‘Maintaining Systems-of-Systems Fit-For-Purpose’

A technique exploiting Material, Energy and Information Source, Sink and Bearer Analysis

by

Steven W. Hinsley

A Doctoral Thesis

Submitted as partial fulfilment of the requirements
for the award of
Ph.D. of Loughborough University

Submitted September 2016

Revised with Corrections April 2017

Loughborough University

Wolfson School of Mechanical, Electrical and Manufacturing Engineering

Engineering Systems-of-Systems Group ESoS

Loughborough University

Certificate of Originality
Thesis Access Conditions and Deposit Agreement

Students should consult the guidance notes on the electronic thesis deposit and the access conditions in the University's Code of Practice on Research Degree Programmes

Author…………...…………Steven W. Hinsley……………………………………………………………...……

Title……………Maintaining Systems-of-Systems Fit-For Purpose…………………………………………………..

I Steven W. Hinsley of Garland, Rothley, Leicestershire, "the Depositor", would like to deposit Maintaining Systems-of-Systems Fit-For Purpose, hereafter referred to as the "Work", once it has successfully been examined in Loughborough University Institutional Repository

Status of access OPEN / ~~RESTRICTED / CONFIDENTIAL~~

Moratorium Period……………………………………years, ending…………../…………20………………………

Status of access approved by (CAPITALS):………MICHAEL HENSHAW………………………

Supervisor (Signature)……M.J. de. Henshaw……………....…………………………………..

School of……Wolfson School of Mechanical, Manufacturing and Electrical Engineering…...………………

Author's Declaration *I confirm the following :*

CERTIFICATE OF ORIGINALITY
This is to certify that I am responsible for the work submitted in this thesis, that the original work is my own except as specified in acknowledgements or in footnotes, and that neither the thesis nor the original work therein has been submitted to this or any other institution for a degree

NON-EXCLUSIVE RIGHTS
The licence rights granted to Loughborough University Institutional Repository through this agreement are entirely non-exclusive and royalty free. I am free to publish the Work in its present version or future versions elsewhere. I agree that Loughborough University Institutional Repository administrators or any third party with whom Loughborough University Institutional Repository has an agreement to do so may, without changing content, convert the Work to any medium or format for the purpose of future preservation and accessibility.

DEPOSIT IN LOUGHBOROUGH UNIVERSITY INSTITUTIONAL REPOSITORY
I understand that open access work deposited in Loughborough University Institutional Repository will be accessible to a wide variety of people and institutions - including automated agents - via the World Wide Web. An electronic copy of my thesis may also be included in the British Library Electronic Theses On-line System (EThOS).
I understand that once the Work is deposited, a citation to the Work will always remain visible. Removal of the Work can be made after discussion with Loughborough University Institutional Repository, who shall make best efforts to ensure removal of the Work from any third party with whom Loughborough University Institutional Repository has an agreement. Restricted or Confidential access material will not be available on the World Wide Web until the moratorium period has expired.

- That I am the author of the Work and have the authority to make this agreement and to hereby give Loughborough University Institutional Repository administrators the right to make available the Work in the way described above.

Author's signature Steve W. Hinsley Date 1st September 2016

user's declaration: for signature during any Moratorium period (Not Open work): ***I undertake to uphold the above conditions:***			
Date	Name (CAPITALS)	Signature	Address

Abstract

Across many domains, systems suppliers are challenged by the complexity of their systems and the speed at which their systems must be changed in order to meet the needs of customers or the societies which the systems support. Stakeholder needs are ever more complex: appearing, disappearing, changing and interacting faster than solutions able to address them can be instantiated. Similarly, the systems themselves continually change as a result of both external and internal influences, such as damage, changing environment, upgrades, reconfiguration, replacement, etc.

In the event of situations unforeseen at design time, personnel (for example maintainers or operators) close to the point of employment may have to modify systems in response to the evolving situation, and to do this in a timely manner so that the system and/or System-of-Systems (SoS: a set of systems that have to interoperate) can achieve their aims.

This research was motivated by the problem of designing-in re-configurability to the constituent systems of a SoS to enable the SoS and its systems to effectively and efficiently counter the effects of unforeseen events that adversely affect fitness-for–purpose whilst operational.

This research shows that a SoS does not achieve or maintain fitness-for-purpose because it cannot implement the correct, timely and complete transfer of Material, Energy and Information (MEI) between its constituents and with its external environment that is necessary to achieve a desired outcome; i.e. the purpose.

A mixed-method concurrent triangulation research approach has been used to create a scalable technique that reveals functionality within a designed system that does not appear in the usual design definition, together with a new system design artefact to capture it: this is a system meta-model of MEI Sources, Sinks and Bearers (SSBs).

The analysis of MEI transfers and MEI SSBs has not been previously used for this type of problem. Unmanaged and uncontrolled MEI SSBs may create risks that require management, but they may also provide opportunities for exploitation to ensure the system's fitness-for-purpose throughout its lifecycle.

The method and engineering process developed from the technique created by this research provide a novel viewpoint and hence a more complete understanding of the System-of-Interest (SoI). This greater understanding can be applied in numerous ways as can any knowledge of the SoI, but here the focus is on three general purposes:

- Revealing concealed root causes of potential problems in the SoI

- Guiding system suppliers to enhance the affordance of SoS constituent systems for the transfer of material, energy and information
- Indicating prospective avenues for innovation.

This research has provided a new engineering technique delivered in a form that addresses a gap in systems engineering theory and provides a thought provoking point-of-departure for further academic research, together with an engineering method and process that facilitates exploitation by the industrial sponsor; it will impact their engineering processes and their products. It guides system suppliers and allows them, in a resource efficient manner, to aid SoS stakeholders in difficult and time-constrained situations who have to adapt what they have to hand to respond in a timely manner to unforeseen events.

Key Words

Capability; Fit-For-Purpose; Affordance; Material Energy Information; Socio-technical; Systems; Systems-of-Systems; Resilience; Robustness; Transfers; Agility; Re-configurability; Reuse; Product Line Architecture; Fit For Purpose; System supplier; Systems integration

Acknowledgements

I would like to thank Loughborough University for giving me the opportunity to do this PhD and the many other people who have given their time and thoughts on my work over the last four years.

I'd like to mention specifically Mike Henshaw, Carys Siemieniuch and Murray Sinclair of the Engineering Systems-of-Systems group specifically in recognition of them giving me the benefit of their considerable experience, encouragement and good humour.

I'd like to also mention Angus Johnson and Jean-Luc Garnier for their efforts on my behalf at Thales and Paul Davies for instigating the industrial engagement.

Last but by no means least, my partner Sue who has supported me through this PhD and through two previous part-time degrees, a BSc and an MSc, who thoroughly deserves her new kitchen after 22 years.

Terminology

Research Definition of Terms

Term	Definition
Affordances	Features that provide the potential for interaction by “affording the ability to do something”(Sillitto, 2011)
Agile	Property of a system that can be changed rapidly
AOF	UK MoD Acquisition Operating Framework
(MEI) Bearer	A transferor of material, energy or information.
Capability	The ability to form systems of interacting systems
Closed Loop Design	A design where a portion of its output combined with its input
CONEMP	CONcept of EMPloyment: describes how a capability will be employed to meet mission accomplishment in various scenarios
CONOPS	CONcept of OPerationS: describes how systems are operated and utilised in operations from the users’ viewpoint
CONUSE	CONcept of USE: describes an overview of how a specific system or systems might be used to support various stakeholders
Created System	The created system is the one to be delivered to some customer and user.(Hitchins 2005)
Creating System	The creating system is the one that exists inside the organization or enterprise, and it is this creating system that delivers the goods on time and within budget, i.e., makes a profit for the business – or not.(Hitchins 2005)
Delivered System /SoS	The System / SoS delivered to the customer
Design Opportunity	A time when there is an opportunity to make design alterations to the System-of Interest (SoI), such as a major maintenance period
Duty	The usage of something over time
Dynamic (MEI meta-model)	A MEI meta-model that shows MIE SSBs and their connections and also incorporates the quantities of MEI associated with the MEI SSBs in the model
Engaged Stakeholder	A stakeholder that directly engages with the SoS of interest at the time they use its results, hence requiring it to be fit-for-purpose
Emergent Property	“Property of the whole that is not evident from the parts” (Workinger 2007)
Engineering the “ilities”	Engineering for desired system properties. The ilities are desired properties of systems, such as flexibility or maintainability (usually but not always ending in “ility”), that often manifest themselves after a system has been put to its initial use. (De Weck 2011)
Transfer Affordance	Features that enable the transfer of MEI
Feedback	A portion of system output fed back to be combined with the system input

Term	Definition
Fitted for but not with	A system that has mass, space, services etc. provided for a component but is not fitted with it
Fit For Purpose (Dictionary)	"Good enough to do the job it was designed to do" (Macmillan, n.d.)
Fit For Purpose (System / System-of-Systems)	Able to satisfice the operational task stakeholders, after unpredictable changes in operation, composition or external factors
Horizontal Integration	Integration of a SoI with legacy and successor systems to provide continuity of capability
Improvement through spares	System improvement obtained by replacing original parts with improved versions of them
Intended	Designed-In; part of a system of interest by design
Inherent	Integral with an 'intended' part of a system of interest
Independent	Independent of a system of interest, but affecting the system of interest
Innovation Route	A course of action towards innovative products and services
Kinematic (meta-model)	A MEI meta-model that shows MIE SSBs and their connections only; it does not incorporate the quantities of MEI associated with the MEI SSBs
Known Factors	Known variables whose values and variations are known, that affect a SoS' outcome
Known-Unknown Factors	Known variables whose values and variations are unknown, that affect a SoS' outcome
Line Replaceable Unit	A unit forming part of a system that can be exchanged in the operational environment
Live Spares	Operational system components that can be re-assigned for multiple applications
Living Document	A document that is maintained, for example to represent the current status of its subject matter as it changes over time
ME(I)	The quantity as utilised by the FFP technique with a de-emphasis on the Information component
(TCA) Method	The systematic approach created by this research that reveals and characterises MEI SSBs
Technical Credit	System functionality in excess of what was required
Transform	A function that converts something into something different
Transfer Affordance	A MEI SSB arrangement able to transfer MEI
Open Loop Design	A design that does not utilise feedback to control its output
Operational Outcome	What outcome results from operating the SoS
Operational Task Stakeholders	Personnel working with, or in, the operational System / SoI
Pain Point	A major issue in the area of Systems of Systems operation, management and systems engineering

Term	Definition
Potential (MEI transfer)	A collection of MEI SSBs with some common operating bandwidth and activity periods
(TCA) Process	The series of actions derived from the TCA method to reveal and characterise covert MEI SSBs
Prospective (MEI transfer)	A collection of MEI SSBs with some common operating bandwidth
Resilience	The “Ability to adapt to changing conditions and prepare for, withstand, and rapidly recover from disruption” (DHS 2010)
Robustness:	The degree to which a system or component can function correctly in the presence of invalid inputs or stressful environmental conditions” (ISO/IEC/IEEE 2010)
Satisfice	To satisfy the minimum requirements for achieving a particular result
(MEI) Sink	A destination or terminus for a transferred quantity of material, energy or information
Situational Awareness	The understanding of the operational environment in the context of a person’s task
(MEI) Source	A source of a quantity of material, energy or information
Speciality Engineering	A component of Systems Engineering that complements the technical activities required to deliver a project. (Keswani 2016)
Stem Cell	A simple cell able to develop into any one of various kinds of cells (such as blood cells, skin cells, etc.)
System of Systems	A set or arrangement of systems that result when independent and useful systems are combined into a larger system that delivers unique capabilities. (Henshaw 2011)
System	A system is a construct or collection of different elements that together produce results not obtainable by the elements alone. The elements, or parts, can include people, hardware, software, facilities, policies, and documents; that is, all things required to produce systems-level results. The results include system level qualities, properties, characteristics, functions, behaviour and performance. The value added by the system as a whole, beyond that contributed independently by the parts, is primarily created by the relationship among the parts; that is, how they are interconnected (Rechtin 2000)
System Asset	A candidate system for inclusion as a constituent of a composing SoS
System-of-Systems Constituent	A system that operates with other systems as part of a SoS
System of Interest	The particular system that is the topic of examination
(TCA) Technique	The way of revealing the covert MEI SSBs in a system of interest
Unknown-Known Factors	Those variables we know, but either don’t acknowledge their existence (although they may still influence the SoI), or just ignore

Term	Definition
Unknown-Unknown Factors	Variables that affect a SoI outcome which are unknown
Vertical Integration	The integration of a SoI with supra-systems and sub-systems above and below it respectively

Acronyms and Abbreviations

Term	Definition
ACFC	Air Cooled Fuel Cooler
BITE	Built-In Test Equipment
CADCAM	Computer Aided Design/Computer Aided Manufacture
CADMID	Concept, Assessment, Development, Manufacture, In-service, Disposal
CMMI	Capability Maturity Model Integration
CSEP	Certified Systems Engineering Professional
DAR	Decision Analysis Review
DD	Data Dictionary
DDQS	Design Development and Quality Solution
DLoD	Defence Lines of Development
FFD	Function Flow Diagram
FFP	Fit For Purpose
FMECA	Failure Modes Effects and Criticality Analysis
HUMS	Health and Usage Monitoring System
ICT	Integrated Computer Technology
IET	Institute of Engineering and Technology
INCOSE	International Council On Systems Engineering
IR	Infra-Red
ISTAR	Intelligence, Surveillance, target Acquisition and Reconnaissance
TI	Thermal Imaging
TRAK community	The Rail Architecture frameworK community
LED	Light Emitting Diode
LoD	Lines of Development (e.g. see TEPID-OIL)
LoD+	LoDs plus Commercial, Finance and Legal constituents
LRU	Line Replaceable Unit
LU	Loughborough University
MEI	Matter, Energy or Information
ME(I)	The quantity as utilised by the FFP technique with a de-emphasis on the Information component.
MFC	Military Fuel Container
MoD	Ministry of Defence
MWC	Military Water Container
NATO	North Atlantic Treaty Organisation
OEM	Original Equipment Manufacturer

Term	Definition
PCB	Printed Circuit Board
PIVS	Process Implementation and Verification System
PLA	Product Line Architecture
PLM	Project Lifecycle Management
POST	Power On Self-Test
PRS	Process Reference System
QFD	Quality Function Deployment
RoI	Return on Investment
SE	Systems Engineering
SoI	System of Interest
SoS	System-of–Systems
SoSE	Systems-of-Systems Engineering
SSB	Source, Sink, Bearer
TCA	Transfer Component Analysis
TEPID-OIL	Training, Equipment, Personnel, Information, Doctrine – Organisation, Infrastructure, Logistics
TRS	Technical Reference System
UK	United Kingdom
USGI	United States Government Issue
UOR	Urgent Operational Requirement
WBS	Work Breakdown Structure
WO	Wave-Off

Contents

Figures

1 Introduction

This chapter contains a short description of the motivation for this research which has produced a novel technique together with a method and process to employ it, and the environment in which systems-of-systems constituents are created, operated, maintained and retired. This is followed by a statement of research aims and objectives, an outline of the research methodology used, and concludes with a description of the structure of this thesis and a reprise of this first chapter.

In today's changing world, new and ever more complex societal challenges constantly appear that require timely and effective solutions, and this trend is likely to continue as both the challenges, the systems and the system-of-systems developed to address the challenges become more interconnected and dynamic. The growth of the Internet-of Things (IoT), not including computers, mobile devices and tablets, as forecast by both technology and business organisations (Lueth 2014) predicts a dramatic increase in the number of connected devices as shown in Figure 1.1 below:

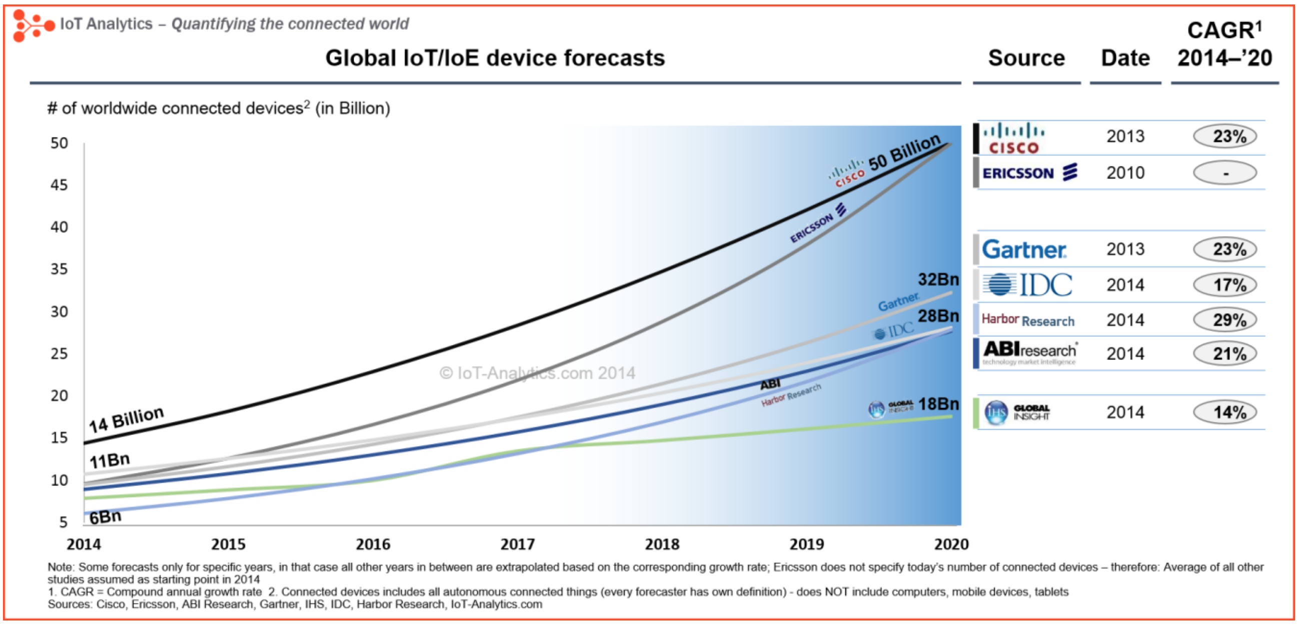


Figure 1.1: Global IoT/IoE Device Forecasts (Lueth 2014)

For instance, the challenge of maintaining the country's public health changes with population mobility, education and demographics; the healthcare response to this challenge is a complex System of Systems (SoS) that includes governmental healthcare provision, private bodies, voluntary organisations and emergency services. Furthermore, both the challenge and the response to it are affected by external influences such as the economy and political decisions; these interact and affect each other.

Financial constraints and environmental concerns increasingly influence us in both our professional and domestic lives to 'do more with less'; repair, reuse, recycle … In complex socio-technical systems, it is often the human elements that have to bridge gaps between problems and capabilities available for solutions: the aim of this work is to help them!

This situation means that capability-providing systems of systems will have constituents that are needed to operate in ways that they were not originally designed to do, will have their service lives extended, and new constituents will have to integrate into a brownfield environment. Designers are able to design for agility, robustness and resilience against the specified or foreseeable uncertainty, but any benefit from the provisions they are able to make against "unknown-unknown" (Rumsfeld 2002) factors is largely due to serendipity; but not to provide *anything* for people to use against these factors and leave them to their fate in a world of ever-increasing populations and decreasing resources seems wrong.

1.1 Aim and Objectives of the Research

A primary aim of this work is therefore to create a theoretical technique to provide a more complete view of a SoI. A secondary aim is to develop a method and process that system suppliers can use to make provision in their products to facilitate personnel close to the point of employment of a system-of-systems constituent to reconfigure their system-of-systems constituent in a timely manner to address unforeseen problems.

Personnel close to the point of employment of a system-of-systems constituent may be its operators, maintainers, controllers; whoever on a case-by-case basis is advantaged by using the facilities provided by the system supplier exploiting the outcomes of this research.

In order to fulfil the aim, a number of objectives have been formulated. The links between these objectives and the research outputs are provided in section 1.2 below.

1. Review the current literature to verify the need and formulate the research questions
2. Analyse and from this assert generically why a SoS becomes unable to do what is required of it related to the root causes for this state
3. Create a novel viewpoint of the problem and a method/process to address the problem
4. Develop and validate the concept/method/process with examples and case studies
5. Capture the research in a thesis able to assist others to implement and benefit from the research outcomes

Many successful PhD research outcomes often fulfil the academic requirement of 'Adding to the body of human knowledge' by collecting data, analysing it to find patterns and threads previously unknown and drawing conclusions from them. However in addition to this the author wanted from the outset to create something not only academics could build upon but also that systems practitioners could tailor and at a convenient time, exploit in order to provide systems practitioners an acceptable return on their investment to benefit themselves and their customers. With this in mind the author set some research tenets, viz.

- Research should supply both theoretical and practical outcomes: not 'Shelf-ware'
- Outcomes should be incremental: 'Quick Wins' en-route
- Use of the method/process should not be a burden on users: A 'minimal extra effort' on staff
- This research should use an iterative, developmental approach
- The end result should be able to be integrated and harmonised with a systems supplier's Product Lifecycle Management (PLM) system

During the first year of research Thales, an international major supplier and systems integrator of complex socio-technical systems, expressed their interest in supporting the work and subsequently became the industrial partner, providing material for method and process development.

The method and process created by this research gives an industrial exploiter a more complete insight into their SoI and its contribution to a composing SoS. The exploitation of this more complete understanding that is the focus of this thesis facilitates the maintenance of fitness-for-purpose of a SoI over its lifecycle. However it is quite likely that exploiters may use it for other purposes, such as the determination of innovation routes. It is to be understood that to get benefit from the method and process herein it has to be used thoughtfully with an understanding of the SoI, the environment in which the SoI operates and the context in which it is used. Some of the most powerful tools engineers and scientists have at their disposal are used to great effect, but by virtue of their potency also have the ability to cause highly undesirable situations with consequences ranging from increased costs to loss of life or property if used inappropriately or unwisely.

1.2 Research Outputs

This research delivers a technique that reveals covert functions in a SoI that can be utilised and built upon by academic researchers, and also a method and process to facilitate industrial exploitation. It does not deliver a 'plug-and-play' industrially deployable solution. This is outside of scope, because the design of such a deployable solution will be highly dependent on the Project Lifecycle Management (PLM) system of individual industrial exploiters, and is an engineering, rather than research task. This research does deliver a concept solution as a method with an implementing process and a PC-based concept demonstrator, and is supported by a functional demonstrator produced by a BEng. student as their final-year project.

The following research outputs have been delivered to Thales under the studentship agreement.

- Fit-For-Purpose (FFP) Research Thesis (Objective 1,2,3 and 5) containing
- Transfer Component Analysis (TCA) concept and technique (Objective 3)

- ‘Inherent’ and ‘Independent’ Material/Energy/Information Source/Sink/Bearer (MEI SSB) identification method (Objective 3)
- TCA process (Objective 3)
- PC-based implementation of the TCA concept (Objective 4)
- TCA process implementation guide (Objective 5)

1.3 Research Methodology

In essence, the methodology that has been adopted has been to abstract-up from causes of problems encountered in the design, development, verification and validation of System-of-Systems constituents, and from this abstraction to create a novel technique to provide a more complete view of a SoI, with a method and process that is practicably applicable throughout the lifecycles of System-of-Systems constituents to benefit people engaged in theorising, creating, using and maintaining the engineered systems within System-of-Systems.

1.4 Structure of this thesis

The structure of this thesis is designed to facilitate both academic and industrial readers to benefit from the research described within it. Firstly the abstract, introduction and problem formulation chapters are described which contain a brief introduction, an exploration both the problem area with associated past and current thinking on Systems-of-Systems, and then introduces the concept of ‘Fit-For-Purpose’ as used here, with an emphasis on maintaining it throughout the lifecycle which is of interest to all readers. Secondly the subsequent chapters in “Part A: Research” describe the research from an academic viewpoint and relates the TCA technique using current visualisation and analysis techniques, and thirdly those in the following “Part B: Exploitation” describe the research from an industrial viewpoint including case studies that illustrate the incorporation of these research outcomes into a system suppliers ‘creating system’ of processes and procedures, and also into their created products and services (Hitchins 2005).

Lastly Part C, the discussion, conclusion and references chapters contain analysis of the outcomes, conclusions and recommendations for further work that are of interest to all readers. Each chapter in this thesis starts and ends with brief statements about its content.

The diagram of the structure of this thesis appears as Figure 1.2 below. This structure does result in some repetition for readers of all parts, whose forbearance is requested. The numbers in brackets in the boxes in the diagram refer to the chapter numbers.

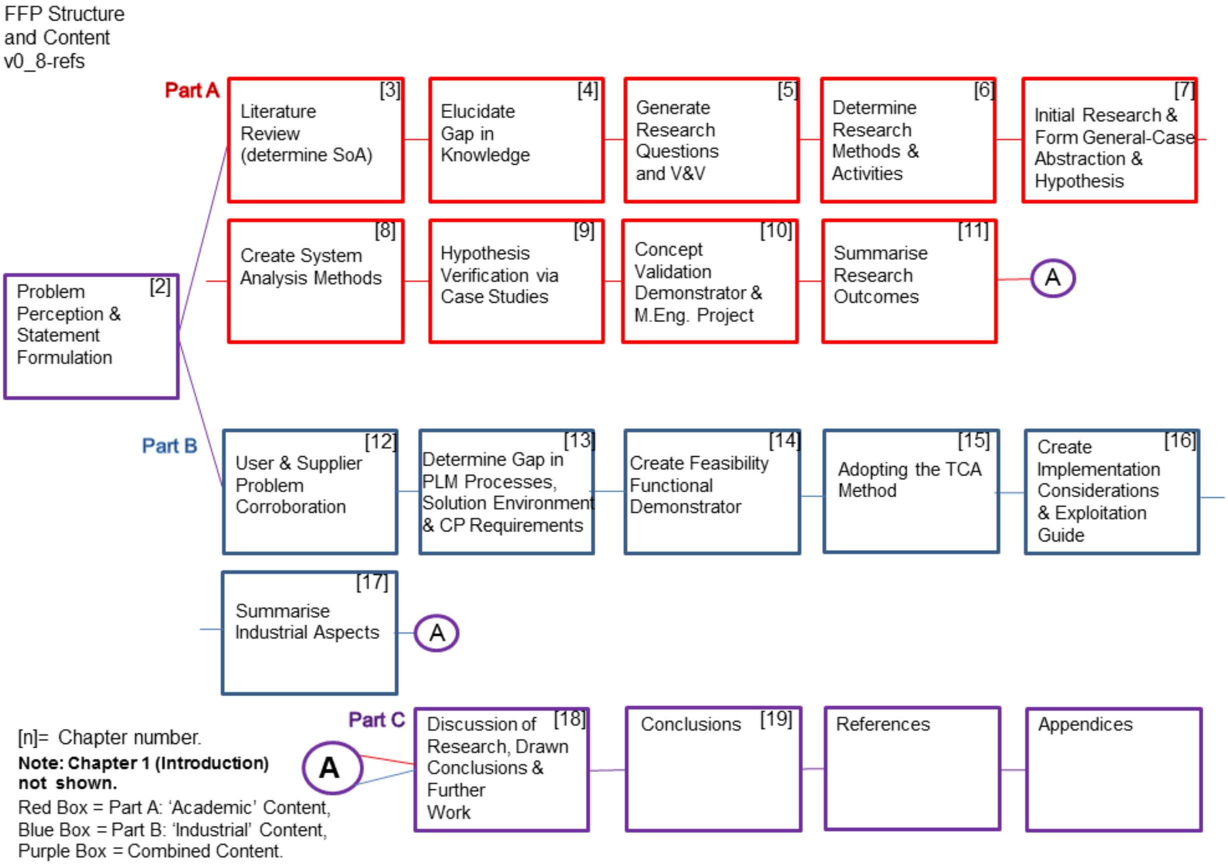


Figure 1.2: Thesis Structure

The incorporation of the TCA system analysis method/process created and developed by this PhD by a system supplier into their PLM processes will assist in exposing ME(I) SSBs that are neither captured in the system defining documentation nor managed by the design authority. These covert ME(I) SSBs might form hidden, uncontrolled and unmanaged functionality likely only to be revealed late in the system lifecycle; from the systems integration stage onwards. Revelation and timely management of covert ME(I) SSBs likely to cause undesirable emergent properties earlier in the lifecycle will be faster and cost significantly less if done in the design and development stages as opposed to being done after validation or during the in-service stages when a supplier may have to advertise stop use notices, make and fit modification kits, recall products, pay compensation and refund buyers, consequently suffering a loss of reputation in addition to significant financial cost.

The quantitative assessment of value and return-on investment from adopting the outcomes of this research can only be determined by the industrial system suppliers themselves, so this work shows the generic benefits of adopting the TCA system analysis method/process that should be obtained. Similarly, the quantitative value proposition of adoption has to be similarly ascertained on a case-by-case basis. It was in recognition of this that the method/process realising the created technique was made scalable so individual exploiters could tailor their usage to provide their preferred cost-benefit. As previously noted, it is outside the scope of this research to produce an end-to-end 'plug and play' implementation of the TCA method/process as time and resources were considered best expended on research oriented work rather than the development and engineering oriented effort necessary for a full implementation. Figure 1.3 below illustrates the scope and boundary of this research.

