Advisory Committee charged with taking longer term project perspective, to identify potential dangers to project delivery • No specific in-project role identified for NASA- style Mission Assurance	• The establishment of a 'mission assurance' (MA) function is unfamiliar to Australian based science projects • There is no role assigned in ASKAP for a specific mission assurance function	• The establishment of a MA function is unfamiliar to European science projects • Current budget restrictions preclude establishment of a formal MA function • Internal and external engineering reviews (e.g. PDRs), fulfil part of the role