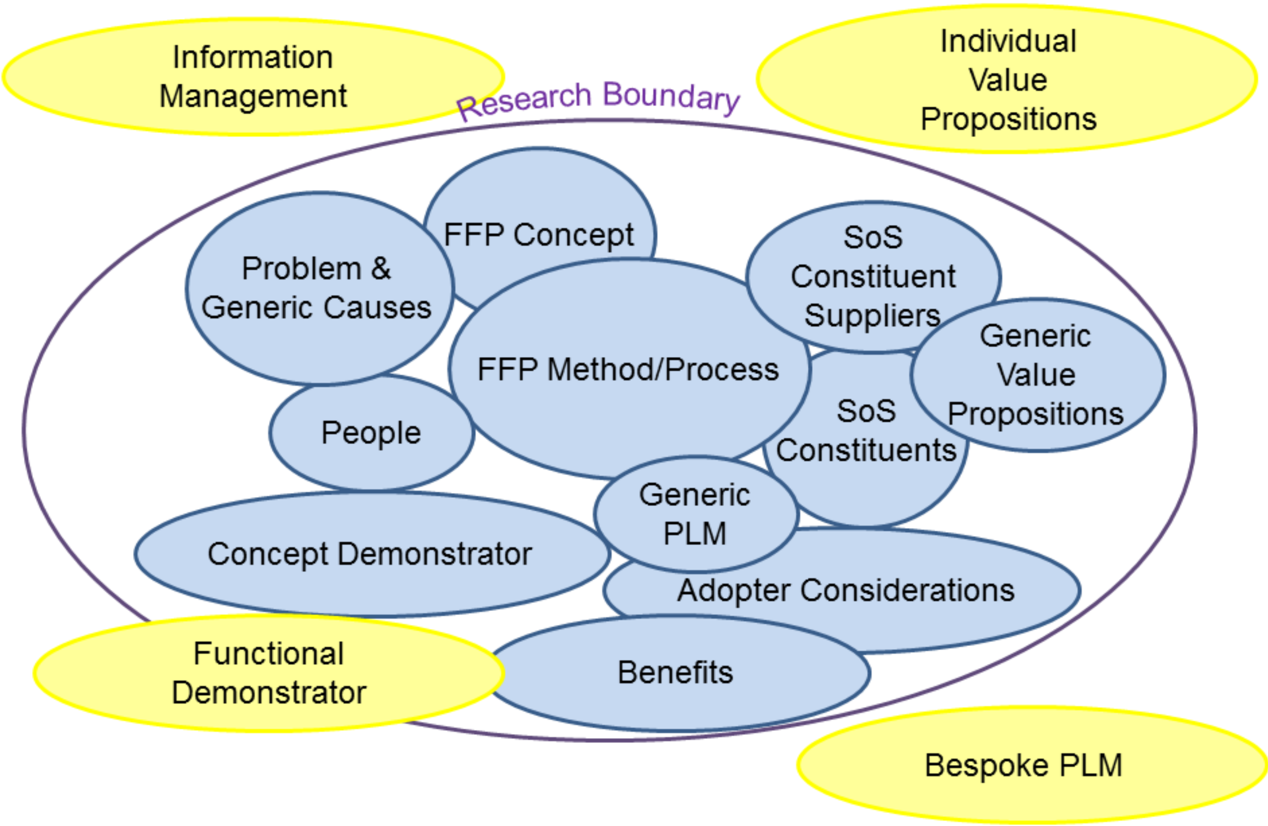


Figure 1.3: Research Scope and Boundary

This research has produced a novel technique providing a more complete view of a SoI, together with a method and process to analyse a SoI to reveal covert ME(I) SSBs that are not captured in the SoIs design definition documentation. This revealed information can be visualised and evaluated as a ME(I) meta-model utilising common representations and analyses used to design a SoI. A concept demonstrator created by the author demonstrates the validity of the concept created by this research, with a functional demonstrator demonstrating that the concept can be feasibly implemented as a tangible benefit. The functional demonstrator was developed by an undergraduate as their final year project. Both demonstrators are hosted on widely used PC applications. Whilst the literature review found work of several researchers that seemed to have resonances with this research, and it is recognised that much work has been done in the information management field (i.e. the “I” in “ME(I)”). Because of this extensive body of prior work the information aspect of transfer components is not extensively covered by this research. However the importance of information management in complex socio-technical systems is acknowledged by this research, (which an industrial partner described as a physics-oriented complement to information management), and is shown by retaining the “I” in brackets in ME(I) when referring to a MEI transfer and its components. Virtually none of the prior work reviewed seemed to draw together fitness-for-purpose with Material, Energy and Information (MEI) Sources, Sinks, Bearers (SSB) and transfers, or into a practicably applicable method, able to integrate with modern industrial engineering processes. This is the novelty that is required of this research.

1.5 Chapter Summary and Subsequent Chapters

This first chapter has introduced the perceived problem, the motivation to address it and described the desired research outcome as something to be both of academic benefit and also to be practically applicable and beneficial to those engaged with complex socio-technical Systems-of-Systems and their constituents.

Chapter 2, “Description of the Problem Area” contains a short description of the problem area, the current situation, gaps in our understanding of how to practically equip System-of-System constituents to be reconfigurable to address unforeseeable new requirements, what specific problems the research will alleviate and how the outcomes will address the gaps.

PART A: Research

Chapter 3, “Literature Review” describes the strategy and focus of the literature review pertinent to the problem addressed by this research, analyses published literature that corresponds to issues pertinent to the problem and concludes with a summary of the research focus and its novelty.

Chapter 4, “Knowledge Gaps” elucidates the gaps in current knowledge from the viewpoints of systems theory, the end-users of socio-technical systems and the suppliers of systems as constituents of an SoS.

Chapter 5, “Research Questions” Contains the research questions, how they were formulated and the validation strategy for the research outcomes.

Chapter 6, “Determine Research Methods” describes the work done to define and decide upon a research philosophy. An objective of recording a philosophy for this work is to provide a reference point for the research activities, assist structure, consistency and attempt to show where this research ‘is coming from’.

Chapter 7, "Abstraction, Hypothesis and Basis for Solution Design" contains a description of the thought process starting from the generalisation of observed problems and their abstraction into a general case, from which a hypothesis and a basis for the development of a solution was developed.

Chapter 8, "Current Engineering System Analysis and the TCA Method" contains an overview of the analysis of engineering systems as related to the creation of SoS constituents, and draws explanatory examples from the equipment component of capability. It provides a methodological platform for academics to use as a bridge between academic research and industrial exploitation by potential industrial stakeholders on the adoption of TCA: the engineering process owners who would have to integrate TCA with their existing PLM system and engineering processes, and the engineering practitioners who would use TCA to benefit their products and their engineering staff.

Chapter 9, "Hypothesis Verification Case Studies" describes examinations of case studies to verify the hypothesis and develop and mature the TCA method and process, and how they support the hypothesis developed from the abstracted problem.

Chapter 10, "Concept Validation Case Studies" firstly describes a validating concept demonstrator in the form of a concept model utilising PC-based application programmes. A complex socio-technical system forming a major part of a large SoS was modelled in the form of a case study. Secondly a validation case study of part of a fast-jet aircraft fuel system is described which was undertaken by an M.Eng student who applied the TCA technique to a current project at a major defence manufacturer as their final-year individual project.

Chapter 11 "PART A Summary" summarises the work of part A.

PART B: Exploitation

Chapter 12, "System Example, User and Supplier Problem Corroboration" firstly provides an example of a scenario where a major sub-systems ability to transfer ME(I) is enhanced and how this enhancement is capitalised upon to restore the capability to its host system SoS after an unforeseen event. Secondly the viewpoints of industrial stakeholders on their experiences and on the adoption of TCA: both the engineering practitioners who would use TCA to benefit their products and their engineering staff, the engineering process owners who would have to integrate TCA with their existing PLM system, and the customers of the system suppliers.

Chapter 13, "Process Gap, Solution Environment and Solution Requirements" describes the gap in existing PLM process that lets unintended and independent ME(I) SSBs in a SoI remain hidden. This is followed by a brief description of the THALES PLM environment and some of the processes within it. This is followed by a description of the cardinal point requirements for a TCA analysis solution able to be integrated in such a hosting PLM environment.

Chapter 14, “Feasibility Validation: Functional Demonstrator” describes a final-year individual project of a B.Eng student who developed a functional demonstrator from the concept demonstrator and the cardinal point requirement specification.

Chapter 15,”Adopting the TCA Method” is a description of the potential adoption of the technique proposed by this research as a method by an industrial user by means of a transfer cascade and a Function-Flow Diagram (FFD) representations. This is followed by an example of how they might implement the method as a chronological process.

Chapter 16, “TCA Method Implementation Considerations and Exploitation Guide” provides the guidance for potential industrial stakeholders on the adoption of TCA and how to practically incorporate it into their existing PLM system and incorporate enhancements into their products in a cost-effective manner. Stakeholders include engineering process owners who would have to integrate TCA with their existing PLM system and engineering processes, and the engineering practitioners who would use TCA to benefit their products and their engineering staff.

Chapter 17, “Part B Summary” summarises the work in Part B.

PART C: Discussion, Conclusions and Further Work

Chapter 18, “Discussion” discusses the new insight into a system that the TCA technique provides, relates the course of the research and some reflection of it to help future researchers.

Chapter 19, “Summary and Conclusions” appraises the achievement of the research aims and objectives, and summarises the responses to the research questions, the contribution to knowledge and what could be done in the future to build upon this research.

The References contain references to literature used throughout this research.

The Appendices contain further information for those readers wishing to look deeper into aspects of the research covered in the main body of this thesis.

2 Description of the Problem Area

This chapter starts by providing an overview of systems, systems-of-systems and some of the ways they are recognised, defined and engineered. This is followed by a description of some of the problems associated with systems and SoS, the concept of undesirable emergent properties and how SoS engineering can obviate or mitigate against them. Lastly the part that this research can play in preparing for unforeseen problems is described and the chapter concludes with a summary.

2.1 Systems, Systems Engineering and System-of-Systems Overview

2.1.1 Systems and Systems Engineering

A system can be considered to be a set of components connected together by design so that they act together to do something (Rechtin, 2000). What a system does is often an emergent property of the system; not attributable to any of its components, but achieved only by the components interacting as a whole in their environment (De Weck 2011). Engineering systems are often transformations; they have inputs which they transform into outputs. Initially a system may appear straightforward, but closer examination is likely to reveal a complex system where apparently simple transformation functions require people, methods, information, support infrastructure and logistics as well as the hardware and software items traditionally thought of as being under the remit of 'engineering'.

2.1.2 Systems, Lifecycle and Capability Provision

Non-trivial systems will probably contribute to the provision of a capability. Systems engineering involves the engineering of a set of components that work together to do what is required; its activities manage the vertical integration of components to create a fit-for-purpose solution. Lifecycle engineering is concerned with the engineering of a product to be fit-for-purpose throughout its life, including its horizontal integration with any predecessor and successor systems. Capability engineering ensures that the stakeholder needs are continually met as internal and external changes happen over time.

In the past customers for engineering products purchased products that they could combine together with their existing assets to provide solutions to their needs and problems; typically they procured equipment with a level of product support. Nowadays customers increasingly want to procure capability (Henshaw 2011): that is virtually everything that is required to enable them to do what they wish to do, which is likely to change over time! New systems usually fail… at least initially, and suppliers nowadays take the risk of 'getting it wrong' i.e. the delivered solution not being fit-for-purpose, and the consequences of this are also being increasingly moved from the procurer/user onto the supplier of a capability or of a component of capability.

One view of the components of capability is as Lines-of Development (LoD), of which there are several versions. Typical of these are the UK MoD Defence Lines of Development (DLoDs) (UK MoD 2008) which are seen as the components of military capability. Capability is not solely provided by equipment; the common acronym TEPIDOIL (Training / Equipment / People / Information / Doctrine / Organisation / Infrastructure / Logistics) is used to remember them (UK MoD 2008). Other LoDs such as Finance, Commercial and Legal components are all necessary for the successful provision of capability in the civilian environment. All of these capability components will have differing levels of maturity that will change over time, but nevertheless are required to combine to provide a satisfactory level of capability at any given time.

Each capability component will have a lifecycle. System components such as maintenance facilities or platform components such as vehicles will mature from conception through design and manufacture to in-service support and finally disposal. There are several lifecycle models, some of which are described later. One of these is the UK MoD CADMID lifecycle (UK MoD 2008). CADMID is an acronym for the Concept (conceptualise the component), Assessment (assess the concept against needs), Design, Manufacture, In-service support and Disposal.

An illustration of a capability component lifecycle and capability as a collection of products, for example systems and/or platforms is illustrated in Figure 2.1 below.

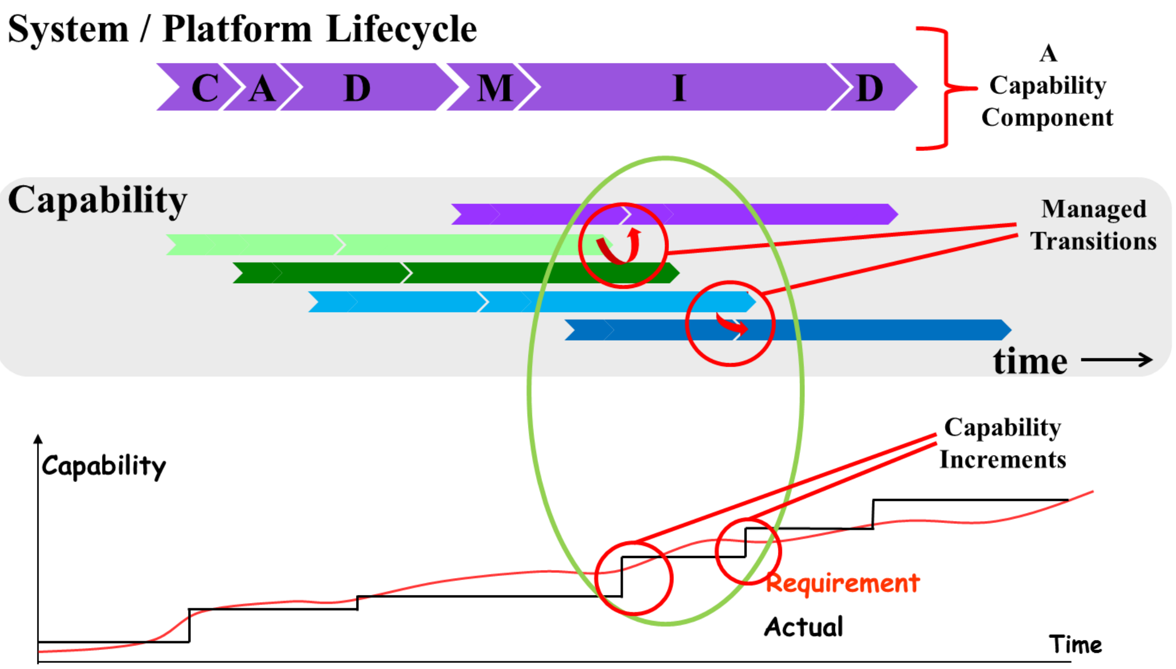


Figure 2.1: System and SoS Capability tracking a requirement

Customers often need the provision of an enduring capability, which will consist of 'lifed' and 'immortal' contributors. The Figure 2.1 above shows capability components working together to provide a capability that tracks a requirement. The red arrows are component transitions, where an existing capability component goes out of service and a new one replaces it. Capability engineering manages these ‘horizontal’ transitions to avoid transient gaps in capability and maintain the necessary capability whilst the changeover takes place. ‘Vertical’ integration of sub-systems, systems and supra-systems normally falls under the remit of systems engineering.

2.1.3 Dealing with Complexity and Reducing Uncertainty

Systems engineering is the discipline that contains tools and techniques to deal with complexity and uncertainty. These tools utilise techniques such as abstraction, modelling and simulation that are well-proven in science and engineering. Systems engineering takes a holistic approach to design systems and tailors a selection of the available tools and techniques combining them in a balance and proportion that best suits the problem at hand on a case-by-case basis to manage a system’s emergent properties (both desirable and undesirable) so that preferred system solutions can successfully address complex and uncertain problems, which may well not have a single ‘correct’ solution. As systems get larger and more complex, their constituents themselves may be systems; a System-of-Systems (SoS). A SoS might be described as a system whose constituents also have a ‘day job’, insofar that the constituents provide useful outputs in their own right as well as contribute to outputs of the SoS as a whole.

Significant amounts of prior work exist on system modelling, each technique having its advantages and disadvantages. The author does not get embroiled in the pro’s and con’s of the various system modelling techniques and their suitability for different systems engineering applications, as prior work is readily available: Loughborough University library provides access to over half a million texts on system modelling. Additionally, decisions of ‘what’ and ‘how much’ need to be decided on a case-by case basis by a projects systems engineering team that has the knowledge and experience to make an informed choice of the bespoke modelling hybrid design they consider is best suited to benefit their particular application.

2.1.4 Bounding the system of interest

It is the interactions between the constituents of a system that differentiate it from a collection of parts. The authority that these interactions have upon the status and operation of their recipients (for example internally upon other system constituents and externally upon other entities in the system environment) may vary from control to influence. The author’s concept of these interactions is as transfers of Material, Energy and Information (ME(I)) that consist of ME(I) Sources, Sinks and Bearers (SSB). These interactions are a major source of emergent behaviour. If these behaviours are to be managed, the causal interactions need to be within in the system of interest. Kinder (Kinder 2012) offers a multidimensional description of a SoS SoI that identifies nine dimensions and the relationships between them necessary to define a SoS as shown in Figure 2.2 below.

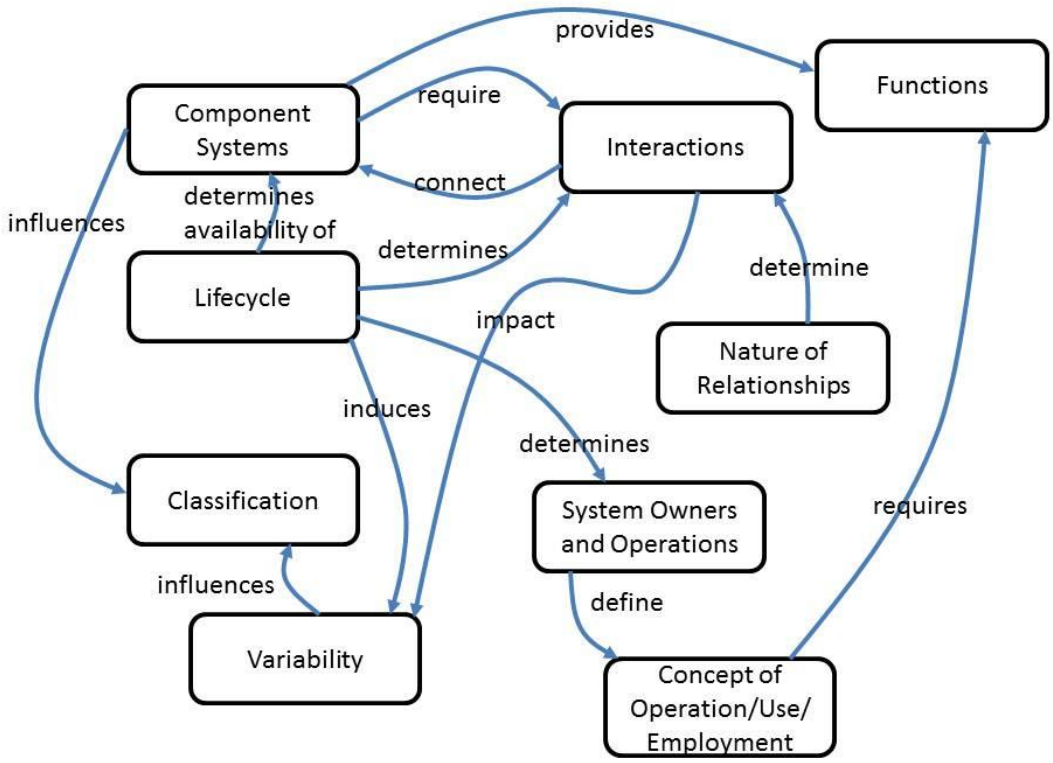


Figure 2.2: SoS Dimension Relationships (Kinder 2012)

Kinder exemplifies these dimensions with two case studies, a counter-air mission to provide protection of military assets from air attack, and the UK national programme for Information Technology in the NHS for the UK which was designed to provide an electronic patient care record and link 30,000 General Practitioner doctors to 300 hospitals. The dimension exemplars from the case studies are shown in Figure 2.3 below.

Dimensions	Case Studies	
	Counter Air Mission	National Programme for IT in the NHS (NPfIT)
Component Systems	Counter Air Aircraft (Typhoons) Command and Control Unit (E3-D, TACC) JRE Gateway (KC-135) TDL gateway (Type 45) Air Defence Artillery (Type 45) ISR (E3-D) CVS Aircraft Carrier Satellite (Skynet 5)	Choose and Book Electronic Prescription Service (EPS) National Network for the NHS (N3) NHS Mail Picture Archiving and Communication System (PACS) The Spine
Interactions	Digital Communications (Link 11/16, Satellite) Voice Communications Track Data Command and Control Imagery	N3 Network eMAIL Appointment Data Image Processing Patient records Prescriptions (electronic)
Lifecycle	Requirement, Planning, Assembly, Execution Dispersion	Concept, Design and Development , Operation, Reconfigure/Upgrade, Disposal
Variability	Assets may change during mission. The purpose may evolve as the mission progresses. This SoS may exhibit a high level of variability.	Intuitively one assumes variability is low because of the directed nature of this SoS. However, due to the poor definition of requirements component systems were frequently changed which resulted in a higher level of variability than would perhaps be expected.
Classification	Collaborative/Acknowledged. Directed elements, e.g. Link 11/16 networks	Originally Directed but later moved towards Acknowledged.
Functions	Surveillance, Reconnaissance, Targeting, Detect , Identify, Intercept, Destroy, Aircraft Control, Battle Management.	Choose and Book appointment, Change appointment, Produce prescription, Picture Archiving
Systems Owners and Operations	Nations (Governments), Services (Air force, Navy, Army), Overarching control, e.g. NATO.	Project Team, NHS Connecting for Health Local Authority / Strategic Health Authority Project Board, Board of Directors / PCT Executive Group
Concept of Operation	The SoS provides protection from air and missile threats.	Provide a single, centrally-mandated electronic care record for patients and to connect 30,000 GPs to 300 hospitals.
Nature of Relationships	Hierarchical (military C2)	Plural system of procurement. Client-Server.

Figure 2.3: Case Study Data to SoI Dimension Mapping (Kinder 2012)

Kinders work is reproduced here to stimulate thinking of SoS interactions in the reader and hence assist them to bound their SoI such that causal interactions are not omitted.

2.1.5 Systems of Systems Engineering

There are differing views on the engineering approach to large and complex systems that are described as a SoS. These range from 'It's just system engineering on a large scale' to SoS engineering as being a separate discipline associated with systems engineering.

Earlier work from several authors defines and categorises systems of systems, differences between a SoS and a system and how the approach to engineering a SoS differs from the engineering of a system, examples of which are provided below.

In 1991 Eisner, Marciniak and McMillan, (Eisner, Marciniak, and McMillan 1991) felt a SoS engineering discipline necessary because systems engineering did not have the tools and techniques to deal with very large and complex systems. They defined seven features differentiating a system from a SoS. For example a SoS is a system that has constituents having outputs useful in their own right as opposed to a system having constituents whose outputs were useful only as a contribution to the overall system output. They asserted that systems engineering that was oriented towards achieving system-level goals did not accommodate operation and behaviour of constituents having degrees of independence and duties in addition to those contributing to the larger system of which they are a part. Their seven differentiating features are:

1) There are several independently acquired systems, each under a nominal systems engineering process.
2) Overall management control over the autonomously managed systems is viewed as mandatory.
3) The time phasing between systems is arbitrary and not contractually related.
4) The system couplings can be considered neither totally dependent or independent, but rather are interdependent.
5) The individual systems tend to be uni-functional and the system of systems multi-functional.
6) The optimisation of each system does not guarantee the optimization of the overall system of systems.
7) The combined operation of the systems constitutes and represents the satisfaction of an overall coherent mission.

Eisner, Marciniak and McMillan contrasted the above citing when the well-known systems engineering discipline *is* directly applicable:

1) subsystems are acquired under centralized control
2) the program manager has almost complete autonomy
3) subsystem timing is planned and controlled
4) subsystems are coupled and interoperating
5) the system is largely uni-functional
6) trade-offs are formally carried out in an attempt to achieve optimal performance
7) the system largely satisfies a single mission.

In 2009 Jamshidi defined a SoS saying: “Systems of systems are large-scale integrated systems which are heterogeneous and independently operable on their own, but are networked together for a common goal” (Jamshidi 2009). In addition to the features of Eisner et al, Maier, and DeLaurentis described a further five and three SoS characteristics respectively.

Maier’s (Maier 1998) five characteristics distinguishing a SoS from ‘conventional’ systems are:

- Operational independence of component systems
- Managerial independence of components systems
- Geographic distribution
- Emergent behaviour
- Evolutionary development processes

Operational Independence. Any system that is part of an SoS is independent and is able to operate serviceably if the SoS is disassembled.

Managerial Independence. Despite collaborating with the other members of the SoS, the individual systems are self-governing and individually managed so that they not only can operate independently, they do operate independently."

Geographic Distribution. The parties collaborating in an SoS are distributed over a large geographic extent. Although the geographic extent is defined vaguely, it is stressed that the collaborating systems can only exchange information and not considerable quantities of mass or energy.

Evolutionary Development. An SoS existence and development are evolutionary in the sense that objectives and functionality can be under constant change, as they can be added, modified or removed with experience. Thus an SoS never appears completely formed.

Emergent Behaviour. Through the collaboration between the systems in an SoS a synergism is reach in which the system behaviour fulfils a purpose that cannot be achieved by, or attributed to, any of the individual systems. This is an emergent behaviour of the SoS through which its principal purposes are satisfied.

DeLaurentis (Delaurentis 2005) added three more characteristics:

- Inter-disciplinarily
- Heterogeneity of the systems involved
- Networks of systems.

Several pieces of previous work exist on the definition of a System-of-Systems and how they differ from large systems that reasonably concur. A typical example from an INCOSE working group is "A set or arrangement of systems that result when independent and useful systems are combined into a larger system that delivers unique capabilities." (DoD 2004)

2.1.6 System Structure and Behaviour

A SoS cannot only be defined in terms of its structure, but also in terms of its behaviour. For example a structural representation of the number, type and arrangement of a SoS interconnected constituents may be as a hierarchy of levels as in an enterprise architecture, typified by the Zachmann framework (Zachman 2008).

Alternatively a SoS could be defined with behavioural models that represent systems in terms of how they operate as described by Dahmann and Baldwin in 2008 below, or as a set of entities connected by flows, such as the widely used System Dynamics technique by Forrester (Forrester 1961). System Dynamics uses influence diagrams to model positive flows, negative flows and feedback between its constituent nodes which facilitates visualisation of supportive and detractive mechanisms that influence desired system outcomes. These visualisations can be utilised as a decision support tool. Another technique, Soft-System Modelling (SSM) by Checkland, Wilson, Scholes, and others (Checkland and Scholes 2000), (Wilson 2001) is frequently used to identify influences on and within large complex systems by qualitative and informal methods that are not readily apparent by using other methods, and hence reduce the likelihood of omission errors.

Dahmann & Baldwin (Dahmann & Baldwin, 2008) from practical experience identify four types of SoS:

- Directed: built to be a SoS in order to fulfil specific purposes.
- Acknowledged: Has agreed control with specific purposes, but only of individual systems which make up the SoS
- Collaborative: Has agreed purposes but not agreed control for how to achieve those purposes
- Virtual. Without control and agreed purposes but manages to exist regardless.

The characteristics and types outlined above are concepts that do not apply to standalone systems. Most SoS are composites of the four types with a predominant type, and may have some or all of the characteristics defined by Maier and added to by DeLaurentis. These characteristics may cause problems, or may indeed underpin the capability a SoS provides over and above that achievable by stand-alone systems.

2.1.7 Problems associated with Systems of Systems

Whilst it may be possible to predict some forms of emergent behaviour within a SoS, it is unlikely that total understanding of the interactions in a large SoS that lead to emergent behaviour can be achieved due to factors such as sheer scale, resource constraints, information dispersion, and visibility. This issue of uncertainty is exacerbated by the spread of ‘Plug and Play’ networks such as that which has been brought about by the mobile devices revolution in society.

A further problem besides emergence (and not directly addressed by Jamshidi), that this work states is that in attempting to maintain fitness for purpose, a SoS can also face “unpredictable change in operation, composition and external factors”. This issue is not one with any easy remedy, due to the range of types of systems of systems and the characteristics that these may have. However the TCA technique presented in this thesis provides one way in which this problem area can be addressed.

2.2 Undesirable Emergent Properties

Inadequate systems engineering effort can result in undesirable emergent properties and unexpected system behaviours that are often only discovered late in a system’s development phase, at systems integration, set-to-work or even in-service, when rectification is increasingly costly and time-consuming to achieve. The exposing and visualisation of obscured arrangements can show the potential for unexpected behaviour early in the lifecycle so that any avoidance and mitigation actions considered necessary can be taken early in the lifecycle.

"Directions in systems of systems engineering", an EU Commission report (EU_Commission 2012) based on a workshop in Brussels, Belgium which focused on synergies among projects and directions in advanced systems engineering, states the following:

"A key problem is that it is not possible to have a complete view of the overall system state. It is thus difficult to represent what the SoS should do, what it can do and what the SoS actually does. Quite often there are conflicting goals, e.g. traffic management, where all cars want to go the same routes for speed. Reaction times for emergency services depend on the time of day, etc. System behaviour is not predictable because the constituent systems have their own goals and the overall system has partial observability and authority. These systems may have tens of thousands of leaf systems. A challenge is to aggregate subsystems in an appropriate way eliminating unwanted behaviours by construction."

An exploiter of the outcome of this research will have a view of the 'inherent' and 'independent' material, energy and information sources, sinks and bearers in their SoI, enabling them to analyse and determine if these sources, sinks and bearers are likely to cause problems, and if considered necessary reduce unwanted behaviour to tolerable levels by informed design interventions. Interactions between these 'inherent' and 'independent' ME(I) SSBs may cause many undesirable emergent properties and behaviours exhibited by the SoI, often revealing themselves at, and after, the end of the design phase of the lifecycle when they are difficult, costly and time-consuming to suppress.

A study researching the return on investment from using Systems Engineering (SE) was conducted by the INCOSE Systems Engineering Centre of Excellence (SECOE) beginning in 2001(Honour 2004). The results uncovered an inverse correlation between cost and schedule overruns and the amount of SE effort applied to a project or development activity. Cost and schedule overruns on the reported projects are illustrated in Figure 2.4 below:

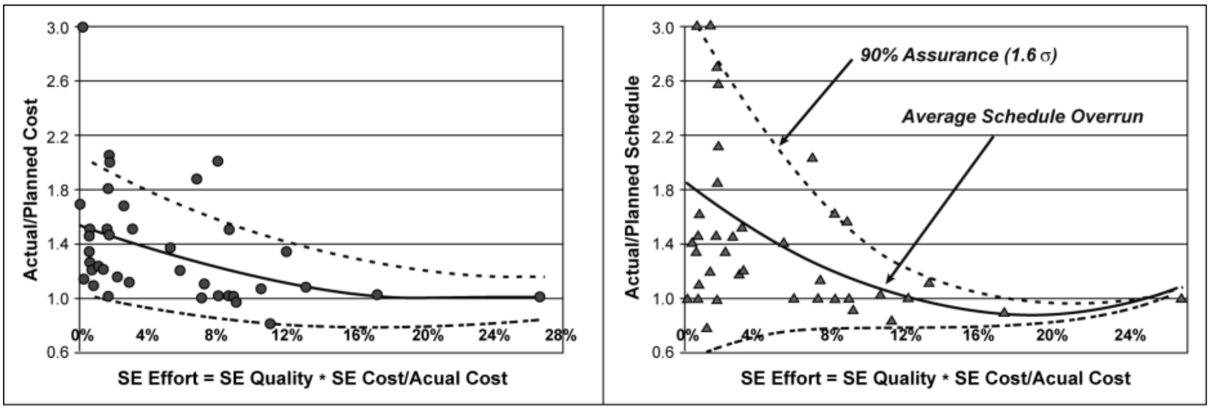


Figure 2.4: Cost and Schedule Reductions against SE Effort (Honour 2004)

Figure 2.4 shows the following effects:

- Cost overrun lessens with increasing SE effort and appears to minimize at something greater than 10% SE effort.
- Variance in the cost overrun also lessens with increasing SE effort.
- At low SE effort, a project has difficulty predicting its overrun. At 12% SE effort, the project cost is more predictable.
- Schedule overrun lessens with increasing SE effort and appears to minimize at something greater than 10% SE effort, although few data points exist to support a reliable calculation. The solid line is the least-squares trend line for a second order curve.
- Variance in the schedule overrun also lessens with increasing SE effort. At low SE effort, a project has difficulty predicting its overrun. At 12% SE effort, the project schedule is more predictable.

2.3 Research Importance

Especially in the event of unforeseen situations, Systems-of-Systems may not be fit-for-purpose, so personnel (for example maintainers) close to the point of its employment have to modify its constituent systems in response to the situation occurring; and do this in a timely manner so the system/SoS can achieve their aims. A system may become not fit-for-purpose within a SoS due to environmental changes, changes in other systems within its SoS with which it operates, or a change within itself. If necessary system modifications to restore its fitness-for-purpose are not feasible, the user's inability to complete their mission successfully may have consequences ranging from inconvenience to loss of life or property.

Effective changes required by unforeseeable situations rely on domain knowledge, situational awareness, ingenuity and resourcefulness. The output of this research aims to enable suppliers of system-of-system constituents to provide at an affordable scale something in their scope of supply which their operational customers can use their knowledge, wisdom and abilities to work with and help prevent unforeseen situations resulting in undesirable outcomes.

2.4 Coping with Unknown-Unknown Changes

At NATO HQ in Brussels in 2002, the US secretary of defence Donald Rumsfeld at a press conference spoke of an agreement made to “decide on specific new military capabilities to meet the new military threats that face us.” He went on to say:

“Now what is the message there? The message is that there are no ‘knowns.’ There are things we know that we know. There are known-unknowns. That is to say there are things that we now know we don't know. But there are also unknown-unknowns. There are things we don't know we don't know. So when we do the best we can and we pull all this information together, and we then say well that's basically what we see as the situation, that is really only the known-knowns and the known-unknowns. And each year, we discover a few more of those unknown-unknowns.”(Rumsfeld 2002).

2.5 Chapter Summary.

Users and maintainers of system-of system constituents need resources to help them reconfigure what they have to hand in a timely manner to prevent systems failing to achieve what is required of them due to unforeseeable changes in situation. This chapter began by providing an overview of systems, systems-of-systems and some of the ways they are recognised, defined and engineered then related a description of the problem area, the current situation, gaps in our understanding of how to practically provision System-of-System constituents to be reconfigurable to address unforeseen new requirements and what specific problems this research will alleviate.

PART A: Research.

This part of the thesis describes the research activities undertaken to investigate the problem described in the preceding chapters. It firstly reviews current literature to understand how the problem is perceived by others working in the field of complex socio-technical systems-of-systems, comprehend current terminology, assist the development of complementary new terms, and understand the issues pertinent to the field. Secondly, knowledge gaps are identified, and from this research questions and an approach to addressing them formulated. Thirdly some initial thinking and abstraction develops a general-case hypothesis and a technique to address the problem of maintaining fitness-for-purpose of systems-of-systems constituents in the event of unforeseen events, and how this new technique can be applied as a method that complements existing systems analysis methods. Lastly a series of case studies validate the hypothesis and the conceptual TCA technique and method created by this research.

3 Literature Review

This chapter describes the strategy and focus of the literature review pertinent to the problem addressed by this research, analyses published literature that corresponds to relevant issues and concludes with a summary of the focus of this research and the gap it fills.

3.1 Literature Review Strategy

The starting point for this literature review was the set of sources referenced as part of the research proposal accepted in October 2011 (See Appendix A1) that outlined the problem to be addressed and envisaged research outputs. This literature review is not an end product in itself; rather it is one of the first components of the set of research activities that are described in the subsequent chapters below that form a systematic analysis of maintaining a SoS fit-for-purpose. This research differs from many others, in that it does not follow a traditional formulaic gathering of data, subsequent collation, analysis and drawing of conclusions to solely provide an addition to the body of human knowledge, but also creates the foundation of an engineering artefact (a system meta-model of Material, Energy and Information Sources, Sinks and Bearers) exploitable by industry that provides benefit to the personnel that use the products and services that industry supplies, as well as benefits to the industrial suppliers themselves. Chronological literature review strategies following a timeline of documents or trends, or a methodological strategy examining systems methods such as architecting or Model Based Systems Engineering (MBSE) would not be so amenable to producing a new artefact as it might be to producing new knowledge (“Literature Reviews” 2014). Hence this literature review has a thematic, concept-centric (Levy and Ellis 2006) strategy, so as not to be strategically constrained. It follows an emphasis on ‘solving the problem’ and draws from literature across different disciplines. However, when a particular paper was discovered whilst researching a particular theme, other work from the author, associated methods and contemporary peer journals was investigated, taking account of publishing dates to assess current relevance. Although appearing below as a sequential process, in practice literature review activities were iterative; new data and information sources were found in the process of researching a particular aspect by following ‘citation trails’ through references and authors in the literature, both backwards (documents and authors *cited* by paper ‘X’) and forwards (documents and authors *citing* paper ‘X’) (Watson, R, Webster, J 2002).

- Corroborate problem identified in research proposal
- Identify candidate data and information sources
- Formulate research focus
- Identify key words and synonyms
- Define search methods and strings
- Decide source selection criteria and emphasis
- Check references: images / copyright / IP

A commonly posed question, that is often easier to answer in hindsight, is ‘How much is enough?’ In engineering disciplines this question often arises where not only research, but also where analysis, modelling, testing, and indeed systems engineering is concerned. (Levy and Ellis 2006) recognised that a literature review could be an endless task, but they as well as (Leedy and Ormrod, 2005) provide guidance to literature reviewers that ‘enough’ has been achieved when fresh literature doesn’t add to that already discovered. The literature reviewing activity of this research followed something akin to a decay curve, insofar that literature review activity was high in the early stages and reduced as the research resources increasingly focussed on the development of its own ideas, but the literature review activity never reaching zero.

The following subsections describe the strategy and focus adopted for the literature review.

3.1.1 Problem Corroboration

The motivation for this research came from the author’s own experience as an engineer working in the aerospace industry. The initial literature review task confirmed that this experience was not unique and not merely attributable to personal misfortune, and that there was a consensus that something needed to be done. The research proposal was informed by an initial literature review which referenced technical journal papers, conference papers, systems and systems-of-systems engineering guides, governmental policy documents, studies, organisation web pages and textbooks.

3.1.2 Identify data and information sources

Data and information sources include, but are not limited to Thales, Library, professional bodies, engineering journals, texts, engineering periodicals, system creators and user communities, research papers, institutions, conferences, webinars, tool suppliers, consultancies, industrial colleagues, institute working groups, and interest groups.

3.1.3 Research Focus

This research focusses upon the transfers of ME(I) and the SSB components from which intentional (i.e. existing by design) transfer affordances are constructed, and also those ME(I) SSB components that are inherent with the implementation of the intentional ME(I) transfers and those that are independent of the SoI but may affect its operation. This research has less emphasis on information transfer as research on this aspect is relatively widespread.

3.1.4 Key Words

Capability; Fit-For-Purpose; Affordance; Material Energy Information; Socio-technical; Systems; Systems-of-Systems; Resilience; Robustness; Transfers; Agility; Re-configurability; Reuse; Product Line Architecture; Fit For Purpose; System supplier; Systems integration

The strategy and focus can be summarised as:

- Focus and scope research to what is achievable in order to meet academic criteria and provide an industrially exploitable outcome with available resources
- Follow relevant threads of topics, references and authors in the literature to inform determination of root causes, how the research should address them, and what the research outcomes should be
- Continue reading literature within scope on an on-going basis in parallel with other research activities

3.1.5 Literature Review Focus

The foci of the literature review described in the following sections of this chapter firstly starts with an exploration of the need to which this research responds, and secondly examines Systems-of-Systems which this research aims to benefit. These first two provide the research with context and an informed point of departure. The review then looks deeper into the constituent systems of SoS' from the perspective of capability provision and the issues concerning how a SoS constituents fitness for purpose might be realistically maintained from the perspective of ME(I) transfers. This provided information on other work pertinent to inform this research as to what might be practically achievable. Previous work on the assessment of fitness for purpose, its traceability and characteristic decay was reviewed, but these areas were thought not be able to provide research outcomes of sufficiently readily applicable value, and hence were acknowledged but not extensively pursued by this research. Exploration of 'unknown' and 'Wicked' problems tempered the pursuit of universal and definitive solutions for incompletely understood problems in the non-deterministic situations in which complex socio-technical systems-of-systems often operate.

3.2 The Need for Re-configurability

Several quotations below illustrate the issues involved; while there is a military basis for many of them, they are applicable to the civilian world, appertaining to search-and-rescue, emergency services, disaster relief, etc. as well.

General Sir Rupert Smith was quoted earlier, saying that from his experience he considers every operation will require him to re-organise and change methods as a normal and necessary activity to be able to achieve his military objective.

The cause of necessary reconfigurations may be unforeseen, but could be foreseeable. It is common engineering good practice as part of a design review process to conduct a risk and opportunity analysis to inform design for robustness and resilience to eliminate risks or mitigate the effects should a foreseeable undesirable event considered a risk becomes realised. These engineering activities complement this research which has its emphasis on events not foreseeable. "Unknown-unknown" factors pose a significant challenge which is required to be addressed. (Boardman and Sauser 2006) state "the uncertain and unknowable environment in which the SoS must operate presents a mystery of endless proportions, the only proper response to which is to have increasing variety, of a continually emerging nature, to deal with unforeseeable reality that eventually becomes clear and present danger." In the US, the acquisition process has focussed on system development, and "the war fighter has been responsible to integrate the available systems to meet their needs" (Dahmann & Baldwin 2008).

Systems leaders such as military commanders and CEOs "care less about the make-up of the system, as an objective per se, but more about its ability to survive and prosper in uncertain environments perpetually changing in unknowable ways that increasingly appear to be more actively lethal with purposeful intent to secure my system's demise" (Boardman and Sauser 2006). "A system formalized by prescient design cannot respond to unforeseen situations." (Ring, 2012). The MITRE organisation has what it describes as an evolving software-oriented design concept of "Composable Capabilities On Demand "(CCOD)" (D Alberts, Gartska, and Stein 2012) to allow "operators to combine services, data and existing systems to achieve awareness of, or respond to, a new situation", but acknowledges that "CCODs run-time and user-facing tenets that are rarely considered in the systems engineering and acquisition realms".

The above references support the view that some degree of re-configurability is a necessary characteristic of a system-of-system constituent, so that constituents can accommodate changes in their environment and remain able to be maintained as fit-for-purpose. Systems that are engineered cognisant of their role in the provision of a capability take account of vertical (sub and supra systems) and horizontal (legacy and successor systems) and have qualities of interoperability, robustness, resilience and agility built into them. However, the current engineering techniques used to endow these qualities are less effective when the changes the SoI will experience are unforeseeable. The method and process created by this research complements existing approaches, providing a more complete view of the SoI and hence enables systems constituent suppliers to facilitate timely reconfiguration that addresses unforeseeable changes by the users and maintainers that are usually first to experience an unforeseeable change.

3.3 Definition of 'System-of-Systems' (SoS)

There is not a single agreed definition of the term 'System of Systems'. Several definitions exist, each definition appearing to be tailored by its author to their area of interest when it was written. The definition given by (Jamshidi 2009) seems the most relevant to this research to date, viz.

> "Systems of Systems are large-scale integrated systems which are heterogeneous and independently operable on their own, but are networked together for a common goal."

A collection of constituent systems is often referred to as a SoS, however it is the author's view that 'integrated' suggests very tight coupling within and between SoS constituents, which may not always be the case. For example, the coupling between personnel responsible for strategy and those carrying out tasks. This research agrees with the view of Kinder that "A SoS exists only because of the interactions between the constituent systems" (Kinder 2012), the word 'interaction' better representing the variety of transfers occurring within large scale systems. Lawson describes a "Respondent System" formed from selected "System Assets" addressing a "Situation System" (Lawson 2010). If SoS constituents have no interactions pursuant of the SoS goal, this research considers them as "System Assets": i.e. a collection of candidate SoS constituents ready to be composed together and interact with each other as a SoS in pursuit of the SoS' goal. These definitions are 'comfortable' to an engineering discipline dealing with tangible components, connections, behaviours and boundaries, however Skyttner's definition of a system seems better aligned with dynamic situations containing multiple viewpoints and unknown-unknowns. (Sykttner 2006) He defines a system thus:

> "A system is not something presented to an observer; it is something to be recognised. Most often the word does not refer to existing things in the real world but rather to a way of organising our thoughts about the real world. The constructivist view of reality states that systems do not exist in the real world independent of the human mind; ... the fictionalist view takes a further step and states that the systemic concept can be well suited to its purpose even if we know that it is incorrect or full of contradictions in a specific situation".

The constructionist view poses significant problems for bounding the SoI such that practical problems are tractable, but many in the engineering disciplines would agree with the fictionalist view, and it has meaning for this research with its resonance to the concept of a fit-for-purpose SoS being able to "satisfice". Satisfice is defined as "To act in such a way as to achieve the minimum requirements for a particular result".(Sillitto 2012).

3.4 System-of-Systems Constituents, Transfers, Affordances and their Components

An existing constituent of a system of systems to fulfil a need or requirement will have been designed to reflect what the customer wants to achieve with it and how it will be used. The requirement will be influenced by the customers' business model and their way of working, for example their organisational structure, operating processes facilities, skills, etc. that they have established in order to do what they want in the manner that they want to do it. SoS constituents are not capable of working together to provide an enduring capability without the associated training, crew, fuel, maintenance, etc; for example a single system such as a lorry, ship or aircraft would not be capable of sustainably providing the ability to transport goods without these associated supporting components.

The UK MoD considers military capability to consist of eight "TEPIDOIL" LoD components, (Training / Equipment / People / Information / Doctrine and concepts / Organisation / Infrastructure / Logistics). The UK MoD defines Defence LoDs (DLoD) as "the elements that must be brought together to deliver military capability to operational users" and states that "In addition to the defence LoDs, Interoperability is included as an overarching theme that must be considered when any defence LoD is being addressed" (UK MoD 2008). Figure 3.1 below illustrates the relationships between the constituents of a SoS that consist of LoD quantities.

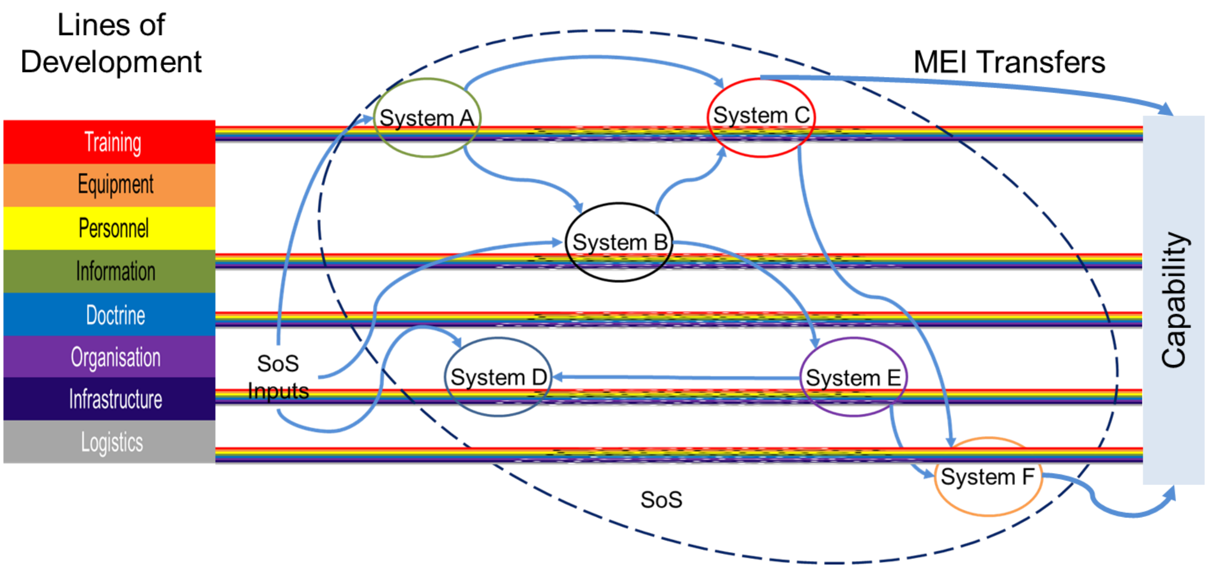


Figure 3.1: SoS and LoDs

However, as previously said there are other supporting capability components which are necessary to be able to deliver capability in the broader sense, such as Finance, Commercial and Legal components that are necessary for the successful provision of capability. This expanded set of LoDs is termed here as 'LoD+': capability components that combine to provide a level of capability at a given time.

Finance, Legal and Commercial increasingly need to be in place as private industry continues to move closer to front-line operations, taking on responsibilities and accountabilities previously held by the customer. The owner operating a SoS may have to transfer commercially sensitive information to a constituent system, and the commercial arrangements would need to accommodate this. The SoS owner may need to be confident in the financial security of a private company supplying spare parts, or training that may have previously been held in-house.

Additionally the maturity of each LoD+ will differ, and also vary over time, and hence needs to be managed over the lifecycle of each system so that it is able to deliver what is required to meet its own requirements and make the contribution necessary for the SoS to meet its requirements at a given time. For example, there are stages in the lifecycle of both a system and its SoS where current functionality, performance, constraints etc. have to be demonstrated to have been met to gain stage payments, conformance certification, legal compliance etc. A necessary level of maturity of each LoD+ is necessary at these stages, which can be visualised using a pipe model shown in Figure 3.2 below, where each 'rod' in the pipe lengthens with increasing maturity and with the others form a profiled surface of LoD+ 'rods' at the end. The development of the LoD+ maturity profile has to be managed to ensure it is sufficient for the system to meet the requirements of each stage.

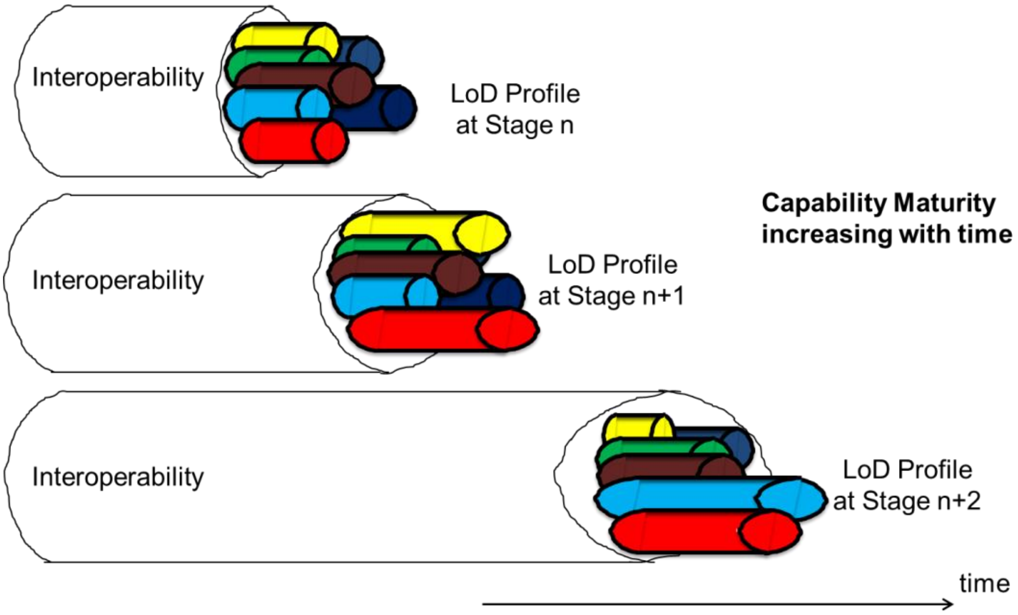


Figure 3.2: LoD Maturity Pipe Model

The The Rail Architecture frameworK (TRAK) community comments that the DLoDs are "Useful to ensure completeness of coverage but there is a tendency to immediately jump into one of these DLoDs and forget 'the whole' i.e. more integration and ownership of the whole not just the individual DLoDs. The whole is almost certainly not the sum of the DLoD parts. It isn't obvious from the [UK MoD Acquisition Operating Framework] AOF whether Interoperability is a DLoD - it seems to suggest that it is not but it is listed with the others and treated in exactly the same way. It would be useful to have a small model showing how the DLoDs affect or depend on each other - this would show where communication needs to occur and identify typical products that are necessary and which need to be managed." (TRAK, n.d.)

System Engineering has been described as "The management of the emergent properties" (Burrowes and Squair 1999). Emergent properties are not attributable to one component of the system, so accordingly SoSE has a strong focus on the interactions between system components, and accordingly this research has a focus on the interactions between the constituents of a SoS. At the fundamental level, the author's conceptualisation of these interactions is as transfers of Matter, Energy and Information (MEI). Maier and Fadel reference the Pahl & Beitz framework and their modelling of [system] artefacts as "generic systems with boundaries and inputs and outputs of material, energy and information" (J. R. Maier and Fadel 2008). Thus the designed operation of an instantiated SoS of interest is predicated upon the correct, timely and complete interchange of matter, energy and information between the SoS constituents.

ME(I) transfers are considered in terms of affordances and their components. The elemental components of an ME(I) transfer are considered to be Source, Sink and Bearer (SSB). The SoS analysed by the method applied to a System of Interest (SoI) will reveal its ME(I) transfer components, some of which will form 'intended', prospective and potential affordances for ME(I) transfer.

3.5 System Transfer Characterisation and Enhancement Considerations

This research has created an analysis method and process that engineers SoS constituent systems to equip SoS to maintain fitness-for-purpose after experiencing unpredictable changes in operation, internal and/or external factors. However as previously said, it is not a panacea for all ills. A SoS' constituent systems will have 'intended' (designed-for) affordances for ME(I) transfer, consisting of ME(I) Sources, Sinks and Bearers (SSBs), as well as 'inherent' and 'independent' ME(I) SSBs that may have the ability and/or opportunity for MEI transfer. Use of the TCA method reveals to systems suppliers ME(I) SSBs that could be exploited using provisions built-in to the SoI at a convenient design opportunity for the personnel close to the SoI's point of employment to exploit them at a later date to enhance the SoI's affordance for ME(I) transfer.

From an implementer's viewpoint, Dahmann et al. state "unanticipated changes in the external environment may occur during development (e.g., changes in national priorities, funding, threat assessments, and magnitude or nature of the demands placed on SoS capabilities), and they may have an overriding effect on user capabilities required or able to be delivered, further complicating the work of the systems engineer." (Dahmann & Baldwin 2008).

Care must be taken in the provision of affordances: in the extreme case, providing the ability to connect anything to anything would result in the ability to produce undesirable and perhaps unsafe configurations. Sillitto remarks that "affordances will lead to interactions whether planned or not" (Sillitto 2011). This research limits itself to identifying the SoIs ability and opportunity for unintended ME(I) transfer, as the bounds and interlocks to prevent undesirable connections are considered largely application specific. Subject matter experts familiar with the SoI should decide if the revealed unintended ME(I) SSBs will be either problematic or an opportunity to be exploited, and subsequently take appropriate action on a case-by-case basis.

Senior stakeholders may need some convincing to fund provision of system affordances that may be rarely utilised and delay or inhibit the introduction of replacement systems, which may have adverse effects on a SoS constituent supplier's business from both commercial and legal viewpoints. McManus and Hastings found that "in general there is no motivation in traditional processes for creating 'excess' capacity once requirements are met." (Mcmanus and Hastings 2006).

Capabilities such as Air Traffic Control are implemented by several SoS, and are required to provide an adequate level of service on a continual basis. The system assets that may become SoS constituents often have a finite availability and useful life. The question is how to manage the transitions of a SoS' constituents coming in and out of usage to maintain the required level of service, as described by Maier (Maier, 2012), the SoS' need for "Stable Intermediate Forms". The use of this phrase in this research is not intended to suggest that these forms are necessarily waypoints en-route to a destination, just that the SoS' evolution may well not be non-linear, for example as loosely planned 'bursts'.

3.6 What is Fit-For-Purpose?

The definitions of Fit-For-Purpose are almost as numerous and diverse as those for 'Systems Engineering'. The Macmillan dictionary defines fit-for purpose as "good enough to do the job it was designed to do" (Macmillan). In engineering design 'good enough' relates to performance requirements; how much, how fast, etc. 'To do' describes the actions of the solution; its functional requirements. 'The job' is the expression of the customer's needs in his terms. This will need translating into requirements expressed in engineering terms against which a solution can be designed. 'It' is the solution delivered to the customer. 'Designed to do' is the whole design process that takes account of implicit requirements, non-functional requirements (constraints), make provision for sub-systems, supra-systems, legacy and successor systems as well as the associated LoD+ described earlier, and additionally what 'creating system' is required to create, accommodate pre- and post-delivery changes and still deliver the solution to deliver a fit-for-purpose within the required timescales.

A definition from the information security domain is that it is the role of the vendor to ensure that its solution "is (indeed) fit for the purpose which their client expects" (RU Secure 2013). The challenge addressed by this research as stated above is to enable systems to be maintained to be fit-for-purpose after unpredictable changes in operation, internal or external factors.

The LoD pipe model in Figure 3.2 above could be used to visualise an end-profile of LoDs at maturities necessary to provide a capability fit-for-purpose. A system has a LoD maturity profile with a history; it has been arrived at through design, development and experience taking place in the environment at the time. LoD profiles other than the system profile could also provide a fit-for-purpose route assurance capability if the development history was different. There is a LoD+ trade space: for example a highly mature equipment line could provide low maintenance automated equipment that did not require such maturity of infrastructure, personnel and training as would be required by a less developed equipment line. Thus, if an unforeseen change means the current system LoD profile no longer provides a fit-for-purpose system, there are options to restore fitness-for-purpose other than making up individual LoD shortfalls. For example, a SoS maintains the safety of land transport routes used by the local community to travel between a town and outlying villages. It was desired to change SoS operation to route proving as a convoy to assist drovers to contain an outbreak of cattle disease, so personnel, information, infrastructure and logistics lines were developed to maintain fitness for purpose with operational change. An internal change such as a change in leadership may mean development of alternative doctrine and organisation. An external change, such as the extension of water supply and drainage to the outskirts of the town could necessitate changes to equipment, training and information LoDs.

The author acknowledges that fit-for-purpose means different thing to different stakeholders, but to find a universally accepted definition of fit-for purpose that is universally accepted by the systems engineering community is not considered best use of the resources available to this research; indeed its definition is an ongoing problem. Challenges as cited by the INCOSE MBSE community included “Fit-For-Purpose Definition, Examples and Best Practices” (INCOSE MBSE WG 2012).

This research considers that a SoS constituent which has been re-configured close to its point of employment in order to address an unforeseen need in a timely manner probably will not have levels of function and performance equal to those it was designed to have to address a known need. With this in mind this research explores the provision of a method to increase the likelihood of a SoS to satisfice the main engaged stakeholders at their time of interest without unduly prejudicing its ability to satisfice in the future. This research considers a SoS fit-for-purpose if it is able to satisfice (i.e meet the minimum requirements of its) integral stakeholders for achieving a particular result. How ‘minimum requirements’ are determined is an associated challenge. Although a noble aspiration, it is considered unfeasible to engineer a SoS that completely satisfies all stakeholders all of the time.

3.7 How to Assess Fitness-for-Purpose: Quantitative and/or Qualitative?

It is acknowledged that it is the stakeholder who benefits from the SoS who judges if it is fit-for-purpose or not. The benefitting stakeholder could be those who are part of the SoS, such as a person located and recovered by a search and rescue SoS, or those that purchased the SoS such as a government requiring an SoS to establish and maintain border security. To be fit-for-purpose a delivered product needs qualities desired by its customer stakeholder. Sillito says “Whether work products are fit-for-purpose is defined not by the person doing the work, but by the person who will use the results” (Sillitto 2010). In a complex socio-technical system / SoS, fitness-for-purpose may be dependent upon several system characteristics, which may be of a readily quantifiable type, such as a performance characteristic, or of a qualitative type, such as culture or morale. However, all factors that significantly affect fitness-for-purpose of both of these types of characteristics need to be sufficiently determined and assessable to demonstrate changes in fitness-for-purpose.

Stakeholder-perceived product qualities as illustrated by the Kano model often decay over time (Jenney 2011) because the product’s operational scenario is not static. Even if fit-for-purpose at a point in time, many factors both internal and external to a SoS will change, as may what is required of it. For example a SoS such as a maritime coastguard contains several complex constituent systems such as vessels, aircraft, satellites, control centres, depots etc. The performance of hardware will reduce and it will become more unreliable as it nears the end of its design life. An information management system may become largely unfit-for purpose within 3-5 years due to increasing processing or storage demands on it, such as updates to its operating system or application programmes. The SoS customer beneficiary may have a change in their situation requiring the SoS user to increase capacity, or run different and more demanding applications. Additionally stakeholders may suffer a reduction or loss of operational outcome whilst maintenance is on-going, which may range from inconvenient to unacceptable.

Tom DeMarco, who amongst others made the often-quoted statement “You can’t control what you can’t measure” no longer believes that metrics are a must for a successful software development project (Demarco 2009), as a software project’s metrics are “much less precise in capturing the things they set out to describe” than a ‘physics’ based project, and must be “taken with a grain of salt, rather than trusted without reservation”. His illustration of this by an analogy to bringing up a teenager, where control is probably unattainable and the desired outcomes are immeasurable could well be applied to complex socio-technical systems, which are the subject of this research. DeMarco recommends the management of people and the control of time and money, which corresponds to the author’s view that attempting to provide a purely quantitative measure of fitness-for-purpose of a complex socio-technical system is folly, and a more representative measure would be a hybrid of both quantitative and qualitative assessments.

3.8 Fitness-for-Purpose Traceability

This section has been included to illustrate conceptually how fit-for-purpose traceability might be integrated into a system supplier’s integrated modelling environment containing the engineering models used to hold a products technical data and build state definition.

It may be desirable to be able to establish fitness-for-purpose traceability. The traceability “stories” between fit-for-purpose, ME(I) transfers and transfer affordances of the SoI need to be transparent, readily comprehensible and credible to a wide range of stakeholders for them to buy-in to fit-for-purpose assessments from the method created as the research output. Traceability could be shown by the use of a concatenated set of Operational Research/ Management Science (OR/MS) models approach as used in industrial litigation cases. Described below is the approach used by Professor Susan Howick of the Strathclyde Business School to argue where responsibility lies subsequent to an industrial incident or stakeholder conflict requiring legal resolution (Howick 2012).

These OR/MS hybrid models have been used in the built environment domain and have a significant engineering content. They are commissioned by one party involved in litigation and used essentially to support argument for the apportionment of blame. Howick only gets one side of the story! The model is constructed from a set of connected models. These range from cognitive maps to systems dynamics simulation models as shown in Figure 3.3 below.

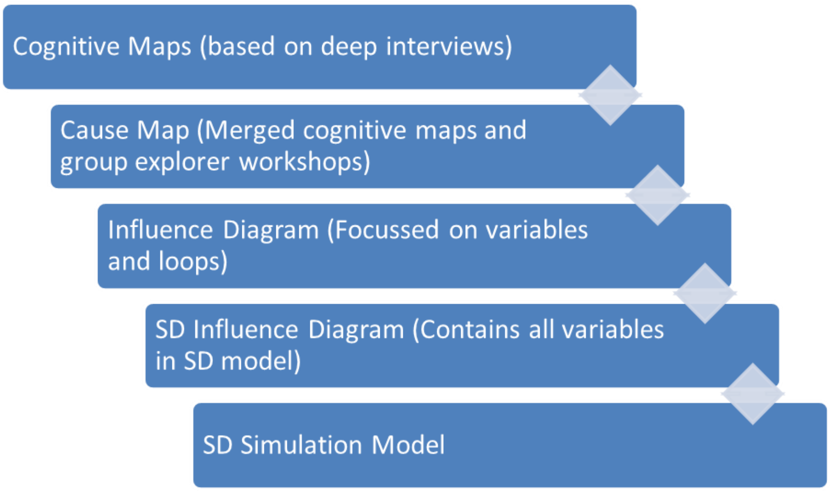


Figure 3.3: OR/MS Hybrid Model (Howick 2012)

The 'Lawyers' are able to relate more to the top end of the set, and 'Engineers' more to the bottom end. The model set was implemented using Vensim, Powersim, and I-Think, with the model links utilising Design Explore, models being kept as simple as possible. Because of the model's usage, it has to be convincing, highly transparent and auditable, and comprehensible to a diverse stakeholder skill set.

Difficulties exist in quantifying some quantities, such as "Decline in Engineering Morale" which is in the cause map, but 'it has to be done'. Cause maps 'capture the story'. Design Explore is used to group / remove quantities for simplification. For the system dynamics simulation model, commentary was stripped away to focus on the key variables.

One application modelled an aircraft modification project to examine productivity for each aircraft modified. The project had significant subjectivity, which was addressed by several sensitivity analyses. Another application modelled the impact of future scenarios on the energy market, and the trading of Renewable Obligation Certificates (ROCs) on the free market. In order to value ROCs, parallel group working was used with the Group Explorer software process utilising a PC for each group member and one public screen, which was found to be very time-efficient for generating ideas. System dynamics models showed how resources were accumulated and distributed over time for various scenarios.

Conclusions from Howick's Experience included:

- Benefits obtained from Individual Models (OA and MS)
- Different models achieve different client objectives
- Client understands model in one language
- Enhanced Client Ownership

Benefits from Both Models

- Clients see links from day-to-day events to system structure
- Triangulation: more robust results (corroborated validation)
- Pulling-in different audiences at different stages of modelling

Combined models showed structure causing day-to-day problems, not the lack of staff competence.

Lessons for modellers include the following:

- Ensure multiple modellers have an appreciation of each other and what they are trying to achieve
- Understand each other's' 'implicit scripts' (Pre-conceptions of what the modelling exercise output will look like)

It is acknowledged that models have a very valuable role as virtual prototypes for the assessment of complex systems / SoS and prediction of their performance and behaviour, but also that they are not all things to all men, have their limitations and are often used outside of their original scope. We can model what we know, but simulation "is a ponderous method of analysis, it is not well-suited to exploring the unknown" (Roske 1998)

Howick's work is a credible candidate to provide explicit traceability of SoS characteristics to SoS constituent system functionality and appears to be a step towards an integrated modelling environment accommodating both qualitative and quantitative assessments. As previously described, what defines fit-for-purpose is determined by the beneficiaries of the SoI, and as such is very much dependant on the case in question. Resources could have been spent exploring fitness-for-purpose traceability and producing a set of models, but would need to be implemented using the preferred tools and able to be integrated the host IT platforms and applications of both the SoI project resources and the industrial partners product lifecycle management system, applied to a detailed case study. However as these were not available, it was considered that the resources available to the author would be better spent developing the method and tool that revealed 'intended', 'inherent' and 'independent' ME(I) SSBs which are the building blocks of the ME(I) transfer affordances present in all engineered SoS that enable system and hence SoS functionality and behaviours necessary for them to be fit-for-purpose.

Howick's work provides a different approach to the examination of mechanisms producing high-level characteristics and behaviours at the system and SoS level that have contributing elements often embedded in sub-systems and components buried at much lower levels. Identification of these low-level contributors which may seem relatively trivial can have disproportionate effects at higher levels, and are notoriously difficult to detect. Engineers are familiar with Failure Modes Effects and Criticality Analysis driven from the viewpoint of the maintenance of system functionality and performance, but this may be usefully augmented with a complementary analysis from a less hard-engineering viewpoint more cognisant of human elements and impacts on the wider (in this case legal) systems.

3.9 Fitness-for-Purpose Drift

In a similar manner to the Kano diagram illustration shown in Figure 3.4 below of a products feature(s) that once delighted the customer now becoming desirable and then essential as time progresses, fitness-for-purpose attributes are also thought to decay over time (Jenney 2011, Baxter 1995*).* This trend is described as being 'with time', and although there may be SoS constituent decay, the trend is rather with product familiarity and usage. Additionally the fitness-for-purpose 'target' may change, and its change dynamics may be greater than the extent to which the SoI can be reconfigured to track it and satisfice benefiting stakeholders.

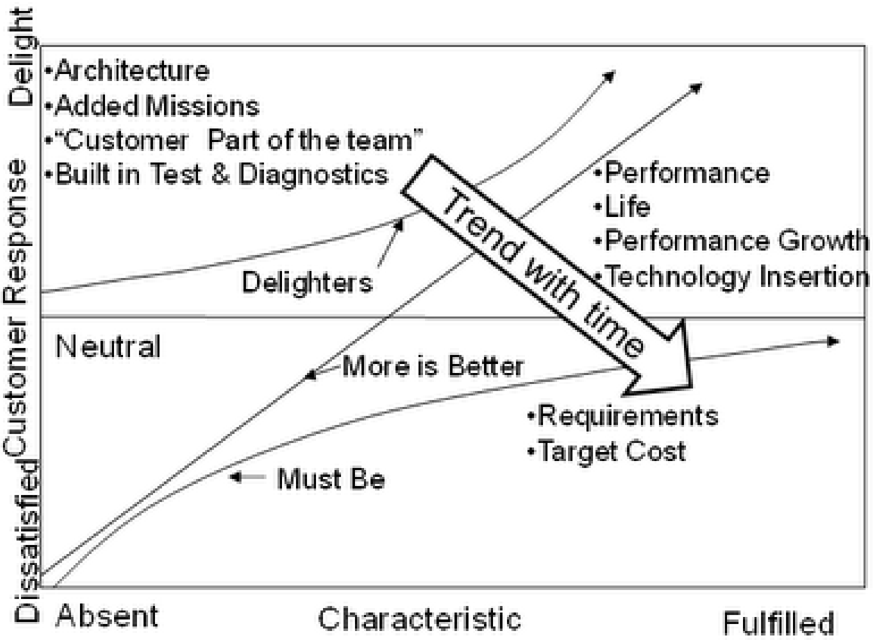


Figure 3.4: Kano diagram (Jenney, 2011 Baxter 1995)

This research is focussed upon enabling reconfiguration of SoS constituents in a timely manner to address unforeseeable change. It is considered that the dynamics of these changes are much higher, and much less foreseeable than the decay in fitness-for-purpose illustrated by Kano, and are relatively effectively addressable by established engineering practices, for example by including improvement-through-spares, fitted-for-but-not-with and planned mid-life upgrades. Hence fitness-for-purpose decay due to the Kano effect is acknowledged by this research but the author felt that the problem of unforeseeable changes not addressed by current engineering practice needed to be the focus of this research.

3.10 The problem of “Known-Unknowns” and “Unknown-Unknowns”

Systems can be successfully engineered to meet known requirements, and also to varying degrees against unknown requirements whose range is known, to ensure fitness-for-purpose over the useful life of the system. For example, factors known from the project outset such as the range of climatic operating environments can be accommodated by specifying relevant standards, engineering component selection policies and protective measures.

Some system characteristics and attributes, such as reliability, availability, maintainability etc., do not fall neatly under the remit of one or more of the traditional engineering disciplines. INCOSE describes these ‘ility’ attributes as “The developmental, operational, and support requirements a program must address (e.g., availability, maintainability, vulnerability, reliability, supportability, etc.)” (INCOSE BKCASE 2016). Such specialist engineering is able to take mitigation actions against “known-unknown” factors: Flexibility and agility amongst the “etc.” typically address known-unknowns in foreseeable system operation. For example the aim might be to generally expedite system reconfiguration and down-time required for a change in role, as in a vehicle used for surveillance which may need to adopt a fire support role.

“Unknown-unknown” factors pose significant challenges which need to be addressed. Boardman and Sauser provide a statement typical of systems leaders such as military commanders and CEOs: “I care less about the make-up of the system, as an objective per se, but more about its ability to survive and prosper in uncertain environments perpetually changing in unknowable ways that increasingly appear to be more actively lethal with purposeful intent to secure my system’s demise” (Boardman and Sauser 2006).

Complex SoS may contain what appear to be irrational arrangements or settings from certain viewpoints both within and outside the SoI. Often these are set for secondary modes of operation or for the greater good, and not optimised for fitness-for-purpose locally. This situation can occur, and can vary dependent on what operations the SoS and its constituent systems are engaged upon. For example, the primary function of military systems is warfighting, and although the designers of these systems appreciate that they will (hopefully) mostly operate in peacetime they have to make design trades to accommodate peacetime duties which are part of the whole sphere of operations. However designers have to ensure that the warfighting requirements are also met which may result in underutilisation or inefficient operation of some parts of the SoS in peacetime operations. If a SoS constituent is operated for maximum efficiency, for example at maximum throughput, this may cause queuing problems at a performance constraint elsewhere in the SoS. There may be 'unknown-known' cases where the drivers for these arrangements and settings are known but are implicit or not publicly acknowledged for security reasons.

This current uncertainty problem is not new: in 2005 Ring and Madni described key challenges as the "Increase in the 'unknown-ness' of the re-used systems and the 'Un-know-ability' of the SoS, and named stretch goals to be seized by systems of systems engineering which included requirements in terms of measures of effectiveness, design for evolution and a focus on renewal rather than disposal (Ring & Madni, 2005).

The efforts to date addressing this problem have largely been focussed on reducing uncertainty and making preparations for the 'known-unknowns' (Rumsfeld 2002). These efforts have diminishing returns, becoming less effective as further resources are spent, and become markedly more inefficient if they attempt to address 'unknown-unknowns'. In the complex socio-technical SoS and their constituents that are the subject of this research there will always be some degree of uncertainty. This research takes a different approach: rather than attempt to provide reversionary or alternative solutions to address changes experienced by the SoI it aims to provide a method with processes to guide system suppliers to incorporate components of solutions that can be configured together in a timely manner by the personnel engaged with the SoI, who are the first to experience the unforeseeable change when it reveals itself.

3.11 "Wicked" problems

Over forty years ago, Rittel and Weber wrote "Designing systems today is difficult because there is no consensus on what the problems are, let alone how to resolve them" (Rittel and Webber 1973). According to them, a 'Wicked' problem could be recognised as such by a number of characteristics including:

- There is no single answer applicable to resolving a wicked problem;
- There is no end point in implementing a solution to a wicked problem;
- There are no true–false answers to resolving a wicked problem;
- There is no complete ante facto understanding of the outcomes associated with interventions intended to resolve a wicked problem;
- Every solution applied to a wicked problem is unique and has a unique outcome;
- There is no fixed number of approaches that will resolve a wicked problem;

- Every wicked problem is unique;
- Every wicked problem is a symptom of another problem;
- The application of one intervention to resolve a specific wicked problem may have a different outcome when applied to a similar problem in a different location;
- The planner has no ‘right to be wrong’.

Rittel and Webers work was mainly concerned with policy making and planning, but Conklin’s 2006 work on dialogue mapping can be more readily appreciated to have applicability outside of policy making and planning. Dialogue is ubiquitous in socio-technical systems, and dialogue maps can be thought analogous to the ME(I) meta-model that captures ME(I) transfers which are central to the author’s research. Conklin’s variation of Rittel and Webers set has five defining characteristics of a wicked problem the author considers to resonate with the research described in this thesis.

Conklins’ characteristics are: (Conklin 2006):

- The problem is not understood until after the formulation of a solution.
- Solutions to wicked problems are not right or wrong.
- Every wicked problem is essentially novel and unique.
- Every solution to a wicked problem is a ‘one shot operation.’ (i.e. no opportunities for trial-and-error)
- Wicked problems have no given alternative solutions.

It can be appreciated from the characteristics above that a ‘top-down’ waterfall approach to the solution of a wicked problem is unlikely to be successful, and that an iterative, developmental approach is necessary. Iteration here does not mean trial and error, but the utilisation of knowledge gained through experience to modify the initial plan to better benefit the project going forward. Rittle and Weber said “attempting to baseline requirements and then use an analytical approach to deal with wicked projects is a recipe for disaster” and “We have to acknowledge the IKIWISI (I’ll Know It When I See It) syndrome”. In 2006, Dylan said “No complex problem is fully understood until you attempt to solve it” (Dylan 2006); which reflects the gain in knowledge, or perhaps hindsight, obtained whilst addressing the problem that an iterative and developmental approach capitalises upon.

The concept of a ‘solution’ may seem incompatible with Rittle and Webers’ “There is no end point in implementing a solution to a wicked problem” characteristic above, but in the context of wicked problems, solutions do alleviate problematic situations by providing a ‘stable intermediate form’ but may be neither complete nor enduring.

The difficulties of dealing with the uncertaintities of a wicked problem and the dynamic nature of requrements and constraints are often exercabated by a unhelpful environment in which the problem has to be addressed. A successful application of TCA processes into a SoS constituent suppliers' PLM system, and hence facilities for ME(I) transfer enhancement into their products, would equip the human elements in a complex socio-technical SoS to reconfigure what they have to hand to address an unforseen new problem in a timely manner.

3.12 Summary of Literature Reviewed

There is a consensus in the literature reviewed that present and future SoS users will need to make adjustments to their SoS to make it fit-for-purpose for their needs. SoS constituent suppliers need to equip their products to enhance the likelihood of a SoS being able to be fit-for-purpose and maximising options for SoS users close to the point of utility. It might be argued that supply-chain reach-back can create concurrent design and use and therefore systems that can adapt to cope with almost any changed situation, but it is considered that the dynamics of this considerable closed-loop system would never be sufficient to track those of the changing situations likely to be presented to the SoS.

Ensuring a SoS maintains fitness-for-purpose can be costly and time-consuming, especially when activities necessary to do this are unplanned. It is difficult to mitigate against future 'known-unknown' factors and 'unknown-unknowns' significantly more so. Ring et. al. state " Is this system still fit-for-purpose? This question becomes critical in a system of systems because many unannounced changes occur throughout the system content and context throughout its operational life" (Ring, Pizzarello, Friesen, & Davies, 2011).

Uncertainty isn't all bad: as "uncertainty may also create opportunity" (Mcmanus and Hastings 2006). Engineers are trained to think concurrently about opportunity when considering risk.

Most of the research papers reviewed and referenced come from either the US or Europe, which indicates where the 'centre of gravity' of research activity lies. Whilst the work of several researchers seems to have resonances with this research and it is recognised that much work has been done in the information management field and hence the transfer of information is not extensively covered by this research (for example a Google scholar search for "Information Management Systems" returns over four million results) but none of the literature discovered seems to draw together fitness-for-purpose with Material, Energy and Information (ME(I)) sources, sinks, bearers and transfers into a practicable method able to integrate with modern industrial engineering processes. This is the novelty of this research.

The literature review has left this author with the impression that competing schools of thought along the lines of 'not that way, this is the way', may contribute to academic thoroughness, but sometimes seem to be an end in itself for the continuance of the adversaries, which does not help industrial exploiters who create the wealth that funds research. The author has tried to find the value to his own research of the work of others conflicting opinions, in an attempt to create an approach having a combination of interventions, some of which may be in conflict, in the preferred balance and proportion that effectively addresses the problem at hand within the constraints of the particular situation. Differing interventions may need to be applied together but with different dynamics and accuracies: some will need to be 'quick and approximate' and others 'slow and accurate'. This is analogous to differing compensation terms in cascaded control systems, i.e. some terms put in a high bandwidth inner loop would not work well in a low bandwidth outer loop and vice-versa.

There appeared to be paucity in the literature of informing the reader what they actually have to do to benefit from its content: i.e. implementation in an exploiting environment (for example, an industrial supplier of complex systems, especially systems destined to cooperate with other systems as a systems-of-systems constituent). This thesis has attempted to strike the balance by creating outcomes that both academics can utilise to benefit their own work and that industrials can exploit to benefit their processes and products whilst enabling both to continue with their activities in the way that suits them best.

The literature review has iteratively tracked and guided the focus of this research onto how the suppliers of SoS constituents can equip their products to have their affordance for the transfer of material, energy and information enhanced by the personnel that engage with it close to the point of its employment. These personnel would be able to maintain such an equipped system as fit-for-purpose to address needs caused by unforeseeable internal and external changes.

A SoS may have several stakeholders at points in its lifecycle, but when and how they engage with it will differ, (Hitchins 2003b) and hence will what they perceive as fit-for-purpose. For example the user of electronic equipment may consider it fit-for-purpose because it meets their need for high reliability in harsh environments. However this might have been achieved by component encapsulation, which may restrict perceptibility and access causing difficulties for trainers and maintainers who may consider the equipment not fit-for-purpose. It is envisaged that these stakeholders needs may conflict, will need to be prioritised, and trades made as part of the engineering actions to increase the likelihood of fitness-for-purpose.

The author acknowledges this problem of providing the right capability to the right people in the right place at the right time; which perhaps could be called 'capability logistics'; and that it is mostly addressed by current systems engineering practices such as maturity management and lifecycle management that control a systems' fitness-for-purpose during the design phase of the lifecycle to provide at set points levels of functionality, behaviour and performance which are necessary precursors for further development, stage payments and incremental delivery. Cognisant of this, the author decided that resources were better spent concentrating on a new solution to the problem of addressing the ‘unknown-unknowns’ described previously.

It is considered that the proposed fit-for-purpose enhancement method is required not only to include a whole-life appreciation of the SoI including its foreseeable interactions, usage and abusage but also provide some mechanism to mitigate unpredictable events from concept to disposal that the SoI may experience when designers make trades, otherwise there is a risk of subconsciously designing-in SoS fitness-for-purpose shortfalls at some future time during its life.

It is with this in mind that the word “maintenance” appears in the title of this research, to reinforce the idea that the method and process are designed to be used at design opportunities throughout the SoI lifecycle and not just at the initial design phase, which is partially addressed by ‘design for the ‘ilities’ activities such as agility, re-configurability etc. Some examples of design opportunities occurring over the SoI lifecycle are when the SoI undergoes refurbishment, service and mid-life improvement.

A major role of engineering discipline institutes for current practitioners is to facilitate them to benefit from the wisdom of their peers and predecessors to make their SoI outcome better than it would have been without the benefit of the institute’s repositories of best practice, tools and techniques.

Traditional and contemporary system analyses support the engineering of a solution in response to a need from ‘lust to dust’ (need to disposal), therefore current tools and techniques are aimed to produce solutions that meet cost, time and quality requirements over the whole lifecycle.

To fulfil functional and non-functional requirements derived from the need, current systems analysis concerns itself with facilitating the development of the functionality and behaviour of the solution required to meet requirements, which this research describes in terms of ‘Intended’ transfers of ME(I) arising from the design process.

This research provides a method and process that reveals other ‘Unintended’ ME(I) Sources, Sinks and Bearers (SSBs) that are either innate with the solution implementation (termed ‘Inherent’) or are external to the SoI but have an effect upon it (termed ‘Independent’) that may risk unexpected system behaviour or be opportunities for exploitation.

4 Knowledge Gaps

This chapter elucidates the gaps in current knowledge from the viewpoints of systems theory, the end-users of socio-technical systems and the suppliers of systems as constituents of a SoS.

4.1 The Unknown-Unknowns Problem

The efforts to date addressing this problem have largely been focussed on reducing uncertainty and making preparations for the ‘known-unknowns’ (Rumsfeld 2002). These efforts have diminishing returns, becoming less effective as further resources are spent ‘second-guessing’ an increasing number of probable futures, and become markedly more inefficient if they attempt to address ‘unknown-unknowns’. Addressing the ‘unknown-unknown’ knowledge gap is the focus of this research, acknowledging that in the complex socio-technical SoS and their constituents there will be some degree of uncertainty.

4.2 International Council On Systems Engineering (INCOSE)

INCOSE is a not-for-profit organisation that promotes and upholds the discipline of systems engineering world-wide. It is a professional organisation that provides a centre for systems engineering and research engaging with academia, industry and government. It hosts frequent international workshops, conferences and establishes standards. Members achieving the required standard of competency as Certified Systems Engineering Professionals (CSEP) can attain chartered status via a third party institution, such as the Institute of Engineering and Technology (IET), licenced by the UK Engineering Council to award chartered status.

4.3 Knowledge Gaps: Systems Engineering Theory

4.3.1 Pain Points

The INCOSE Systems-of-Systems Working Group canvassed the systems engineering community to flush out what they consider as major “Pain Points” described by the working group as “major issues or 'pain points' in the area of Systems of Systems operation, management and systems engineering” (INCOSE SoS Working Group 2012).

Two of these have significance to this research. The first of these was “What are effective approaches to integrating constituent systems into a high-functioning SoS?” and contained the responses:

“Legacy systems which … are not configured or managed to allow insertion into the overall System-of-Systems. This creates interoperability concerns between the older and newer systems. In the cases where systems are owned/operated by different organisations …. the systems may transfer data and information reliably between systems (if you're lucky) but different processes, cultures, working practices between different participating organisations can lead to problems."

The second question was "How can SoSE [Systems-of-Systems Engineering] provide methods and tools for addressing the complexities (e.g. analysis, modelling, prediction and architecture) of SoS interdependencies and emergent behaviours?" the responses to which included:

"Systems often have interdependencies that are either unknown or unacknowledged. This is exacerbated by interdependencies between systems in development, a system in development and fielded systems; further, this is compounded by multiple combinations of these."

At the time of writing the INCOSE SoS Working Group is developing responses to address the identified "Pain Points".

4.3.2 Covert Functionality

An engineered system contains much non-obvious functionality inherent with the chosen implementation of the preferred design. For example, a steel wire armoured DC power cable selected to electrically connect two components will also conduct AC as well as connecting the components thermally, magnetically and mechanically. The following chapters show that inherent energy bearers like these as well as other inherent functions can be revealed and visualised to assess their likelihood of contributing to undesirable emergent properties early in the lifecycle before the system is built.

This research contributes to alleviating these pain points by identifying 'inherent' and 'independent' Material, Energy and Information (ME(I)) Sources, Sinks and Bearers (SSBs) affecting a SoS constituent.

- A ME(I) 'Source' is considered here to be a source of some transferred material, energy or information.
- A ME(I) 'Sink' is considered here to be a destination or terminus for some transferred material, energy or information.
- A ME(I) 'Bearer' is considered here to be a transferor of some transferred material, energy or information.

'Inherent' and 'Independent' ME(I) SSBs are not managed, controlled or perhaps even not captured in the SoS constituent's defining documentation, and may cause undesirable emergent properties in operation or when integrated with other constituents into a SoS.

An illustration of the terms ‘Intended’, ‘Inherent’ and ‘Independent’ used to describe ME(I) Transfers and SSBs may assist the reader here. For example, a maritime surveillance radar system is the SoI.

- To supply the electrical radar control cabinet the designer specified an ‘*Intended*’ ME(I) (electrical energy) transfer from the ship’s supply to the cabinet by a steel wire armoured cable.
- The *‘Inherent’* mechanical rigidity (mechanical energy Bearer) of a power cable supplying energy to a radar equipment cabinet may interfere with the correct operation of the electrical control cabinets shock mounts when the vessel experiences a shock from an underwater explosion.
- The structure of the vessel (mechanical energy Bearer) may conduct vibrations from an *‘Independent’* ME(I) (mechanical energy) Source, such as the vessels propulsion engine, to the radar antenna mast (mechanical energy sink) and degrade the radar’s stabilisation performance.

4.3.3 Unknown-Unknowns

Factors that might adversely affect a SoS being fit-for-purpose can be categorised as known, known-unknown, unknown-known and unknown-unknown. We can take engineering actions to enhance fitness-for-purpose, and according to Pich et.al. “the more well-known these factors are the more directly they are affected by these engineering actions” (Pich et al. 2002).

Ring and Tenorio, in INSIGHT July 2012 Volume 12 Issue 2 p.11 state “A system formalized by prescient design cannot respond to unforeseen situations.” Robustness and resilience can be designed-in to a system but any benefit design provides against unknown-unknown factors is largely due to serendipity: the major Line of Development contributor to fit-for-purpose maintenance in this circumstance is often the personnel working as part of SoS constituent systems (such as users, maintainers, re-suppliers etc.) and so prescient design of a socio-technical technical system should ideally include the provision of ‘stem cells’ that can be used as universal building blocks to facilitate the human ingenuity and resourcefulness that is a major contributor to the solution of unforeseen problems.

4.3.4 Information Transfer

Information science, for the purposes of this research includes soft aspects such as culture (in all its guises), language and overt behaviour. In terms of theory, architectures, management, etc., there already exists a lot of good work concerned with information management in fields such as management science, computer science, social science, etc. (for example a Google scholar search for "Information Management Systems" returns over four million results) thus demonstrating it is a well-trodden path. It was decided to focus the research reported in this thesis on the less well addressed aspects of Material and Energy transfer, and the Source, Sink and Bearer components of transfer. However because information management has such a significant role in the successful operation of systems / SoS, and furthermore in the successful exploitation of the outcomes of this work, (although not a focus of this work), consideration of 'I' is retained in brackets in the acronym ME(I) to indicate the importance of information and to keep mindful of it.

Currently systems engineering has a gap that the outcomes of this research addresses: a new viewpoint and appreciation of a SoI is needed to influence designs such that covert functionality is revealed early in the lifecycle and its effects managed so as a consequence products might be more readily adapted in a timely manner close to their point of utilisation to meet an unforeseeable future need.

4.3.5 Too-Slow Reconfiguration

It is likely that there will be time constraints on the reconfiguration of a system to exploit its 'inherent' and 'independent' ME(I) SSBs to enhance system affordances to source, sink and conduct the ME(I) necessary to successfully meet a new requirement. Pre-emptive work is the usual expeditor, but this work can be nugatory if it attempts to provide solutions when addressing the unforeseeable (Alberts 2011). Hence this research is concerned with pre-work that provides enablers / building blocks / components which can be utilised as part of solutions to new requirements created by unforeseeable changes in situation. Admittedly this approach will take longer to provide benefits than would a pre-emptive solution, but the most informed decision of the balance between components and solution (as exemplified by research into agile systems and agile systems engineering into the selection of modularity size and variation, such as Sillitto's work in granularity or 'chunking' (Sillitto 2014)) will come from the engineers familiar with the SoI on a case-by-case basis.

4.4 Knowledge Gaps: End-Users of SoS

General Sir Rupert Smith states:

"On every occasion that I have been sent to achieve some military objective in order to serve a political purpose, I, and those with me, have had to change our method and re-organise in order to succeed. Until this was done we could not use our force effectively. On the basis of my lengthy experience, I have come to consider this as normal - a necessary part of every operation" (Smith 2005).

Dealing with operational uncertainty is not unique to the military: emergency services, suppliers who repair and service systems in remote areas or large-scale industrial plant such as those in the chemical or oil industry, or suppliers tasked with providing uninterruptible services may find application for the outcomes of this research.

Two fundamental prerequisites to changes necessary for successful actions as described by Smith above are firstly having personnel with domain knowledge, situational awareness, ingenuity and resourcefulness, and secondly these personnel have something to work with. These personnel probably do not know the required changes until after arrival on-site and assessment of the situation, and any identified changes will likely require timely completion. Providing the 'something' to assist reconfiguration for foreseeable situations can be achieved to varying degrees of success by modular design, design for agility, robustness and resilience, but suppliers can only guess at what changes will be needed to address unforeseeable events, thus efforts to provide something that helps changes to deal with unforeseeable events are likely to be of limited utility. The outcomes of this research aim to enable system suppliers to provide personnel with 'something to work with' that takes advantage of their human attributes so they can address unforeseen situations with greater efficacy.

4.5 Knowledge Gaps: System Suppliers to SoS

4.5.1 Unforeseeable Situations

How to engineer systems to accommodate "unknown-unknown" factors poses a significant challenge to be addressed. Systems can be successfully engineered to meet known requirements, and also to varying degrees against unknown requirements whose range is known (partially known-unknowns; for example the range of atmospheric pressure in which a SoI must operate is known but not how fast the pressure can change), to ensure a system is fit-for-purpose over its useful life.

4.5.2 Practical Difficulties: Problem Alleviation Overview

This research provides a method and process that creates a novel and more complete view of a SoI that shows the material, energy and information (ME(I)) sources, sinks and bearers (SSBs) that exist in the SoI. Some of these are evident as they arise from the design process ('Intended'). The less apparent unintended others are either innate with the solution implementation ('Inherent') or are external to the SoI but have an effect upon it ('Independent').

Revealing unintended ME(I) SSBs, exposes what could be the seeds of problems that only exhibit themselves later in the lifecycle when they are costly and time consuming to rectify: at best this may be before an interim system maturity demonstration, project milestone, at systems integration, or at worst in-service which may dictate costly product recalls.

The TCA method examines the unutilised capacity of all the ME(I) SSBs, showing their ability and opportunity to undesirably transfer ME(I) that could cause undesirable emergent properties, but also their exploitation potential to create new transfers of ME(I) enabling new or increased capabilities necessary for the SoI to meet a previously unforeseen need. The steel wire armoured cable example electrically connecting two components will also conduct AC as well as connecting them thermally, magnetically and mechanically; one or more of these inherent connections could cause problems. Alternatively, the thermally conductive armour could be used as a heat-sink to enable a piece of equipment to be operated at increased power without exceeding its thermal limitations, or be used to suppress radiated electromagnetic interference.

Exploitation of enablers to enhance a systems ME(I) transfer may have to be done close to the point of its employment, as it is at this location where the response necessary to effectively address an unforeseeable change is best understood. Cost effective incorporation of enablers for ME(I) transfer enhancement needs to be able to be done by system suppliers at almost any ‘Design Opportunity’ in the lifecycle, such as Mid-Life Improvement (MLI), refurbishment, obsolescence recovery, scheduled maintenance, overhaul, repair etc. as well as at the design phase, and the implementation needs to take account of where an enabler will be exploited.

4.5.3 Dealing With Uncertainty

In some industries, dealing with uncertainty has always been part of the day job. Paul Otellini, CEO of the Intel Corporation in a BBC News interview at the consumer Electronics Show held in Las Vegas, 8.1.2008 said:

“Our business model is one of very high risk: We dig a very big hole in the ground, spend three billion dollars to build a factory in it, which takes three years, to produce technology we haven't invented yet, to run products we haven't designed yet, for markets which don't exist. We do that two or three times a year.”

4.6 Chapter Summary

This chapter has related knowledge gaps from the viewpoints of systems engineering theory, the personnel within a socio-technical SoS and systems suppliers of SoS constituents. This research does not attempt to produce solutions for unforeseeable problems, but rather provides visualisations of obscured inherent resources, potential exploitations and enhancement opportunities to enable personnel to use their ingenuity and resourcefulness to make a practicable reconfiguration that accurately addresses a previously un-encountered and unforeseen problem.

In Summary,

- System Theory does not cover the system-wide transfer of Material and Energy so comprehensively as Information transfer

- System Engineering does not have a technique to efficiently and effectively equip socio-technical systems to deal with the unforeseen
- System Engineering does not have a multidisciplinary appreciation of unintentional ME(I) SSBs
- System Engineering does not have a multidisciplinary process to reveal unintentional ME(I) SSBs and capture them as an integral part of design definition
- System Engineering does not have a cross-discipline appreciable representation of a systems intended, Inherent and Independent ME(I) SSBs
- The suppliers of System of System constituents may be unaware of the covert functionality in their products and the exploitation of this functionality by the users of their products.
- The human elements of socio-technical systems of systems may not know in advance what obstacles they will encounter in attempting to achieve their purpose.

The outcome of this research as described in the following chapters reveals these inherent and 'independent' Material, Energy and Information (ME(I)) Sources, Sinks and Bearers (SSB) and shows how they might be captured in a readily comprehensible form to stimulate thought as how they may be opportunities as well as risks as described earlier. For example, in the 1960's, Colin Chapman of Lotus Cars revolutionised the design of single-seat racing cars by using the latent mechanical structure of the gearbox casing to double up as the rear chassis of the car, an innovation subsequently copied by all competing teams and still used today. Latent functionality in the form of 'unintended' (i.e. 'inherent' and 'independent') Sources, Sinks and Bearers may be exploited to realise useful transfers of Material, Energy and Information (ME(I)) in addition to those intended by the original design necessary to meet a new requirement.

5 Research Questions

This chapter contains a brief expansion of the research questions, how they were formulated and the validation strategy for the research outcomes.

5.1 Questions

The preceding literature review and knowledge gap analysis give rise to the following research questions, which are related to the viewpoints of systems theory, system supplier and the 'human-in-the-system'.

- What can be done to address the 'unknown-unknowns'?

Directly addressing the 'unknown-unknowns' from the human-in–the-system viewpoint is outside the scope of this research. However, investigating the problems of several systems and abstracting a commonality from these problems addresses the systems theory viewpoint, and using this theoretical knowledge to create a mechanism addresses the system suppliers viewpoint so that they gain a more complete view of their product and are enabled to equip users to better deal with their 'unknown-unknowns' is in-scope.

- Why is the current situation problematic?

The current system analysis and representation at the system level capture the interconnections between system components that the designer intentionally implemented in the product, thus forming an incomplete view of the SoI. The system supplier using these analyses and representations to create the product inherently creates connections not recorded in the product definition. The human elements in the system are unaware of the latent capability in the system they have to hand that could be utilised to counter unforeseen problems.

- When will fit-for-purpose maintenance be done?

Throughout the lifecycle of a system there will be periods when fitness-for-purpose maintenance has to be done to promptly address a current need, and the timing of maintenance actions will be governed by influences outside the control of the SoS. There will also be opportunities for fitness-for-purpose maintenance, and to make provision for future maintenance conveniently and economically that are within the control of the SoS.

- How will fit-for-purpose maintenance be achieved?

Maintenance may be achieved in a variety of ways, dependant for example on the situation, facilities and personnel available at the time that maintenance actions are carried out.

- Where will fit-for-purpose maintenance be done?

Similar to the previous "How" question, there may be a choice of where maintenance is done, or it may be dictated by factors outside the control of the SoS.

- Who will do fit-for-purpose maintenance?

It may be likely that only personnel within a socio-technical SoS will be available to respond to an urgent need for maintenance, whereas less urgent needs can be met by a choice of personnel that best fit the situation at the time maintenance is carried out.

The answers to the above four questions will largely be dependent on the operating model of individual businesses. This research will address these questions from a generic point of view, but will provide illustrations and suggestions applicable to most business models.

5.2 Validation Strategy

The validation of a system can be visualised as a bridge across the top of its 'Vee' model representation, linking the needs and requirements at the top of the left-hand side of the 'Vee' to the delivered system at the top of the right-hand side of the 'Vee'.

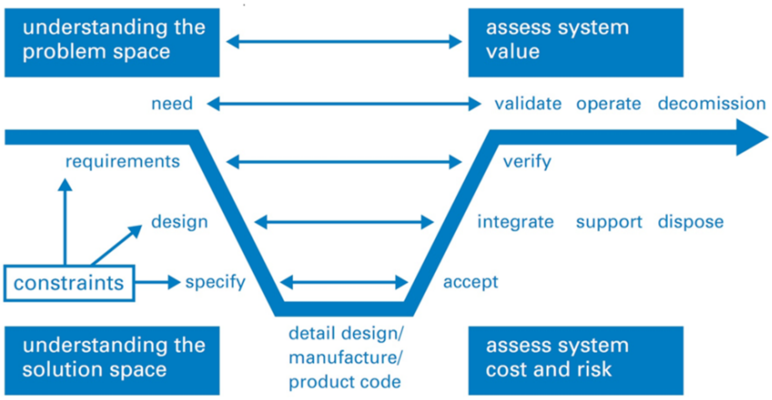


Figure 5.1: Systems Engineering 'Vee' Model (INCOSE 2009)
(© INCOSE UK Ltd, reprinted with permission)

This bridge, for example in the form of a customer acceptance test specification or requirements compliance matrix, can be used to demonstrate that needs and requirements are met by correlating system characteristics of the delivered system. In the context of this research, to be valid a system has to be fit-for-purpose; as Sillitto says "Whether work products are fit-for-purpose is defined not by the person doing the work, but by the person who will use the results" (Sillitto 2010). In other words, process validation is via examination of the outputs of a system developed to customer-useable maturity, and validity can change with situation and over time and for example with variations in the system's environment, internal parameters, inputs and user needs.

This research delivers a novel concept; a technique with a method and process designed to reveal covert connections between system constituents that are either inherent with, or independent of those intended connections placed by the system designer in order that the system fulfils its stated purpose. A process that realises a new concept can be verified, that is shown to be 'built right' but (in the context of this research) not verified to 'add value'; that is be the 'right thing' to the same degree as a system with sufficient maturity to be accepted by a customer who will use its output. Research that provides new knowledge rarely delivers outcomes able to be immediately exploited; to enable exploitation a subsequent development phase to mature novel research outcomes to a stage where exploitation can result in societal and/or industrial benefit is usual.

However, this PhD does contain work to provide some degree of validation commensurate with the maturity of its research outcomes and also to facilitate further development and subsequent exploitation.

This theoretical concept is validated by a concept demonstrator created by the author as part of this research, a trial of the concept on a major subsystem of a current industrial project by a final-year M. Eng. student and a Functional Demonstrator developed from the Concept Demonstrator by a final-year B. Eng. Student. Further development for PLM (CHORUS2) integration and a project trial is suggested for further work.

The description of the research-oriented Concept Demonstrator appears in this part, "Part A: Research" below, and the description of the exploitation-oriented Functional Demonstrator appears in the "Part "B": Exploitation" part of this thesis.

5.3 Concept Demonstrator

An automated TCA process will require the bandwidth and duty (frequency of use over time) characteristics of the ME(I) SSBs in the system definition to be held digitally in the hosting PLM system. This data will exist as component libraries, engineering models and schematics generated by specialist engineering disciplines and systems design artefacts generated by the project system engineers. However, the ME(I) SSB characteristics may not all be in a machine readable form. The potential industrial exploiter will need to do a trade study between the desired degree of TCA automation and the amount of machine-readable data currently in their PLM system with the work necessary to achieve the level of machine-readable data commensurate with the allocation of function (i.e. either manual, semi-automated or fully automated) that they consider best suits them.

The author considered that this work should provide some thoughts to assist those considering an automated implementation of the TCA method/process, and that a concept demonstrator would be achievable and most efficiently provide a useful enhancement to this illustrated description. A TCA concept demonstrator could convey a representative 'form and feel' of an automated implementation and could be used as a point of departure for either a functional demonstrator utilising common software applications, or for a prototype TCA analyser that utilised specialist applications used by the existing engineering processes within an industrial system providers PLM system.

An automated implementation of the TCA method/process was envisaged as having two main functions; firstly a data capture and manipulation function to capture and process the system ME(I) SSBs, and secondly a data visualisation and analytics function to visualise and rearrange the intended and unintended ME(I) transfer connections. These two functions are represented in the concept demonstrator using manually input ME(I) SSB parameters, rather than calculated parameter values that a functional demonstrator determines.

5.4 Chapter Summary

This chapter has related the research questions generated by an exploration of the perceived problem space and provided brief expansions of them, together with a strategy to demonstrate the validity of the responses to the questions generated by this research that is not predicated on entities outside of the author's control.

6 Determine Research Methods

This chapter describes the work done to explore research philosophies and determine a philosophy for this research in order to deliver new knowledge and provide an output that is novel, useful to other researchers and also be exploitable by industrial system suppliers.

6.1 Research Philosophy

An objective of recording a philosophy for this work is to provide a reference point for the research activities, assist structure, consistency and attempt to show where this research 'is coming from'. Research tenets were recorded with the philosophy to provide some reference points to guide the research direction.

6.1.1 Philosophy

Different philosophical viewpoints have contrasting principles and approaches that dictate how a researcher sees and addresses their task; for example how the researcher sees the 'world' in which they operate, the appreciation they take from what they observe, how they collect data and analyse it, and also the standpoint of the researcher with respect to the research task.

Easterby-Smith et al in 1991 described two fundamentally different philosophical viewpoints for research. They describe the first of these as "positivist viewpoint" which comes from a belief that the world is objective, with independent observers and where science is unfettered by human values, and the second as "phenomenological viewpoint" (also known as "constructivist viewpoint") which believes that the world is subjective, observers are part of it and that humans drive science. The table 4.1 below contrasts these two viewpoints ('paradigms') in terms of their beliefs, focus, methods and data.

	Positivist Paradigm	**Phenomenological Paradigm**
Beliefs	The world is external and objective	The world is socially constructed and subjective
	The observer is independent	Observer is part of what is observed
	Science is value free	Science is driven by human interests
Focus	Focus on facts	Focus on meaning
	Look for causality and fundamental laws	Try to understand what is happening
	Reducing the phenomenon to simplest elements	Look at the totality of what is happening
	Formulate hypotheses and then test them	Develop ideas through instruction from data

	Positivist Paradigm	Phenomenological Paradigm
Methods	Operationalizing concepts so they can be measured	Using multiple methods to establish different views of phenomena
Data / Population	Large Samples	Small samples investigated in depth over time

Table 6.1: Research Philosophies (Easterby-Smith, Thorpe, and Lowe 1991)

It can be appreciated that there are pro's and con's to both approaches, and in an engineering context the choice may be decided on a case-by case basis driven by the requirements and constraints of the task at hand. The author's view is that the majority of cases would require a mixture of the two in the preferred balance and proportion that best suits the individual case. Johnson et al in 2007 (Johnson, Onwuegbuzie, and Turner 2007) and Denscombe in 2008 promote this "Mixed-Methods" approach, also known as the "Pragmatism Paradigm", where rigorous adherence to 'either one or the other' will not deliver the best outcome. Engineers dealing with complex socio-technical systems appreciate that it is often necessary to have both quantitative and qualitative appreciations for them to make adequately informed decisions and recommendations to achieve the desired goals. Denscombe describes his pragmatism philosophy as built on the belief that combining positivist and constructionist philosophies was not only allowed but often desirable (Denscombe 2008). Creswell (Creswell 2009) augmented Denscombes' work by providing researchers with strategies for using a mixed-methods approach, enabling them to select a strategy that they consider best suits the characteristics and constraints of their research. Table 4.2 below provides summary descriptions of Creswell's six strategies.

Strategy	Description
Sequential Explanatory	Characterised by: Collection and analysis of quantitative data followed by the collection and analysis of qualitative data. Purpose: To use qualitative results to assist in explaining and interpreting the findings of a quantitative study.
Sequential Exploratory	Characterised by: An initial phase of qualitative data collection and analysis followed by a phase of quantitative data collection and analysis. Purpose: To explore a phenomenon. This strategy may also be useful when developing and testing a new instrument.
Sequential Transformative	Characterised by: Collection and analysis of either quantitative or qualitative data first. The results are integrated in the interpretation phase. Purpose: To employ the methods that best serve a theoretical perspective.
Concurrent Triangulation	Characterised by: Two or more methods used to confirm, cross-validate, or corroborate findings within a study. Data collection is concurrent. Purpose: generally, both methods are used to overcome a weakness in using one method with the strengths of the other.
Concurrent	Characterised by: A nested approach that gives priority to one of the methods and guides the project, while another is embedded or 'nested'.

Strategy	Description
Nested	Purpose: to address a different question than the dominant or seek information from different levels.
Concurrent Transformative Strategy	Characterised by: The use of a theoretical perspective reflected in the purpose or research questions of the study to guide all methodological choices. Purpose: to evaluate a theoretical perspective at different levels of analysis.

Table 6.2: Mixed-Method Strategies (Creswell 2009)

The engineering of socio-technical technical systems rarely deals with a single scenario, and usually involves dealing with multi-layered situations and 'wicked' problems. Different parts of an engineering task will require different approaches: for example finding the properties of a material would use a positivist approach, whereas a constructivist approach would be used to show how a system benefits society. It is the consideration of a system's purpose and context that is important in deciding how to proceed.

Philosophy for this research consists of an:

- Ontology: "Assumptions about how the world is made up, and the nature of things", in the context of the desired transformation.
- Epistemology: "Beliefs about how I might discover knowledge about the world"
- Methodology: "Beliefs about processes and techniques of research I might use" (MacIntosh 2009).

6.1.2 Ontology

In this PhD, there are two main worldviews, each with their own transformation.

Design Worldview

This worldview consists of a creating SoS (e.g. an engineering project) assembled from a set of candidate systems (industrial resources), that designs a system (a SoS constituent) that when created will be a constituent of an operational system-of-systems as described in the operational worldview below. An illustration might be a response to an emergency services requirement, such as an Ambulance project formed from the vehicle manufacturer's resources, designing a vehicle (SoS constituent) that satisfies the emergency services requirement of being able to be directed by the police to a location then evacuate injured persons having been rescued from a building by the fire brigade. The 'design worldview' desired transformation is from a delivered system design with an inherent (what you get is what you get) ability to maintain fitness-for-purpose in-service after unforeseeable internal, external or duty changes, into a design that has an increased ability to be maintained fit-for-purpose beyond the original design. This is achieved by the 'Open-Loop' application of the TCA method where the achievement of a specific goal is not specified.

Operational Worldview

This worldview consists of a formed system-of-systems, undertaking a mission within an operational world environment to satisfice a goal: e.g. bring about a timely change in the operational world within constraints. Within the viewed 'world', the SoS is formed from a set of candidate constituents, which most likely will include humans. The composed SoS constituents interact to achieve the SoS' goal via the complete, correct and timely input and output of matter, energy and information necessary. In the operational worldview applicable to this research, the SoS may be disbanded and its constituent systems stood down after a particular goal is achieved. The SoS considered by this research operates in a spherical space on the surface of the earth (spherical as opposed to hemispherical because some SoS constituents could be sub-surface). The boundary of the SoS' operational space is set commensurate with the transformation desired from the SoS; that is at the limits of the SoS' operational effects. This said, how the SoS is affected and the effects the SoS actions within the operational boundary have outside the boundary is considered, and can be illustrated by the chronological example below:

- The outcomes of TCA application to a SoS constituent provide an ME(I) affordance enhancement.
- A subsequent external change in need degrades the SoS capability to achieve a desired effect within its operational boundary.
- The enhancement is utilised to restore the SoS' capability to achieve the desired effect within the boundary.
- The resumption of desired effects meets the changed external need.

This example illustrates that the changes brought about by exploiting TCA have direct effects within the operational boundary, but can be influenced by, and have indirect effects outside it which are accommodated. The 'operational worldview' desired transformation is of a SoS not fit-for-purpose to fit-for-purpose, i.e. that satisfices stakeholders after internal, external or duty changes. This is achieved by the 'Closed-Loop' application of the TCA method where achievement of a specific goal is required.

The key assumption is that the desired transformation is achieved if the all the SoS constituent interactions necessary are achieved in a correct, timely and complete manner.

6.1.3 Epistemology

Design Worldview Epistemology

Knowledge of the design world has been obtained by research and examination of system design case studies in the industrial partner's domains of interest, mainly defence contracting and from the authors personal experience in the same domain.

Operational Worldview Epistemology

Knowledge of the operational world has been obtained by examination of the interactions between SoS constituent systems from operational scenarios in the industrial partners domains of interest. These interactions between SoS constituents will be characterised in terms of complete, correct and timely transfer of matter, energy and information and the capability and utilisation of the transfer mechanisms.

6.1.4 Methodology

Design Worldview Methodology

The design methodology looked at the creating systems engineering lifecycle processes using the context of Thales UK, to ensure that the TCA method and process were not designed in such a way as to make their incorporation into Thales' PLM system unnecessarily problematic. Data and information was obtained from PLM documentation, de-briefs, reports, verification and validation documents, structured interviews and informal discussions as appropriate to ensure that the extrapolation of deductions drawn from the analysis of the examined set of SoS constituent systems to the whole population is valid. Validity for design methodology means that the research outcome can be usefully applied to a broad range of SoS constituent system projects.

Operational Worldview Methodology

The operational methodology has been to examine operational case studies where formed SoS were able, and were not able, to maintain fitness-for-purpose. Fitness-for-purpose maintained is defined for a system / SoS here as *able to satisfice the operational task stakeholders, after unpredictable changes in operation, composition or external factors*. Data and information are from, but not limited to, de-briefs, reports, semi-structured interviews and informal discussions as appropriate to ensure extrapolation validity. Validity for operational methodology means that the research outcome can be usefully applied to a broad range of SoS utilisations.

6.2 Research Approach

The detailed choice of research process and methods was influenced by the engagement with Thales; a major industrial systems integrator company that has engaged in collaboration, hence this research has made reasonable endeavours to be beneficial to their business. This research deals with mostly qualitative data, but it was considered that it was desirable to retain an avenue for quantitative data analysis with the less subjective positivist approach; hence a mixed-method research design was adopted.

Creswell (Creswell 2009) provides four decisions for mixed-method research designs designed to aid selection of a mixed-mode design strategy.

- What is the implementation sequence of data collection?
- What method takes priority during data collection and analysis?
- What does the integration stage of finding involve?
- Will a theoretical perspective be used?

These questions seem to suggest implicitly a 'waterfall' type process rather than an iterative agile process best able to adjust to discovery. This research needed to collect concurrently both qualitative and quantitative data, the data available and interim analyses would determine method without a pre-determined priority. The integration phase activities would be tailored similarly, and some theoretical perspective will be used to make the research outcome applicable to diverse systems. The concurrent triangulation research design strategy was thought the best fit for this research.

Relationships were made with other researchers and experts in the field to share information and experiences. Relevant conferences have been attended and papers written to enrich the research content.

Initially the necessary agreements and authorities were obtained to access the Thales IT system. This allowed some familiarisation with the company's engineering processes and procedures, in order to ensure compatibility of the research outputs with their existing systems, and experimentation with company engineering process thought relevant to the research.

Historical case studies were used as fit-for-purpose retention examples, using project documents supported with questionnaires and semi-structured interviews with project stakeholders from the supplier and user communities, from both engineering and non-engineering disciplines.

The outcome of this data gathering exercise was analysed to inform the creation of the prototype TCA enhancement process, which was validated against the case studies.

The process was assessed by feedback from a live project and PLM engineers, commensurately modified and made able to be integrated with the companies PLM engineering processes.

6.3 Research Hypothesis

This research asserts that SoS do not maintain fitness-for-purpose because they cannot implement the correct, timely and complete interchange of matter, energy and information between the SoS constituents and externally that is necessary to achieve a particular result. Maier references the Pahl & Beitz framework (Pahl and Beitz 1986) and their modelling of [system] artefacts as “generic systems with boundaries and inputs and outputs of material, energy and information” (J. R. Maier and Fadel 2008).

The functions that implement these transfers can be described in terms of affordances: “Features that provide the potential for interaction by “Affording the ability to do something” (Sillitto 2011).

6.4 The Scientific Method and the TCA Research

The scientific method shown in Figure 6.1 below (Garland 2015) gives the impression that it is a sequence of operations to be followed by the researcher. However, as with the importance of tailoring in the application of systems engineering, it is recognised that the scientific method is better able to be used by and benefit a wider field of research if considered as a “representation of a set of general principles”.

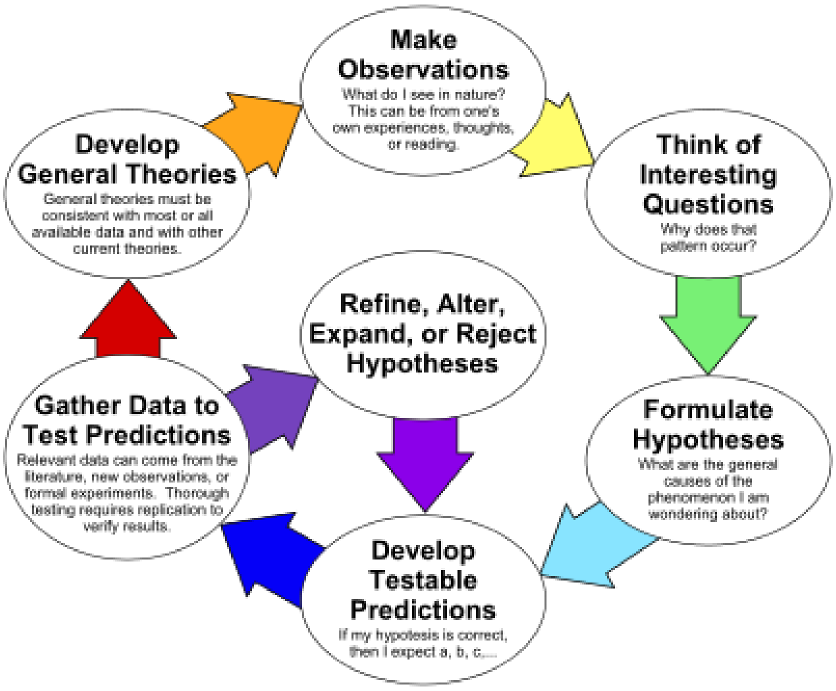


Figure 6.1: The scientific method as an on-going process (Garland 2015)

“Not all steps take place in every scientific inquiry (or to the same degree), and are not always in the same order”. (Whewell 1837) and in (Whewell 1847).

This research has two variations on the scientific method shown in Figure 6.1 above, in that it produces from a hypothesis an assertion with a method and process, rather than a general theory (which would require independent verification and not have any counter argument). It also provides examples and illustrations of the usage and benefits of the delivered method and process.

One of the goals of the scientific method is to develop general theories which can be used to make predictions. The diversity and the case-by-case individuality of problems described by the literature posed a challenge to this research to provide something that could be broadly applied, but not generalised out of usefulness: something that provides value to systems engineers that would satisfy each individual SoI case. The author did not want to be drawn in to an attempt to come up with ‘A Theory of Everything’ and was also apprehensive that an attempt to provide a generic deliverable that was applicable to every case would not provide sufficient return-on-investment of resources, resulting in something that was genericised out of all practical employment by the industrial partner.

This research concerns itself with enabling effective and efficient provision for the unforeseeable, so the development of a predictive theory is rather at odds with this aim. This research does provide an exploitable method and process in terms meaningful to those systems-oriented personnel with the accountability to meet user needs, and also to those engaged in engineering disciplines with the responsibility of ‘making it happen’ to de-risk their creating system, improve the insightfulness of their staff and add value to their deliverables.

6.5 Chapter Summary

This chapter has described the work done to explore research philosophy and develop a philosophy for this research. An object of recording a philosophy for this work is to provide a reference point for the research activities, assist structure, consistency and attempt to show where this research ‘is coming from’. Research tenets were included alongside the research philosophy to provide some reference points to guide the research direction.

7 Abstraction, Hypothesis and Basis for Solution Design

This chapter contains a description of the thought process starting from the generalisation of observed problems and their abstraction into a general case, from which a hypothesis and a basis for the development of a solution was developed

7.1 Socio-Technical Systems

The initial impetus for this research was to help personnel in the field working as part of a socio-technical system to address previously un-encountered problems caused by unforeseen events. The author felt it negligent and unethical not to provide something to capitalise on the tenacity, resourcefulness and ingenuity of personnel working close to the point of employment of the systems to which the author had contributed. Design for Agility, Robustness and Resilience coupled with rigorous Failure Mode Effects and Criticality Analysis (FMECA) accommodated foreseeable events, but to provide against the unforeseen is difficult and likely to be ineffective and inefficient. Risk and Opportunity analyses are a step towards identifying future problems and opportunities for improvement, but are often limited to 'designed for' aspects of the delivered system and its lifecycle management. The author felt that something was missing from the design process that could be used to alleviate unforeseen future problems.

7.2 'Stuff Logistics'

The FFP research started with the experience of problems in the real world: the author observed problems that occurred during the development of engineering systems that formed part of a larger SoS, and also problems that only exhibited themselves during systems integration or operational employment. These systems had human constituents, for example to operate and maintain them throughout their life. These observed problems prompted the author to question 'Is it just me?' With hindsight, it could be said that a significant portion of these problems could have been avoided with improved design and development processes (and the resources to allow them to be effective), but others were not realistically foreseeable, and had to be dealt with using what was available when they revealed themselves.

Despite the fact that delivered systems were developed under a respected systems engineering oriented design process, problems in design, development and operation still occurred, especially with new products. This stimulated the question, 'Why don't things work when put together?' Investigation into this admittedly loose question resulted in an equally loose answer of 'Because some 'thing' didn't get all the 'stuff' it needed to work: the 'stuff' was either incorrect, incomplete or late'. It was appreciated that especially in overcoming operational problems the human elements in the system, using their ingenuity, resourcefulness and adaptability were key to getting things to work. These attributes the author thought should be capitalised upon by product design; systems suppliers should provide them ‘something to work with’ as far as practicable the delivered system could be maintained as ‘Fit-For-Purpose’.

It was recognised that systems suppliers do design for adaptability, robustness, resilience, agility etc. which make some provision for foreseeable future events, but it is impractical to efficiently and effectively cater for all eventualities; and even less so for ‘unknown-unknown’ events that will occur throughout a systems lifecycle and cause problems that the systems human elements will most likely have to address. Provision for ‘unknown-unknown’ events and unforeseen problems was thought to be part of the gap in the design and development process.

The most informed view one ever gets of a project is hindsight. One function of systems engineering and lifecycle management is the ‘left-shift’ of knowledge, or obtaining hindsight early. Unforeseen problems are most effectively and efficiently dealt with when they reveal themselves, that is they become known, and it would be indeed fortunate to have a solution to the revealed problem at hand at that time, or soon enough after to overcome or at least mitigate the effects of the problem to an acceptable level in a timely manner.

Systems suppliers, especially as they are likely to be remote in location and time to a revealed problem cannot realistically provide solutions to unknown problems. The personnel forming part of the system are those close to a revealed problem and are likely to be one of the first to perceive its effects and the urgency with which it ought to be addressed. Systems suppliers could provide help in the form of ‘pre-work’; that is components of solutions able to be put together by those close to the problem.

From the notion of ‘something to work with’ came the thought that system personnel have more than they think they have; they have “unknown-known” resources and capabilities. Revealing these capabilities would enable these covert resources to be ‘on the table’ for consideration for utilisation as part of a constructed solution. Identification of a systems latent capability and exploiting these latent capabilities with solution component provisions is another contribution to filling the design and development process gap.

The concept of ‘stuff logistics’ was thought worthy of further exploration, which led to the assertion that systems that were not fit-for-purpose were so because they could not make the complete, correct and timely transfers of material, energy and information necessary to achieve a desired result. From this came the concept of the systems designers ‘designing-in’ functionality that does implement the transfers necessary for the system to achieve its ‘known’ requirements: that is to have the ability to cause the desired effects.

7.3 'Latent Capability'

Initial thinking considered the concept of latent capability as decomposed in the terms of a collection of Material, Energy and Information transfers that were 'Inherent' with the design solutions chosen to implement the 'designed-for', or 'Intended' ME(I) transfers. Further thinking and investigation into the components of a ME(I) transfer identified two implicit and erroneous assumptions; firstly that ME(I) Source, Sink and Bearer components might not be connected and thus able transfer ME(I), which also gave rise to the concept of 'Independent' ME(I) SSBs that were outside the system of interest as defined by the designed-for system boundary, and secondly that connected ME(I) sources may not necessarily be transferring ME(I). Thus any analysis has to have resolution down to the SSB level.

7.4 System Visualisations

How might a systems ME(I) SSBs be visualised was considered. Engineering staff could appreciate a QFD-Style of transform cascade that related 'Whats' to 'Hows' from top-level system-of-system capability down through system constituents to sub-systems in terms of ME(I) transfers, rather than in terms of functionality as does the QFD. The Function-Flow Diagram seemed to have better traction with engineering staff, as it was more widely used and provided a more intuitive feel of 'how it all works'. The FFD visualisation was considered better as a vehicle to capture and collate the 'Intended', 'Inherent' and 'Independent' ME(I) SSBs as a ME(I) Meta-Model and provided a relatively familiar common reference for a variety of engineering disciplines, however it was understood that an TCA adopter would likely want to use a visualisation that integrated well with their existing PLM system, and that for all but the most trivial of practical systems there would be large amounts of ME(I) SSBs and ME(I) transfers to accommodate. This 'Big Data' issue also dictated that extensive automation would be necessary in a practical TCA method/process used to analyse realistic systems.

The considerations of engineering specialists started from the author's formulation of the question 'What design artefact (for example a model, specification, drawing etc.) in a product's 'technical data pack' accounts for the inherent characteristics of the design solutions?' For example, what artefact considers the mechanical characteristics of electrical elements, electrical aspects of mechanical structures, what information is implicitly transferred with material or energy transfers? From this came the thought that snippets of this information may exist in some form from activities in mainstream engineering and as outputs of specialist engineering discipline; control engineers may consider the mass, inertia and centre-of-gravity of electrical cables carrying power to motors on moveable structures, mechanical engineers consider galvanic corrosion caused by the junction of dissimilar materials, electrical engineers consider the current-carrying capability of mechanical structures under fault conditions, platform signature management engineers consider the multispectral emissions of platform subsystems, similarly to the considerations of EMC/RFI engineers managing conducted and radiated electromagnetic noise. The literature survey found several writings on the problem of the need for agility, robustness and resilience to address the known and the uncertain, a couple on MEI as consumables, but a paucity regarding solutions and their practical implementation; this latter gap resonating with the aim of this research and hence having an influence the content of this thesis.

7.5 The TCA Technique: A New Insight

'Inherent' & 'Independent' ME(I) transfers almost certainly will not appear in a product's design definition: they will not be controlled or managed, but potentially they may well be either problematic or being utilised by some stakeholders such as users and maintainers and thus will cause problems when they change or, without deliberate consideration, are withdrawn from the product due to through-life development and modifications. For example, mechanical connections formed by electrical cables to a cabinet may transmit harmful shocks and vibrations to sensitive components within it. A TCA analysis should reveal for example a source of vibration independent of the SoI and identify the sources' ability, opportunity and capacity to affect the SoI early in the lifecycle to enable timely mitigating action to be taken preventing costly rework should problems only be found later in the lifecycle. Specification compliant replacement components may not have the design margins of original components being exploited by operators and maintainers. One way of encouraging considerations of a system's 'Intended', 'Inherent' and 'Independent' ME(I) transfers could be to make a ME(I) SSB analysis, i.e. a Transfer Component Analysis (TCA), part of a project's Systems Engineering Management Plan.

A TCA technique goal is to stimulate thought that creates new design actions to create the resources for a potential ME(I) transfer at the system level and hence SoS level to enable a new SoS capability, or mitigate risks that may only be realised when products are fielded. The TCA method as appears here deals with ME(I) spectra, duty and capacity: potential TCA adopters may well be stimulated to think of other parameters that could be brought into the project definition to facilitate fitness-for-purpose maintenance.

TCA may appear to be a convoluted route to an end that could be achieved by talented, experienced engineering practitioners using alternative methods with which they are familiar. It is acknowledged that this might be the case, and furthermore that alternative methods to identify 'Inherent' and 'Independent' ME(I) SSBs will exist in some specialist engineering areas, but these may well be sporadic and dispersed. For example, those responsible for platform signature management and spectrum management will identify inherent energy sources and determine their ability, capacity for transmission and crosstalk. The mechanical characteristics of electrical components will be examined by those responsible for such aspects as centre-of-gravity management, mass and space claim budgeting, whilst the electrical characteristics of mechanical structures will be examined by mechanical engineers considering galvanic corrosion and also electrical engineers determining the paths of full-load fault currents and lightning strokes. Working with the assumption that a systems supplier operates using a tailored form of the systems engineering process as described by ISO 15288, INCOSE and others, TCA improves the "Integration with Specialist Engineering" activity by disseminating some aspects of the specialist technical skills as well as those commonly engaged during this activity such as security and human factors. Specialist technical skills like those described above are likely to be busy, scarce resources that may well not be available to systems engineers having a broader viewpoint, to bring aspects of these specialist engineering considerations together in one holistic picture.

This research is not intended to offer a universal and complete solution; it is a contribution that provides a more complete view of a system.

7.6 General-Case Abstraction/ Hypothesis

The research hypothesis is that SoS do not maintain fitness-for-purpose because they cannot implement the correct, timely and complete interchange of matter, energy and information between the SoS constituents and externally that is necessary to achieve a particular result.

7.7 Industrial Influence

The initial thinking gave rise to the conceptual-world assertion that it was the inability to make the necessary correct, complete and timely transfers of Material, Energy and Information that prevented socio-technical systems achieving what was desired, which posed the question of how a systems affordance for the transfer of ME(I) could be enhanced such that when an unforeseen event occurred new ME(I) transfers necessary to address the unforeseen problem could be brought into play. Furthermore, systems had ME(I) transfers, and ME(I) transfer components (Sources, Sinks and Bearers) that were unintentional, that is not 'designed-in'; some were inherent with the means chosen to implement the conceptual solution functions required for it to fulfil its requirements, and others were 'independent', for example belonging to another system but having the potential to affect the system-of-interest under examination. 'Intended' ME(I) transfers had Inherent SSBs that were of the same and/or different types; for example an armoured DC power cable was able to also conduct energy as magnetic flux and mechanical force, and information such as 'supply and connections present / not present'.

Thoughts then were directed to a method that could reveal the 'inherent' and 'independent' ME(I) SSBs, and determine if they were either a risk because they may be likely to cause problems, or they provided an opportunity to enhance a systems ability to transfer ME(I).

Some specialist engineering disciplines do use methods that address some of the risk aspects of some of the 'Inherent' and 'Independent' ME(I) SSBs, but these disparate viewpoints are not currently drawn together in a 'big picture' view that is necessary to reveal what effect these SSBs might have at the system or SoS level, or what latent capability they may hold. The TCA meta-model appearing in this thesis is offered as one way of visualising a SoIs ME(I) transfer affordance 'big picture'.

At the outset of this research the author intended to carry out some of the preliminary activities required for TCA adoption using case-studies of deliverable solutions from the industrial partner, but none could be realised within the research timeframe. A case-study with the Royal Logistic Corps (Section 9.2) was valuable and contributed the benefit to the research that would have been obtained from an industrial case study, albeit not providing the industrial partner with information on their specific products.

A TCA process integral with the adopting industrial's PLM system is envisaged to be used primarily to provide new knowledge of the SoI and hence to reveal potential problems and prospective opportunities from unintended ME(I) SSBs, which will populate a ME(I) meta-model visualisation. Engineering staff include those working at the sub-assembly level up to those working at the SoS level, to benefit from their domain knowledge. It was considered advantageous if the TCA process was designed to use tangible fundamental concepts (frequency, time and amplitude) with which most academic and engineering personnel would be familiar, rather than a new abstract set of concepts that needed to be learned before they could utilise and benefit from the TCA technique.

7.8 Chapter Summary

This chapter has set the scene for the research, design and development of a method, process and visualisation from the TCA technique that reveals covert unintended ME(I) SSBs for assessment as either risks or opportunities. It has additionally included the thought processes to show how the point-of-departure described in this chapter was reached to provide some of the rationale behind it, and to assist those readers without the benefit of significant industrial experience.

8 Current Engineering System Analysis and the TCA Method

This chapter begins with a brief overview of some engineering systems analysis techniques as they relate to the creation of SoS constituents and identifies the perceived common shortfall they have. This is followed by an outline description of the analysis method proposed by this research which address this shortfall, the potential for exploitation of the method created by this research as a process to be used in an industrial environment, and how system suppliers might incorporate provisions for fit-for-purpose maintenance into their products in a cost-effective manner.

8.1 Overview of Engineering System Analysis

Analysis is used to determine which functions are required by the system to meet its requirements. It consists of the decomposition of higher-level functions to lower-levels and the traceable allocation of requirements to those functions (INCOSE_UK 2010 p.16).

There exists a plethora of systems analysis tools, each having their own strengths and weaknesses. Some examples are:

- Flow Charts
- Data Flow Diagrams
- State Transition Diagrams
- IDEFx (Integrated Definition for Functional Modelling)
- SADT (Structured Analysis and Design Technique)
- UML (Unified Modelling Language)
- SysML (System Modelling Language)

Engineering analyses essentially provide a model of a future or existing SoI to assist the prediction or understanding of its construction and behaviour, with the objective of facilitating creation or modification of the physical system. System level analyses explicitly visualise functions, relationships and behaviours, whereas the transfers of Material, Energy and Information (ME(I)) between internal system constituents and externally that produce the functions, relationships and behaviours are often less visible, especially at the system level.

Quality Function Deployment (QFD) (Burge 2007) is a strongly structured system analysis tool that relates customer requirements to supplier requirements at each phase from concept to manufacturing. It provides good traceability and visualisation through the SoI lifecycle, but it is difficult to gain an appreciation of ‘how it all works’ from a QFD alone. System operation is much more readily appreciated with Function Flow Diagrams (FFD) (Burge 2011), that show the SoI’s functions and the flows between them, but FFDs do not show the relationships between the customer requirements, the layers of supplier requirements from design requirements to manufacturing requirements as explicitly as QFDs.

The normal engineering design process creates transfers of MEI, and the designer ensures these SoI's internal and external transfers are complete, correct and timely such that the SoI fulfils its requirements. These 'designed-for' MEI transfers are formed by sources, sinks and bearers created during the design process are termed 'Intended' by this research.

How the Sources, Sinks and Bearers (SSBs) creating the 'intended' MEI transfers are physically implemented will also produce SSBs that are inherent with the chosen physical implementation. Taking the steel wire armoured cable example, a FFD may show the 'intended' transfer of DC power between two parts of the SoI, but not the mechanical, magnetic, AC and thermal transfers inherent with the physical implementation of the requirement for the transfer of DC electrical energy. This research uses the term 'Inherent' to describe ME(I) SSBs such as these.

A supra-system or the host platform of the SoI could contain ME(I) SSBs that are external to the SoI but have an effect upon it. An example of this might be a vessel's propulsion engine transmitting mechanical vibrations through a common structure to perturb an on-board stabilised tracking radar platform, as well as transmitting externally to potentially be detected by a surveillance device such as a SONAR hydrophone. This research uses the term 'Independent' to describe ME(I) SSBs such as this.

Engineering system analyses do not usually explicitly represent transfers of material, energy and information between SoI constituents and externally as such; one exception being Hubka and Eder, (Hubka and Eder 1988) who consider MEI as process consumables, rather than constituents of process inputs and outputs. However the MEI transfer-enabling Sources, Sinks and Bearers (SSBs) that are the means by which MEI transfers are implemented are not considered. Pahl & Beitz (Pahl and Beitz 1986) on p.21 subsection 2.1.2 do consider that technical systems involve the conversion of energy, material and signals as an outcome of the intended designed solution, but do not extend this to unintended conversions as the 'inherent' and 'independent' transfers of ME(I) covered by this research.

These inherent ME(I) SSBs may be dormant or active, and the active SSBs may be unconnected, partially connected or form ME(I) transfers. Some engineering discipline specialists, guided by system level policy documents do assess potential problematic inherent transfers at the detailed design level, for example radiated and conducted radio frequency interference and electro-magnetic compatibility assessments, but although design is guided by plans and policies these are done after the system design has been 'chilled' (i.e. the central design aspects of the solution have been fixed ('frozen') but secondary aspects can still be changed) and the implementation fundamentals have been largely chosen.

System-level visualisations are often incomplete, because engineers may not have the facility to capture 'inherent' and 'independent' ME(I) SSBs, which may well have been unknown when the system-level visualisation was created. The TCA method and process provide a more complete system level representation by revealing the 'inherent' and 'independent' ME(I) SSBs, which allows engineers to assess if these inherent ME(I) SSBs are either likely to cause a problem (e.g. crosstalk) or have the potential to be exploited to enhance the SoI's affordance (at the time of exposure or at some time in the future) for the transfer of ME(I).

Examination of the unutilised capacity of all these ME(I) SSBs shows their ability for undesirable transfer of ME(I) that could cause undesirable emergent properties, and also their exploitation potential to create new transfers of ME(I) enabling new or increased capabilities necessary for the SoI to meet a previously unforeseen need.

The following sections in this chapter describe in outline the TCA method.

8.2 TCA Method

This section describes the TCA method created and developed by this research. It will introduce several new concepts and terms, which are explained in the glossary and definition of terms provided earlier in this thesis, and also summarised at the end of this section to assist the reader. The section starts with a brief description of the systems engineering 'Vee' model as used by the International Council On Systems Engineering (INCOSE) and how two common systems analysis tools correlate to it, followed by a description of the TCA method and how this complements and provides a more complete visualisation of a system of interest.

The TCA method considers a ME(I) Source to be a source of some transferred material, energy or information and a ME(I) Sink to be a destination or terminus for some transferred material, energy or information and a bearer a transferor of some transferred material, energy or information. As described above, the TCA method completes the representation of ME(I) SSBs in the SoI by including those inherent with the chosen implementation of the 'intended' ME(I) SSBs or those 'independent' SSBs that could affect the SoI. This complete picture complements other visualisations, such as the systems engineering 'Vee' model, in Figure 8.1 below (The V Lifecycle Model © INCOSE UK Ltd, reprinted with permission.) (INCOSE 2009).

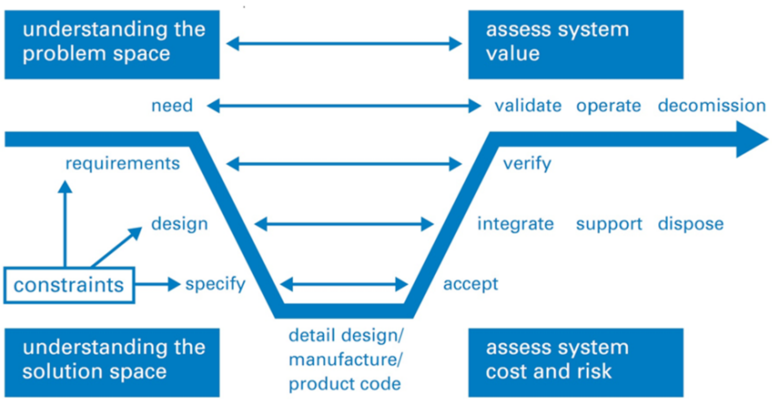


Figure 8.1: Systems Engineering 'Vee' Model (INCOSE 2009)
(© INCOSE UK Ltd, reprinted with permission)

In terms of the equipment component of capability for example, the left-hand side of the 'Vee' relates high level needs and requirements, down through systems-of-systems, systems, major assemblies to Line Replaceable Units (LRUs) and components. Each of these junctures can be represented by a Quality Function Deployment (QFD) transform (sometimes known as 'the house of quality') as one part of a cascade of transforms. This is illustrated in Figure 8.2 below.

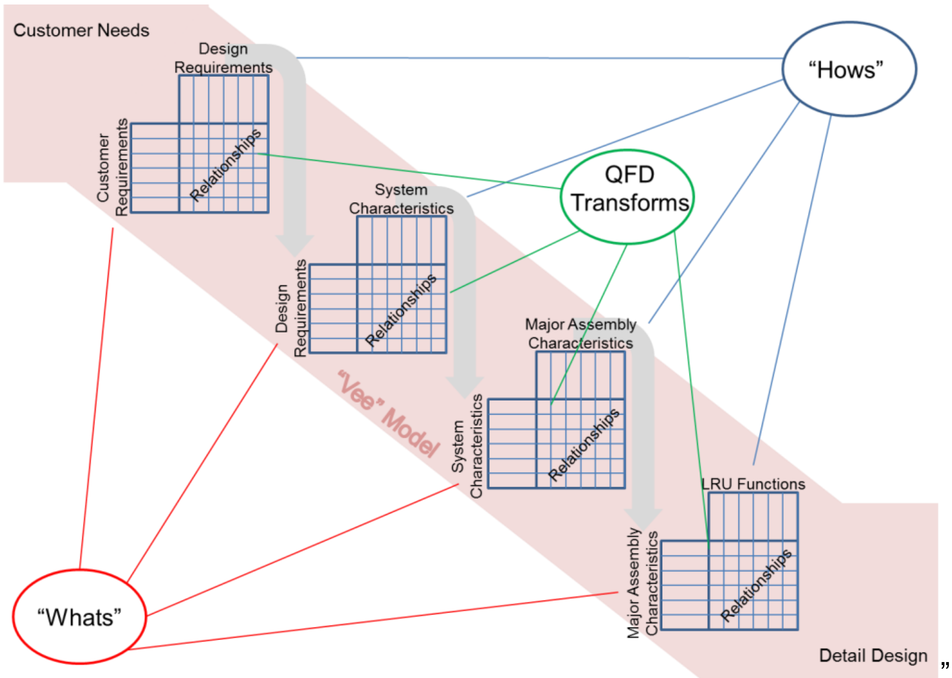


Figure 8.2: QFD Transform Cascade

The QFD cascade starts with the customer needs: "What" the customer wants. The 'Hows' are functional responses that will fulfil the 'Whats'. For example, a customer requirement ("What") of a data terminal expressed as 'Easy to Use', might have responding 'Hows' of Multilingual, Standard Keypad, Auto-brightness Display, Fingerprint Access, Assistance Prompts etc. which are the 'Whats' of the subsequent transform and so on down through the cascade of transforms as shown by the grey arrows, until the last transforms ‘Hows’ are expressed such that engineers are able to design implementations of them as hardware/software/mechanical structures.

Whereas QFD transforms relate requirements to functions (‘Whats’ to ‘Hows’) at each juncture, the TCA method uses a similar transformation that complements the QFD ‘What’ to ‘How’ relationships, with a representation of those ME(I) transfers that are ‘intended’ and designed-in to bring about the ‘What’ to ‘How’ transformations. (Burge 2007)

The ‘intended’ ME(I) transfers consist of ME(I) Sources, Sinks and Bearers (SSBs) that execute the transfers necessary for the SoI to operate as required. This is illustrated in Figures 8.3.and 8.4 below.

As well as the ME(I) transfers that are ‘intended’, i.e. those that are ‘designed-in’ to make the SoI operate as required, the TCA transforms also capture unintended ME(I) SSBs that may or may not be actively transferring ME(I). These unintended ME(I) SSBs will be either ‘*inherent’* with the SoI design or affect the SoI despite being *‘independent’* of it. The TCA cascade shown in Figure 8.3 below corresponds to the left-hand side of the ‘Vee’ relating SoS capability through subsystem functionality to Line Replaceable Unit (LRU) in terms of three types of ME(I) SSBs: those that are intended to implement the designed solution, those that are inherent with the design, and those that are independent but nevertheless have an effect on the SoI.

Figure 8.3 below illustrates this initially in a simplified form.

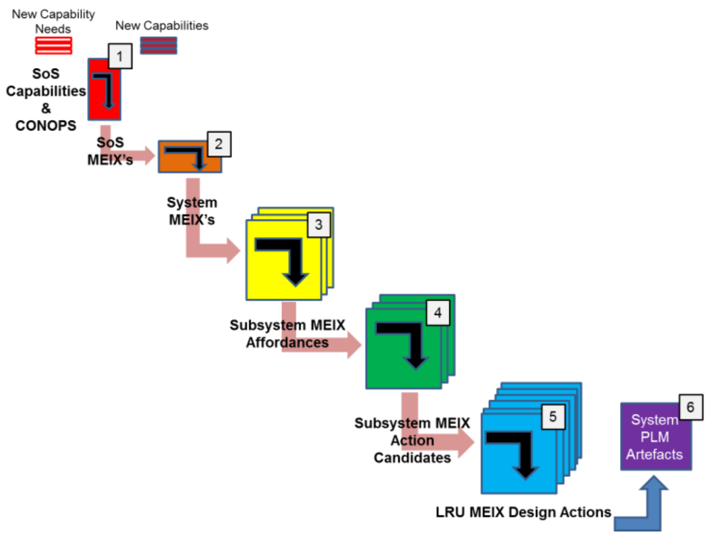


Figure 8.3: TCA Transform Cascade

Transform 1 (Red) relates the SoS capabilities in the context of its operational concepts, to the ME(I) transfers across its boundary that realise the SoS’ capabilities. At this stage the ME(I) transfers and their SSBs are all ‘Intended’: i.e. those designed-in to the SoI that realise its functions.

Transform 2 (Orange) in the cascade relates the SoS ME(I) transfers to the constituent system ME(I) transfers, and also incorporates the ‘Inherent’ and ‘Independent’ SSBs at the system level.

Transform 3 (Yellow) groups all the system SSBs into prospective system ME(I) transfers into a set of affordances and identifies the relevant subsystems. This better enables examination and assessment of ME(I) transfer enhancement from a subsystem viewpoint.

Transform 4 (Green) analyses the prospective affordances for ME(I) transfer and collates them into three sub-sets: those not requiring further action, those to be exploited to enhance the systems affordance for transfer of ME(I) and those requiring action to prevent them causing unintended ME(I) transfers which may be problematic. This assessment at the system / subsystem level would be done by the relevant system and specialist discipline engineers.

Transform 5 (Blue) associates system design actions with the unintended ME(I) transfer affordances, guided by the original system design actions and any others that will be concurrent with subsystem ME(I) transfer enhancement exploitation or problematic unintended ME(I) transfer risk reduction actions.

The purple ‘System PLM Artefacts’ box 6 represents the Project Lifecycle Management documents, drawings, models etc. into which the exploitation/risk reduction design actions are integrated for incorporation into the SoI at a convenient and cost-effective ‘design opportunity’.

This transform representation shows well the relationships between the levels in a SoS / SoI, but does not so clearly show ‘how it all works’, which is better illustrated by a FFD. Figure 5.4 below is a simplistic top-level function-flow representation of a SoS showing the ‘designed-for’ ME(I) transfer connections between its constituent systems (Note that “MEIX” in the figures is used as an abbreviation for ‘ME(I) transfer’).

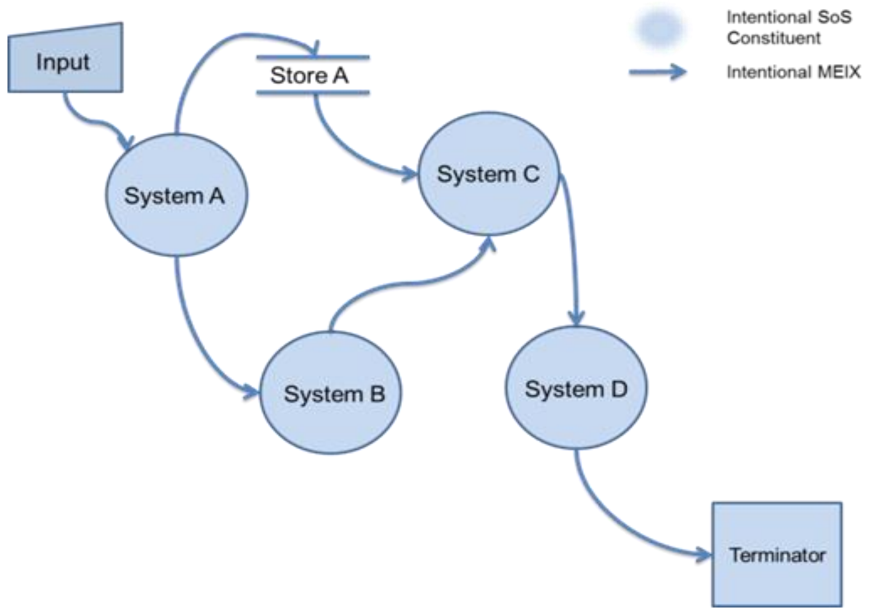


Figure 8.4: Simple function-flow diagram of a SoS showing Intentional ME(I) Transfers

This simple FFD represents the ME(I) transfers that have been designed to flow between the constituent systems of a SoS, that is the 'intended' ME(I) transfers. For example, system A has a source of material, energy or information that is transported via a bearer to a sink in system B. For example this transfer could represent part of a lubrication system, a reservoir supplying oil via a pipe or gallery to a large shaft bearing. Systems suppliers have their own preferred representations of their products, depending on what they consider is best for their particular business. This research does not constrain exploiters to the use of any particular representation. What follows is a description of the theoretical process that identifies the 'intended', 'inherent' and 'independent' ME(I) SSBs in a SoS using FFD layers.

8.2.1 Theoretical TCA Method

The FFD in Figure 8.4 above is a simplistic top-level representation of a SoS that shows the connections between its constituent systems that have been designed and implemented to realise the complete, correct and timely transfers of ME(I) necessary to achieve what is required of the SoS. These transfers and the ME(I) SSBs that achieved them are classified as 'intended'. At the level below, each SoS constituent system can be examined, and their 'intended' ME(I) SSBs captured on system level FFDs, and so on down to the Line Replaceable Unit (LRU) level. The architecture of these FFDs is reflected in the Work Breakdown Structure (WBS) in the relevant design definition artefacts held in the PLM system, and could be said to be a representation of the SoI in terms of '**What we *think* we've got**'.

The physical implementations (for example a reservoir/pipe/bearing, a generator/cable/power filter, an antenna/atmosphere/aerial, a ration pack/helicopter/vessel etc.) of the 'intended' ME(I) SSBs are examined to determine ME(I) SSBs that are inherent with how they will be implemented. For example the steel wire armoured cable previously described electrically connecting two components will also inherently conduct AC as well as connecting the two components thermally, magnetically and mechanically.

The wider environment around each SSB at each level is examined to identify '*independent'* ME(I) SSBs, that is those that are not part of the SoI nor have an 'intended' connection to it, but may have an effect on the SoI. For example the structure of a vessel (mechanical energy bearer) conducting vibrations from the vessels propulsion engine to the radar antenna mast (mechanical energy sink) thereby degrading the radar's stabilisation performance.

The 'inherent' and 'independent' ME(I) SSBs are added to the 'intended' ME(I) SSB FFD as shown in Figure 8.5 below to provide a more complete picture, which might be thought of as representing the SoI in terms of '**What we *actually* have**' as an ME(I) Meta-Model.

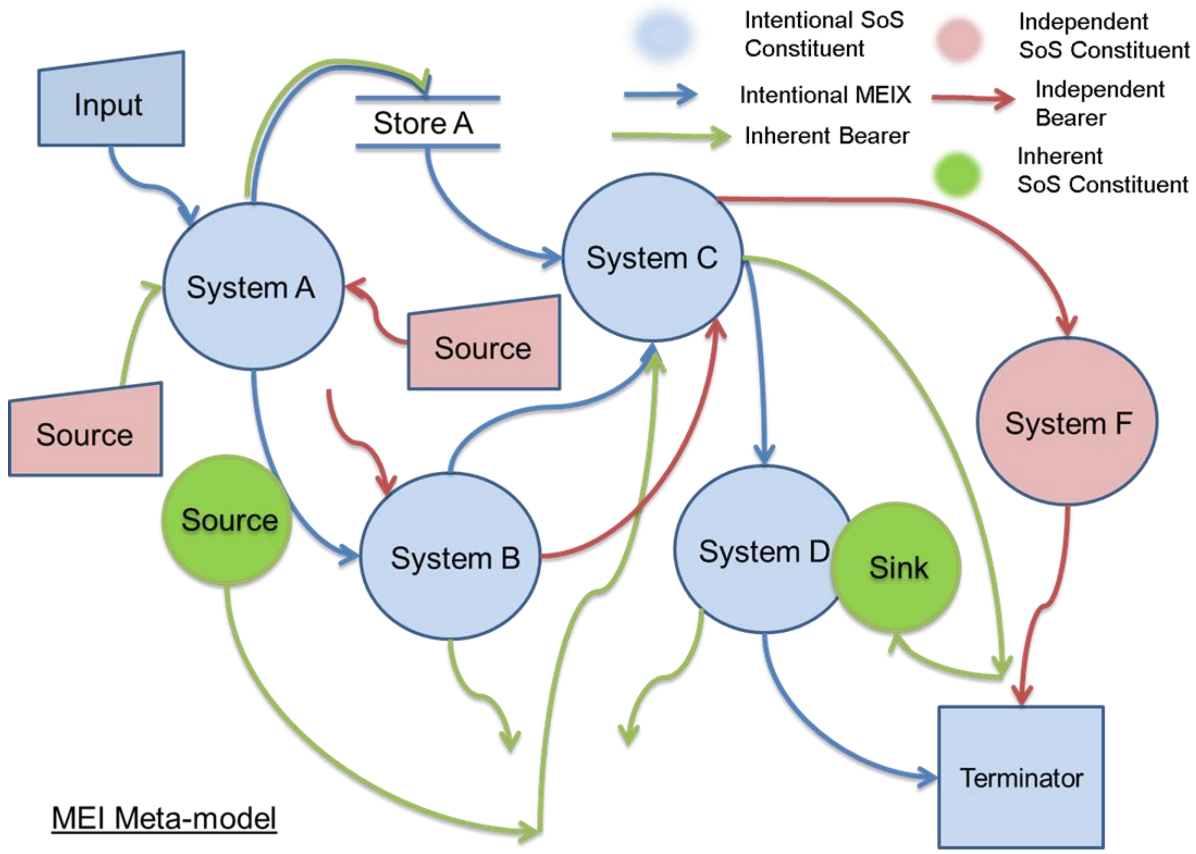


Figure 8.5: ME(I) Meta-Model showing all ME(I) SSBs

The analysis of a SoI may well reveal 'untidiness'. For example, ME(I) SSBs may have the ability to source, sink and transport ME(I), but do not have the connections to do so. Sources and sinks may be connected by several bearers in series or parallel combinations. Examples are illustrated in Figure 8.5 above as singly terminated bearers and bearers connected together. It is important that

SSBs like these and ‘floating’ ME(I) SSBs seemingly without connections are not discounted in the TCA method as they may be potential causes of undesirable system behaviour or exploitation opportunities.

Although the FFD above provides a more complete picture of the SoI, it tells us little about the characteristics of the ME(I) SSBs. The diagram above could be thought of as being similar to a kinematic representation of a mechanical system, in which the motion of a system of parts are represented without considering their mass or the forces acting on them. FFDs are usually enriched by function descriptions and flow specifications that capture their characteristics. To transfer ME(I) from a source, via a bearer to a sink, there has to be some ‘common ground’ in the characteristics of all three. The speed, timing and capacity characteristics of all three have to be able to accommodate those of the transferred quantity.

This new viewpoint of the SoI poses two immediate questions: (i) ‘Are these ‘inherent’ and ‘independent’ SSBs going to cause problems?’ and (ii) ‘Can I exploit them to advantage?’

The consideration of the first of these two questions and its answer may have significant impact on the SoI design, as it will reveal unintended ME(I) SSBs that may otherwise remain as covert potential causes of unexpected emergent behaviour. Addressing the second question may enable incorporation of features into a SoI that otherwise may be impractical or uneconomic to provide.

In order to answer these two questions the *ability*, *opportunity*, *capacity* and connection of these ME(I) SSBs to make ME(I) transfers needs to be determined. The ability to transfer ME(I) between a source and sink via a bearer is evaluated by determining the operating bandwidth over which each source, sink and bearer outputs, receives and transports respectively. This frequency domain analysis finds sources sinks and bearers with common spectral bandwidths which are termed prospective affordances for ME(I) transfer, which is followed by examination of the SoI and its architecture to determine SSB connectedness. The opportunity to transfer ME(I) between a source and sink via a bearer is evaluated by determining if the prospective affordances identified by frequency domain analysis have sources, sinks and bearers which can output, receive and transport at the same time. The capacity of connected ME(I) SSBs to transfer ME(I) is determined by examination of the SoI implementation build state defined in the technical design data pack. The frequency and time domain analysis identify those ME(I) SSBs with both the ability and opportunity to transfer ME(I), and are termed potential ME(I) transfer affordances. How potential ME(I) transfer affordances are identified is described below.

The analysis of the SoI to determine its ME(I) SSBs and characterise their capabilities is described here by firstly dealing with the ‘intended’ ME(I) transfers and their associated SSBs, then following with the analysis of the inherent and then the independent SSBs. However SoI analysis could be done in a different sequence if it better suits individual cases.

Figure 8.6 below illustrates the frequency domain analysis of a simple 'intended' ME(I) transfer affordance, consisting of a source, a sink and a bearer.

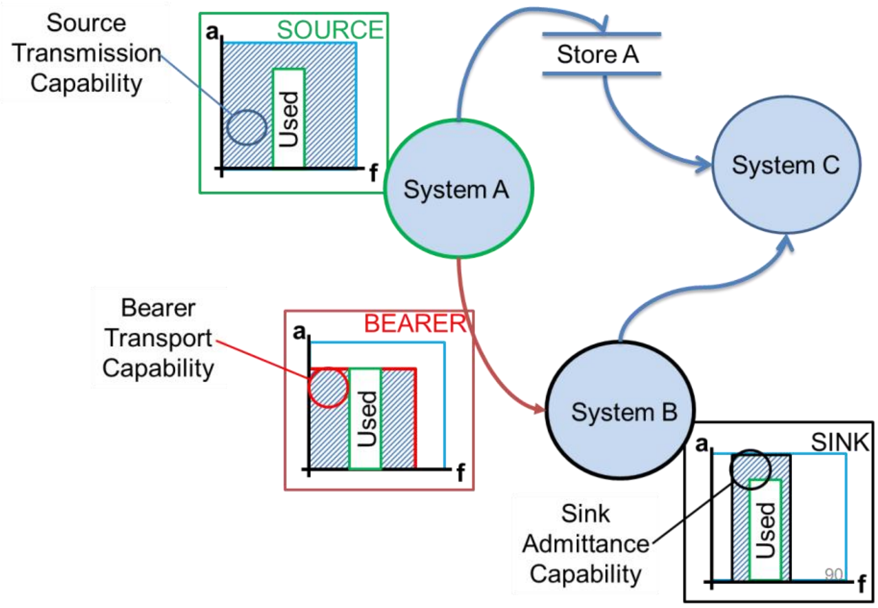


Figure 8.6: SSB Characterisation Example

Figure 8.6 shows the transmission, transport and admittance capabilities of the ME(I) transfer affordance's source, sink and bearer, with the 'Used' portion that the design uses to make the 'intended' transfer superimposed. In this simple example the source has the bandwidth to output both above and below the spectra and at greater quantity than is used by design. The bearer is able to transport at frequencies above and below the spectra used by design, although it does not have the bandwidth of the source, and cannot carry a greater quantity than is used. The sink does not have the bandwidth of either the source or the bearer, but can accommodate the full capability of the source.

If the source, sink and bearer frequency domain characteristics are overlaid, the common portion is the bandwidth available for ME(I) transfer. Part of this common portion is used by design, shown as a white rectangle within the hatched area, and the unused part of this common portion is termed 'headroom'. A circle shows a portion of the hatched headroom area to assist discernibility in Figure 8.7 below.

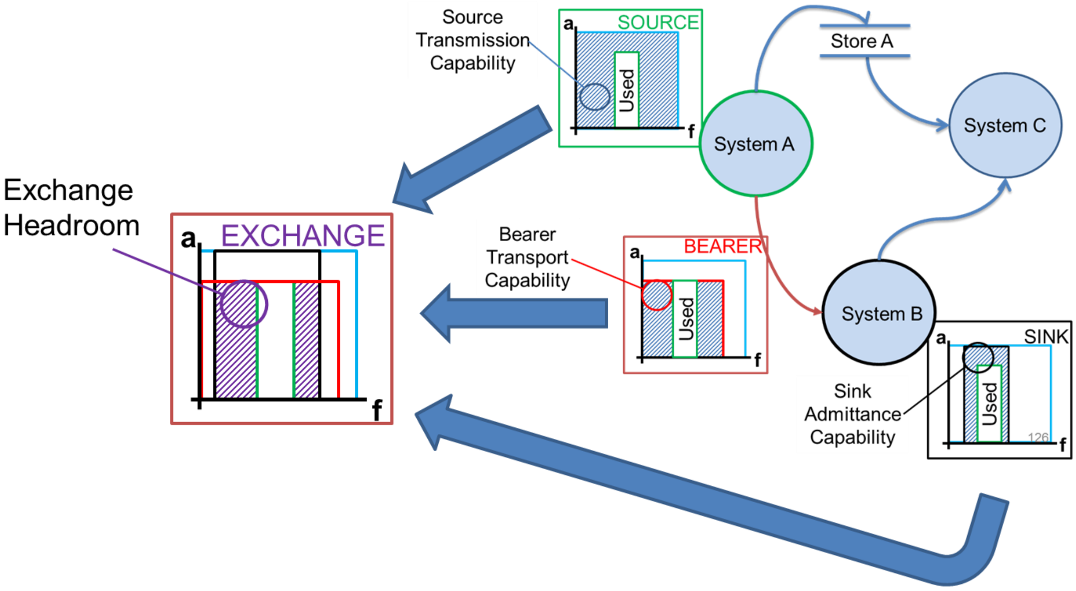


Figure 8.7: ME(I) transfer Bandwidth Headroom Determination

Figure 8.7 illustrates how an 'intended' ME(I) transfer affordance consisting of one source, one sink and one bearer is expanded to illustrate the identification of headroom that is inherent with an 'intended' ME(I) transfer.

The frequency domain characterisation process above is repeated for the 'inherent' and 'independent' ME(I) SSBs, however these will not have a 'used' (by-design) portion of their bandwidths. However, if an inherent quality of an 'intended' ME(I) transfers source, sink or bearer is utilised - for example if a moving parts shield is used to provide structural support to other components - this part of its mechanical load bearing capability is an 'intended' ME(I) transfer and captured as such. The frequency domain analysis of the 'inherent' and 'independent' ME(I) SSBs that informs subsequent grouping into prospective ME(I) transfer affordances by examination of its connectedness is described and illustrated below.

Figure 8.8 below shows the first step of examining the implementations of the SoI's 'intended' ME(I) transfers to detect their inherent SSBs, then recognising which inherent SSBs have connections that may either (i) enable transport of ME(I) from/to 'intended'/'unintended' sources/sinks (i.e. form ME(I) transmission or reception affordances) or (ii) form inactive SSB connections (i.e. form ME(I) transfer affordances) or (iii) be active ME(I) transfers between a source and a sink.

A determination of common headroom between the bearers and their connected sources and sinks identifies those bearers with the ability to transport a ME(I) quantity from a source or to a sink. Note that the diagram shows one instance of where this step revealed an inherent ME(I) transfer from 'System A' to 'Store A'.

Note that inherent bearers revealed by analysis may not be connected to a source to a sink, or form a ME(I) affordance by connecting together a source and sink, or create a ME(I) transfer by transferring ME(I) via an affordance; however as stated previously these must be captured by the ME(I) meta-model as they may become significant if the SoI changes at a future date, or be revealed as significant if the SoI's role or partnering SoS constituents are examined or changed.

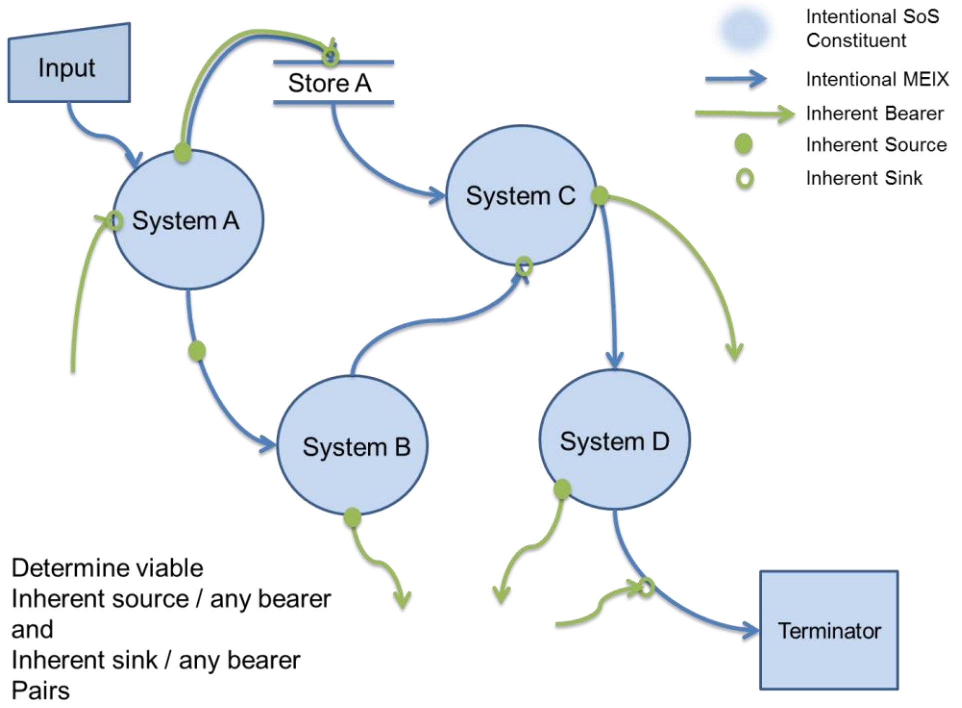


Figure 8.8: Determine Inherent SSBs

Expanding Figure 8.8 above, the figure 8.9 below illustrates the process for inherent SSBs repeated for 'independent' SSBs to determine what 'independent' SSBs exist, their connections and which of them form ME(I) affordances and ME(I) transfers. Note that the diagram shows one instance of where this step revealed an 'independent' ME(I) transfer from System B to System C.

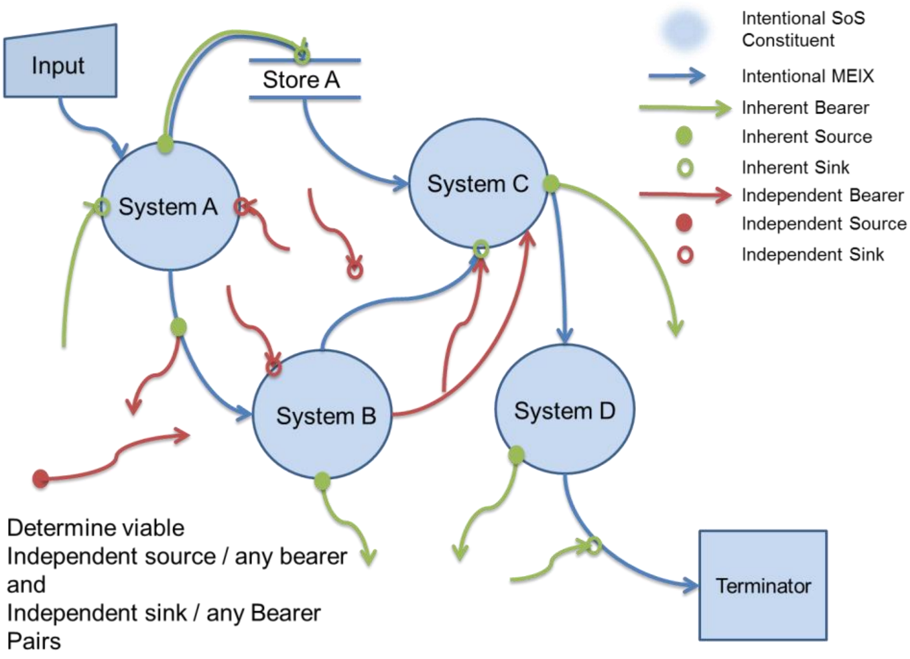


Figure 8.9: Determine 'Independent' SSBs

The 'intended' and unintended SSBs, ME(I) transfer affordances and ME(I) transfers need to be assessed as mechanisms for unintended transfer (in response to the 'Is this likely to cause problems?' question) and also as opportunities for exploitation to enhance transfer (in response to the 'Can this be exploited?' question).

To answer these questions a time domain analysis establishes if all the elements of the transfer affordance or ME(I) transfer are capable at the same time. For instance, the microwave waveguide to a single-antenna tracking radar will not be available to the transmitter when being used by the receiver and vice-versa; therefore although a frequency domain analysis suggests the possibility for unintended transfer exists, the opportunity for it does not.

If the source, sink and bearer time domain characteristics are overlaid, the common portion where the source, sink and bearer can all function simultaneously is the period available for ME(I) transfer. This is illustrated in Figure 8.10 below, where part of this common portion is used by design, shown as a white rectangle within the hatched area, and the unused part of this common portion is termed 'headroom'. A circle shows a portion of the hatched headroom area to assist discernibility in Figure 8.10.

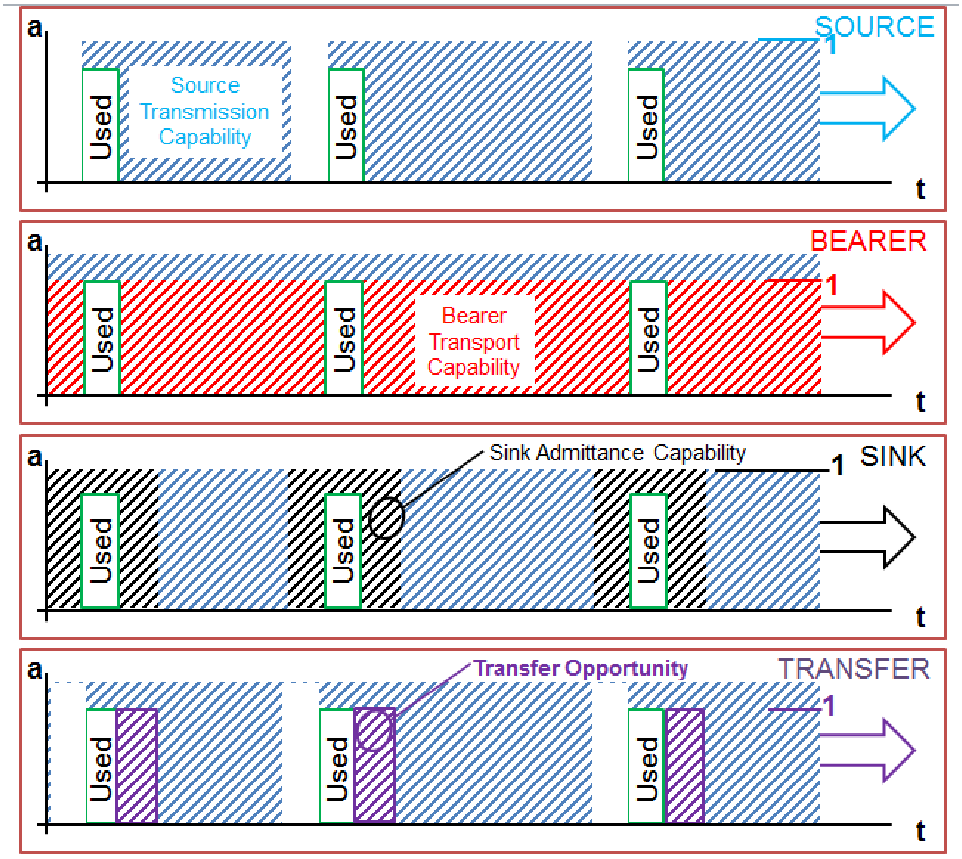


Figure 8.10 ME(I) transfer Temporal Headroom Determination

Figure 8.10 above shows four time plots with the same time (t) axis of a ME(I) transfer affordances constituents. The top plot ('SOURCE') shows the temporal source transmission capability. The second plot ('BEARER') shows the bearer availability periods. The third plot (SINK) shows the sink reception periods. The fourth plot (TRANSFER) shows the source, sink and bearer plots overlaid to show the transfer opportunity headroom periods in a similar manner to the three SSB frequency domain analyses used to determine transfer bandwidth headroom.

Note that in the case of discontinuous SSBs the 'Used' period might not always be actually used, but might be considered as a period where immediate availability of the 'intended' ME(I) transfer capability is required: this may be categorised as a reserved period or exploited on an opportunistic basis by the TCA method exploiter's specialist engineering staff on a case-by-case basis as they consider best suits their needs.

A SoI will contain many 'inherent' and 'independent' ME(I) SSBs that may or may not form ME(I) transfer affordances, or may or may not form unintended ME(I) transfers. The combination of the frequency domain headroom and time domain headroom data will highlight to engineering staff those SSBs that form potential unintended transfer affordances by virtue of having both the ability (bandwidth headroom), connectivity and opportunity (temporal headroom) to transfer ME(I). One way that engineering specialists familiar with the SoI could use their domain specific tools to show which potential affordances and ME(I) transfers could be problematic or provide an opportunity for exploitation would be by firstly determining sink susceptibilities, then if any ‘inherent’ or ‘independent’ source connected to them by a bearer would transfer ME(I) sufficient to either cause a problem, or be an opportunity by augmenting it to provide enhanced ME(I) transfer that enables a new or improved system or SoS capability, but the engineers may consider an alternative sequence or method is preferable to the way they operate.

The determination of which potential ME(I) transfers could feasibly transfer amounts of ME(I) to be either a risk or an opportunity is conceptually illustrated by Figure 8.11 below which makes a comparison with noise margins between the inputs and outputs of digital logic circuits.

For example, if the voltage from a digital output in the ‘Low’ (0) state is sufficient to exceed the noise margin of a connected digital input, what this ‘Low’ output may be read as by the receiving input is indeterminate, and requires some level of remedial or mitigating action.

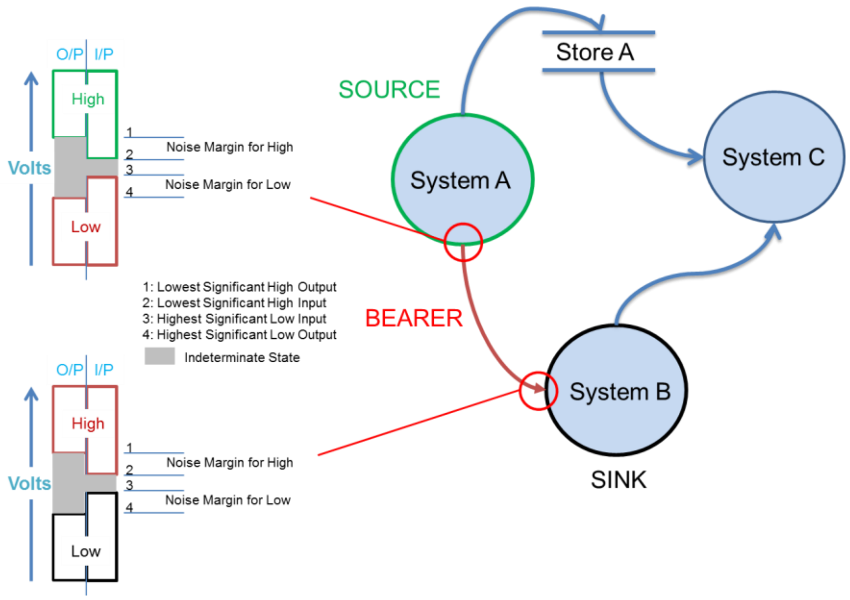


Figure 8.11 ME(I) transfer capacity Determination

Similarly, an unintended ME(I) source (‘inherent’ or ‘independent’) output could be examined to determine if it is sufficient to exceed the noise margin between it and a susceptible ME(I) sink.

If an unintended ME(I) source (‘inherent’ or ‘independent’) output from system A arrives via the bearer at system B sink sufficient to exceed the sink’s lowest significant output threshold, System B may react to the System A output. The specialist engineer has then to decide if this may be problematic and take some level of remedial or mitigating action. The threshold is considered to be the lowest level of non-intentional transfer capable of affecting the SoI.

8.3 Quantitative Analysis of SoS Constituents

The TCA method and process analyses SoS constituent engineering systems from the viewpoint of their capacity, and the utilisation of this capacity, to source, transport and sink material, energy and information within itself and externally. At the systems level, valuation of the fitness-for-purpose of a SoS or a system constituent will have subjective as well as objective content, differ between different stakeholders in a given role in the SoS/system and be expressed in different terms by different roles. The TCA method does not seek to provide a quantitative assessment of the fitness-for-purpose for any analysed SoS/system (such as a figure of merit) as the author considered that it would not provide an accurate representation of any systems fitness-for purpose over such a diverse range of possibilities, or provide a worthwhile contribution to the aim of the research. The author is aware of other research that attempts to provide assessment figures for similarly difficult-to-quantify system characteristics using tools such as fuzzy logic and Bayesian networks (Kinder, Henshaw, and Siemieniuch 2015) (Kinder, Henshaw, and Siemieniuch 2014) in instances where a generic figure would be meaningful and useful, so has included below thoughts on how an FFP assessment using these kinds of techniques and others that are able to accommodate both quantitative and qualitative assessments might be applied to a SoS constituent for the benefit of the reader interested in developing a figure of merit for fitness-for-purpose.

8.4 Fitness-For-Purpose Assessment

Changes in the SoS situation, e.g. operational environment, requirement or 'LoDs' can render the SoS not fit-for-purpose due to a combination of the two reasons below in various proportions:

(i) The SoS capability was degraded and could no longer bring about the desired outcome it was designed to do.

(ii) The SoS needed to provide different functionality to that which it was designed to do in order to achieve the desired outcome.

This research does not provide an assessment of the fitness-for-purpose of a SoI, however consideration was given to assessment and how might this be implemented in a SoS constituent (a System-of-Interest (SoI)). An outline to assist and provide food for thought for readers considering such further work follows.

One option for assessment of fitness-for-purpose is by a form of Built-In Test Equipment (BITE). (Coppola 1979), (Moore and Damper 1986).

The author considered that two assessments of fitness-for-purpose may be effective in a three-level structure. The two assessments are passive and active. Passive assessment purely monitors SoI (SoI) variables, and the SoI remains unaltered by the measurement. Active assessment stimulates the SoI and the response to the stimuli is recorded. The three levels are be akin to Power-On Self-Test (POST), 'On-Line' monitoring and 'Instigated Test'. 'On-Line' assessment will be passive, and could emulate a Health and Usage Monitoring System (HUMS) implementations. 'POST' and 'Instigated Test' would be a mixture of both active and passive. The results would support the user's decision as to whether the SoI was fit-for-purpose in order to achieve the desired outcome.

In a similar way that BITE test results are used for fault-finding and diagnosis, it was considered that fit-for-purpose BITE could be built upon to provide decision support to SoS users via FFP Diagnostics and Prognostics. This would be achieved by FFP BITE providing the quantity monitoring to inform a real-time mimic model of the SoI. The model would be continually validated by monitoring and adjustment to mimic the behaviour of the real 'Live' system. It could be used diagnostically to determine the root cause of fit-for-purpose shortfall, prognostic prediction of fit-for-purpose, what-if analyses, etc. Opportunity identification may be a further enhancement; as McManus & Hasting note: "In particular, exploiting the upside of uncertainty to achieve flexible, evolvable, or adaptable system does not have an explicit place in current systems engineering practice" (Mcmanus and Hastings 2006).

System FFP Diagnostics and Prognostics are outside the scope practically achievable by this research, and cognisant of the thought that "Whether work products are fit-for-purpose is defined not by the person doing the work, but by the person who will use the results" (Sillitto 2010), it seems folly to attempt to create a fit-for-purpose assessment mechanism that can be generically applied to any SoI and yet provide a credible measure of its fitness-for-purpose as a credible measure is highly dependent on the context and idiosyncrasies of each individual case; 'One man's meat is another man's poison …'

8.5 Research Emphasis Profiling and Meanings

This section describes the scoping of this research in terms of the research assertion and its constituent parts. The assertion encapsulates the 'Big Picture' view of why SoS become not fit-for-purpose, and some key words have been extracted from it to guide the scoping of the research such that it is achievable within the constraints of a full-time PhD, namely the available duration, level of effort and not least the academic requirement of novelty: a contribution to the human body of knowledge. The research boundary is not a hard line; rather a decaying analogue band where factors affecting fitness for purpose are given varying degrees of address to provide a research outcome of acceptable value to all stakeholders within constraints.

In the following paragraphs factors that are explored by this research are described as a focus, considered factors are those which are addressed to a degree that provides an acceptable return on investment for the research outcomes, and acknowledged factors are those not extensively explored but where the research has been mindful of their roles. The emphasis of this research upon the big picture constituents are described below.

This research asserts that SoS do not maintain fitness-for-purpose because they cannot implement the correct, timely and complete interchange of matter, energy and information between the SoS constituents and externally that is necessary to achieve a particular result.

Information: The area of information science, for the purposes of this research includes soft aspects such as culture (in all its guises) language and overt behaviour, in terms of theory, architectures, management, etc. As said, there already exists a lot of good work concerned with information management in fields such as management science, computer science, social science, etc. (for example a Google scholar search for "Information Management Systems" returns over four million results) thus demonstrating it is a well-trodden path. However because it has such a significant role in the successful operation of systems / SoS, and furthermore the success of the outcomes of this work will be predicated on good knowledge management, therefore it is a consideration of this research.

Energy: Standardisation of energy transfer has an important role, and again is an area of significant activity, but there are many standards! In a reconfigurable SoS, whichever standard is chosen will not suit somebody, and new standards, often not backward-compatible, are constantly emerging. This work is bounded to the acknowledgement of standards and their importance in the transfer of ME(I), but does examine the risks and potential exploitation of energy transfer mechanisms inherent with those intended by the system designer.

Material: A similar situation to Energy; considered by this work at an acknowledgement level but with the appreciation of where the standardisation of materials and consumables are concerned, and an emphasis on the identification of risks and opportunities from inherent transfer mechanisms

Correct: The correctness of a transfer is a requirement that is addressed by the normal engineering process, but is acknowledged here.

Timely: The timeliness of a transfer is a requirement that is addressed by the normal engineering process, but is acknowledged here.

Complete: In the extreme case, completeness equals zero (nothing was transmitted, carried or received). The primary beneficiaries of the research outcomes are those close to the system's point of employment; the desire is to build on their resourcefulness and ingenuity, and in order for them to utilise these talents they have to have SOMETHING to work with; hence the enhancement of completeness is a focus of this research.

Unforeseeable: Impossible to foresee. The causes of necessary reconfigurations may be unforeseen, but could be foreseeable. We can design for foreseeable change; there is much activity to endow delivered products and services with characteristics such as agility, resilience and robustness. However preparing for the unknown is difficult, likely to be inefficient and preparations for the unforeseen can be ineffective. This research takes a different approach: its aim is to provide enablers that can be used to reconfigure SoS constituents to adapt the SoS to deal with the unforeseen as quickly as necessary when it becomes observable, i.e. becomes known. Dealing with uncertainty is a focus of this research.

Changes: The environments and problems within them are in a state of constant change, and their rate of change can outstrip our ability to reconfigure solutions to meet the changed need. There are several techniques to increase productivity, reduce timescales, reduce costs, increase quality which have a role in responding to a dynamic need, but there will always be limiting factors that are governed by things outside our control, e.g. the laws of physics. An effective way to accommodate these factors is pre-work, however the drawbacks of pre-work to address the unforeseeable has been described above. The approach taken by this research to mitigate this problem is to focus on the prepositioning of solution components that can be rapidly configured and integrated when the unforeseeable problem has shown itself.

Fit-For-Purpose: to be able to do what is necessary. It is not considered that a reconfiguration resulting from a need to address an unforeseeable problem should be the optimum solution to it (in fact it is probably unfeasible, and would not be sufficiently robust) but it should mitigate the problem to a level that's tolerable by the SoS stakeholders, i.e. it should "Satisfice" (defined as "To act in such a way as to achieve the minimum requirements for a particular result".(Sillitto 2012)).

An area of work associated with fitness-for-purpose concerns design for resilience and robustness. These are defined as below:

Resilience: "Ability to adapt to changing conditions and prepare for, withstand, and rapidly recover from disruption" (DHS 2010).

Robustness: "The degree to which a system or component can function correctly in the presence of invalid inputs or stressful environmental conditions" (ISO/IEC/IEEE 2010).

Design for resilience and robustness is often part of current design processes, however research in this area is ongoing and acknowledged by the author being a member of the INCOSE Resilient Systems Working Group. The main difference of the research described by this thesis and the working group is this research's focus on addressing unforeseeable changes.

Thus the research is oriented to address the following research questions as stated previously:

- What can be done to address the ‘unknown-unknowns’?
- Why is the current situation problematic?
- When will fit-for-purpose maintenance be done?
- How will fit-for-purpose maintenance be achieved?
- Where will fit-for-purpose maintenance be done?
- Who will do fit-for-purpose maintenance?

8.6 Risk and Opportunity

The TCA method described above reveals unintended (and perhaps unexpected) sources, sinks and bearers of Material, Energy and Information, and characterises them to determine transfer headroom between ME(I) SSBs having both the ability and opportunity to transfer M, E or I. This new insight to the SoI provoked two main questions stimulated from this more complete view captured and visualised by the ME(I) meta-model; firstly, ‘Is this likely to cause problems?’ for example crosstalk, unexpected behaviour and undesirable emergent properties, and secondly ‘Can this be exploited?’ For example to enhance ME(I) transfer, functionality and provide ‘technical credit’ for future use. The answers to these questions are dependent on the characteristics of each individual case, hence only really determinable by those informed by the TCA method having the relevant skills and familiarity with the SoI, hence it is considered that attempting to provide generic answers would not be worthwhile.

8.7 Revealing and Comprehending ‘What we actually have…’

The TCA method described in this chapter augments the traditional view of a SoS as a functional hierarchy with a novel viewpoint that provides a better visualisation of ‘How it all works’ by building on the transfers of material, energy and information that are the elements of the ‘intended’ (designed-for) functionality of the SoS’ constituent systems. It reveals sources, sinks and bearers of ME(I) that are inherent with the hardware, software, structures etc. that designers select to realise the functionality required of the SoS constituent systems. It also reveals ME(I) SSBs that are independent of a SoI, but have an effect on it.

These ME(I) SSBs, the affordances for, and transfers of ME(I) they form are rarely captured by design definition documents and artefacts in a PLM system, and at best might only exist tacitly within the most competent and experienced engineering specialists. The TCA method collates all ME(I) SSBs together as a ME(I) Meta-Model (exemplified here as a function-flow diagram, (but could be as an alternative representation if it aligns better with TCA users existing visualisation preferences) to provide a more complete representation and enhanced understanding of the SoI appreciable by a broad range of stakeholders.

Finally, it provides a better facilitated and more informed way for operators within systems and SoS to develop ‘work-arounds’ and ‘short cuts’, however temporary they may be, not envisaged earlier by designers and implementers that increasingly seem not to have the opportunity to experience the operational use of their work outcomes.

8.8 What does a ‘Good’ outcome look like?

One successful outcome of this research would be a TCA process forming an integral part of a system supplier’s PLM system that was utilised throughout a products lifecycle that resulted in SoS constituent systems able to have their ability to transfer matter, energy and information enhanced close to the point of utility such that they can be maintained fit-for-purpose despite having experienced unpredictable changes in operation, internal and/or external factors that would otherwise render them not fit-for-purpose.

The successful utilisation of this research might be exemplified by the two examples below. The Galileo Jupiter mission, which was almost lost due to the failure of its high gain antenna…

> “but upgradeable software and general capability in its other flight systems saved the mission (the computer could do data compression, not originally required, and data could be streamed through the low-gain antenna, intended for command data only)” (Mcmanus and Hastings 2006).

And, taking an advantage of a ‘design opportunity’ …

> “In addition, during the delay due to the Challenger accident, the project team investigated a potential solid-state memory failure and decided to double the on-board memory” and “As a backup to the real-time downlink, an on-board tape recorder (the Data Memory Subsystem) had been designed to record data during certain high-activity periods. Both of those resources became critical to the new orbital operations, to buffer high-rate data during the Jovian encounters, and trickle it to Earth over the remainder of the orbit. The high gain antenna anomaly workarounds were truly a team effort involving a system approach that included science, flight, ground, hardware, and software.” (Nilsen and Jansma 1989).

8.9 Chapter Summary

This chapter has provided an overview of the analysis of engineering systems as it relates to the creation of SoS constituents, and outlined the analysis proposed by this research, the potential for exploitation by an industrial user, and how system suppliers might incorporate provisions for fit-for-purpose maintenance into their products in a cost-effective manner.

As a reminder, this research creates a technique with:

(i) a method that provides a novel perspective from the viewpoint of existing and potential matter, energy and information transfers (ME(I) transfers) both external and internal to a SoS which could be considered as an ‘academically oriented’ output.

(ii) a fitness-for-purpose enhancement process utilising the method that provides a process for the efficient engineering of SoS constituent system affordances in order to enhance the likelihood of the composing SoS being able to be maintained fit-for-purpose, which could be considered as an ‘industrially oriented’ output.

A viewpoint of material, energy and information sources, sinks and bearers in the constituents of the SoI could be described as a form of ‘agility credit’ that would assist personnel in stressful times that demanded prompt and effective reconfiguration actions.

It is suggested that despite extensive activities such as Failure Modes Effects and Criticality Analysis (FMECA) common in complex and high criticality projects, events with significant undesirable impacts still occur. ME(I) transfer enhancements would increase the ability of a SoS to be maintained fit-for-purpose and reduce the time required to restore it as fit-for-purpose after an unforeseeable event.

9 Hypothesis Verification Case Studies

This chapter contains examinations of case studies used to verify the hypothesis and develop and mature the TCA method and process with a view to its incorporation by an industrial exploiter into both their PLM processes and the products delivered to their customers. The principal points drawn from each project are related in the sections below.

The TCA method development accommodated the need to port the TCA method onto the project information capture and visualisation processes in use by the industrial partner and make the technique TCA integrate-able with their lifecycle management system. This has been achieved by examination and cognisance of the processes, procedures, reviews, gates etc. prescribed by PLM systems and the project definition artefacts produced in accordance with it.

The author was given access to Thales' IT system as a contractor and provided with a secure laptop. A cardinal point requirements document for candidate case studies (see Appendix A2) was provided to Thales by the author early in the research schedule to assist their provision of case studies.

9.1 Case Study: National Traffic Information Service (NTIS)

This was the first case-study obtained. Provided by Thales, it was the National Traffic Information Service (NTIS) Transformation Project. NTIS is at the time of writing a current project at Thales' engineering transportation systems based at Cheadle Heath, Stockport in the UK. The following text is adapted from the NTIS Systems Engineering Management Plan (SEMP) referenced below.

9.1.1 Project overview

The Highways Agency is an Executive Agency of the Department for Transport (DfT), and is responsible for operating, maintaining and improving the trunk road network in England. The Highways Agency's heritage traffic information services were primarily provided through the National Traffic Control Centre (NTCC). The existing contract was awarded to Serco plc for 10 years in 2001 and ended on 31 August 2011.

Prior to NTIS, the heritage NTCC facility was based at Quinton, Birmingham which was the primary disseminator of traffic information for the Highways Agency. It collected, collated and provided information on the NTIS road network and strategic events that affect the network. A team of technical and specialist advisors provided back-office support, including off-line analysis of systems performance, IT and fault management.

The information provided by the NTCC was also used to support a number of Highways Agency functions, including:

- Generating traffic information services for the public (for example Variable Message Signs, Traffic England, Traffic Radio and Highways Agency Information Points).
- Providing third parties (for example the media) with data and information that they then use to provide their own services to the public.
- Strategic and tactical traffic management in response to events and incidents in real time.
- Measuring the success of the Highways Agency in meeting its performance targets.
- Making well-informed future investment decisions.

9.1.2 Approach adopted

Thales supplied the computing infrastructure and software system for the collection, processing and dissemination of traffic data and information to supersede the legacy NTCC system, and ensure a seamless transition from the legacy to the successor system.

The documents made available were

- NTIS Sub-System Design Specification (WA119-08-007-002-02-02-04 R2.5 v2 dated 24th July 2014)
- NTIS Infrastructure (WA119-08-007-008-01v8.0 dated 24th July 2014)
- NTIS External Interface Design Document (WA119-08-007-03-02-18 v1.00 dated 13th February 2014)
- NTIS Systems Engineering Management Plan (WA119-08-003-003 v3.00 dated 2nd April 2013)

NTIS project members were not available for discussion and access to CHORUS2 training material is denied to contractors, which inhibited in-depth understanding by the author.

9.1.3 Contribution of the case study to development of TCA process

The NTIS project did not comply with the case study cardinal point specification, as THALES involvement was essentially as a software engineering project, hence NTIS could not provide the opportunity to exercise many of the TCA concepts. However it did provide some familiarity with project documentation artefacts under the CHORUS2 PLM system. As the NTIS project was under way prior to CHORUS2, pre-existing documents were not altered merely to be compliant.

NTIS uses the internet as a bearer to send data to providers and receive data from them that does not require any management from the NTIS system. The physical interfaces consist of standard network connections utilising the specified components and data transfer protocols specified by the applicable standard.

The documents examined and referenced did support the view that information required by TCA exists in the CHORUS2 PLM documentation which projects produce as part of the normal engineering process. Examples of these identified by the NTIS Systems Engineering Management Plan on page 44 et seq. are: Concept of Operations, System/Subsystem Design documents, Technical Design Notes and Technical Papers, Software Architecture Document, Test Specifications and Technical Release Notes (which contain technical aspects of operation and maintenance). From this it is considered that adoption of TCA would not necessarily add a significant additional burden on staff to produce artefacts solely for TCA method, but perhaps changes in how existing data was captured and recorded in CHORUS2 would be necessary in addition to some new CHORUS2 functionality to collate existing data for TCA method.

9.2 Case Study: Royal Logistics Corps

The author felt the need to broaden his own experiences from working with fighting vehicles and their military users with the experiences of a different, but associated user community to confirm user need and inform further development. As this research is concerned with the correct, complete and timely transfer of material, energy and information, the Royal Logistic Corps (RLC) seemed a fitting organisation to approach.

9.2.1 Project overview

The Royal Logistic Corps of the British Army helps provide transport for logistical support operations, which is essentially the delivery of material to the right place at the right time to support and sustain military operations in times of conflict, peacetime, and also to support the Civil Contingency Reaction Force.

The 158 Regiment Royal Logistic Corps, is an Army Reserve regiment of the British Army. Its role is to support the Regular Army through its paired Regular Regiment, 7 Regiment Royal Logistic Corps, as well as providing soldiers when required. The 158 regiment is equipped with MAN all-wheel drive vehicles. MAN Military Trucks produce two variants, the SX has a stiffer chassis and coil springs so has much greater mobility, the HX is a lower specification variant. There are 3 HX variants, the 2 axle HX60, the 3 axle HX58 and the 4 axle HX77. The SX comes in two variants, the 4 axle SX45 Recovery Variant and 3 axle SX44 Unit Support Tanker and Cargo. Figure 9.1 below is reproduced under the Open Government Licence v1.0.

Figure 9.1 MAN 3-axle all-wheel drive vehicle

9.2.2 Research method

A first stage of the sequential exploratory strategy used in this research as part of the concurrent triangulation strategy is “gather qualitative data and analyse it”, but this alone may have resulted in the obtained data having too broad a scope and with insufficient focus as the personnel providing the data had a wide demographic, a wide spread of expertise and experience and were all unfamiliar (the RLC officer initially contacted was not present as he thought this might have a biasing or inhibiting effect) with this research. As mitigation against this a brief orientation presentation was given to provide information and context for the workshop activities that generated the data for this case study.

9.2.3 Approach adopted

An initial approach and synopsis to provide an appreciation of TCA research was sent to the relevant RLC officer, who thought the research worthwhile. A discussion resulted in the proposal of a presentation and workshop to be held at their next muster to provide a sizable and diverse range of attendees. A draft workshop programme was designed and subsequently shown at a second staff meeting, and from the subsequent discussion minor revisions were made to improve the presentation and workshop activity to the attendees. The workshop plan appears as Appendix A3.

The workshop started with a presentation of the research and a Q&A session to establish in the attendees a correct and common understanding of the research, what was desired from them to capture their experiences, both good and bad, and a short discussion to start things going. Attendees used flipcharts to provide examples of ‘Whats’ and ‘Whys’ of activities that had gone well or not, and how they thought the presented research may have enabled avoidance and recovery in terms of Material, Energy and Information and its Completeness, Correctness and Timeliness. Attendees captured experiences in groups of 5 and, after this, one person from each group presented their ‘top 3’ experiences to the other groups for basic peer-group assessment, agreement and identification of common themes between groups. The day concluded with an inspection of several vehicles in the garages and the vehicle maintenance and repair facility to discuss and demonstrate the points in the workshop session with the vehicles and equipment. The experiences were collated on a spreadsheet, which appears as Appendix A4.

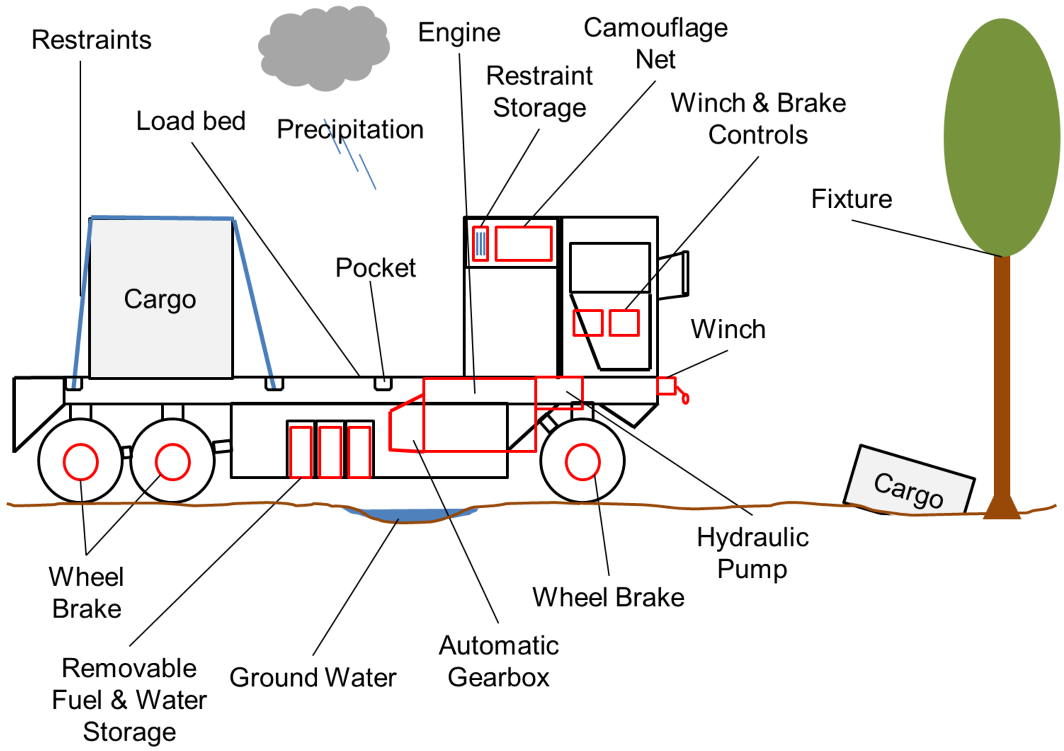


Figure 9.2: Simple model of SX Vehicle as a SoS constituent

9.2.4 Contribution of the case study to development of TCA process

The main points coming from the workshop that contributed to the on-going development of the TCA method/process are bulleted with exemplars below:

- Intentional bearers may transfer ME(I) in the opposite direction to the designed-for transfer, and cause inherent transfers giving rise to unexpected behaviour at the SoS level and adversely affecting fundamental operational tasks.

A simple representation of the SX vehicle appears as Figure 9.2 above. For example, the flatbed transporter is able to carry a variety of material, thus a load may consist of several items of different shapes, sizes, weights, densities, fragility etc. that must be delivered to several locations. The diverse load is secured to the flatbed by straps, anchored to the load bed at hard points. The loadmaster ideally loads the vehicle to a 'last-on, first-off' policy to expedite unloading at the delivery points and reduce the exposure period of the vehicle to hazards to a minimum. However the load bed lashing points in several locations are recessed to maintain a flat surface to the load bed. To avoid the recesses filling with debris and water they go completely through the bed, allowing water and debris to fall through. This has the undesirable effect of allowing water spray, dirt and debris thrown up from the road and road wheels to come up through the holes and contaminate the material being carried. To prevent damage the loadmaster often puts the material least likely to be damaged or degraded directly on the load bed, thus protecting more susceptible material placed on top of it. This often means that some material needs to be off-loaded and re-loaded at a delivery point, thus extending the time the soft skinned vehicle and its load are at risk and lengthening the duration of the mission.

Figure 9.3 below is a partial model of the load carrying function of the SX vehicle showing the intentional ME(I) flows and the unintended material flow (h) in red.

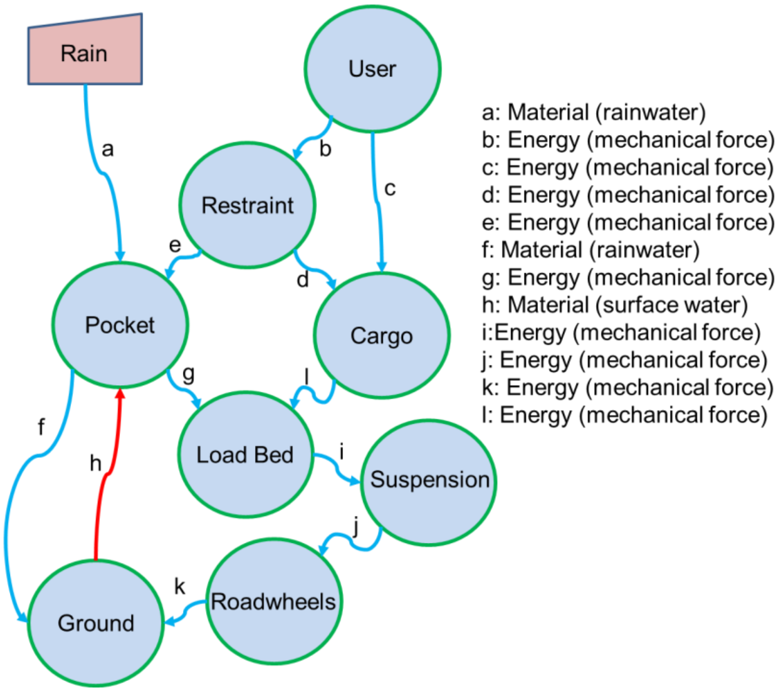


Figure 9.3: Partial model of SX load carrying function.

- Inherent SSBs can be utilised at the operational level to achieve efficient and timely tasks and their use become usual practice and procedure.

However inherent SSBs are unrecorded and uncontrolled, so can cause difficulties should they change or disappear due to changes elsewhere in the SoI, the composing SoS, supporting systems or the supply chain. For example, when a soft-skinned vehicle such as a fabric-backed lorry arrives on station, it is desirable to minimise the time it is exposed by quickly covering it with camouflage nets. To expedite this, a vehicle crewmember climbs on top of the vehicle to pull the net held up by crewmembers on the ground and drop it over the opposite side of the vehicle to other crewmembers to secure to the ground. The supporting 'hoops' that hold the form of the fabric structure that encloses the back of the vehicles were originally made of aluminium. Newer replacements, having the same fit, form and function were fibreglass, and did not have the same degree of load-bearing headroom, being unable to bear the weight of an average crewman. Thus whilst the new fibreglass hoops were just as effective as the aluminium hoops in fulfilling the function for which they were designed, they lengthened the time taken to camouflage the vehicle and the period when it is most vulnerable to detection.

- The inherent characteristics of system components operationally relied upon to be static can become dynamic and change with time, usage and the environment. Problems can occur if only the intended characteristics of these system components are considered when either modifying or replacing them.

For example, vehicles are fitted with cages to hold liquid containers of a standard form (‘Jerry cans’). NATO cans are made from pressed welded steel and colour-coded to identify what liquid should be in them. Becoming prevalent are plastic versions, typically the United States Government Issue (USGI) Military Fuel Container (MFC) and Military Water Container (MWC). With the exception of the pouring spout these have virtually the same form, fit and function as the NATO standard can, and fit into the holders on the vehicle. However the plastic versions bulge out of shape when filled, which is exacerbated by temperature extremes making them difficult (in some cases virtually impossible) to stow and remove them from the holders without damage to the can and/or its holder.

- Intentional ME(I) sources can act as unintentional sinks, and sinks can act as unintentional sources.
- Rigidly ‘Designing to Specification’ may be advantageous to the suppler in terms of economy and protection from litigation, but can severely restrict the user from utilising the resources at their disposal to achieve their needs, especially when these needs are unforeseeable from the supplier’s viewpoint.

For example, some SX vehicles are fitted with a hydraulically-powered self-recovery winch. The vehicle’s hydraulic power-pack that powers the winch is driven from the vehicle engine. The winch is fitted to the front of the vehicle and the cable emerges from between a pair of rollers and out through a slotted aperture in its front bumper. If the vehicle becomes stuck, say in soft ground, the cable can be pulled out through the aperture and attached to an immovable object, such as a large tree. The winch can then be operated, applying a force to the vehicle so the vehicle can pull itself free. Traditionally vehicles used off-road would have a manual handbrake lever (or sometimes two, one for each rear wheel station if not fitted with a limited-slip or locking differential) that applied the brakes via cables tensioned when the lever was pulled up.

Figure 9.4 below illustrates a load-hauling scenario where it is desired to pull a load towards the vehicle. The winch hawser is attached to a moveable object rather than a fixture as it would be in a self-recovery scenario.

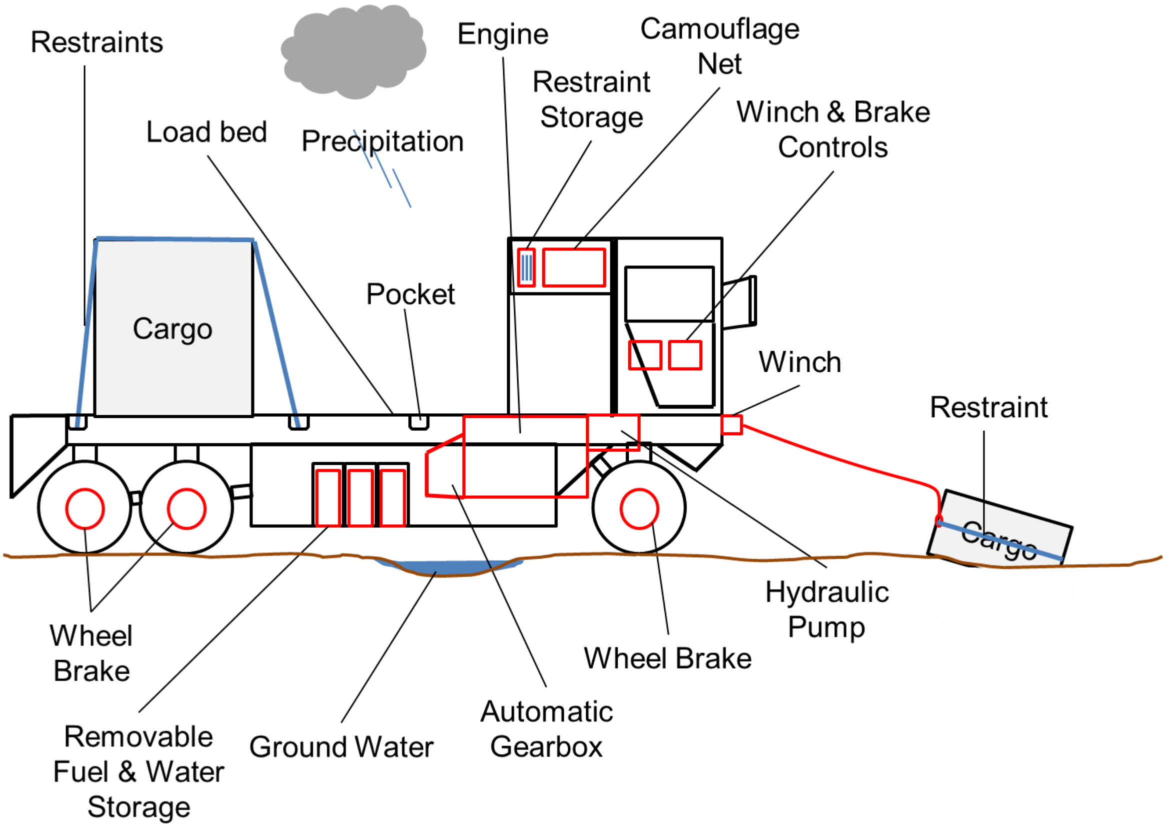


Figure 9.4: SX vehicle load-hauling scenario.

It can be appreciated that a winch on a vehicle is a useful facility that is used by resourceful crews for various tasks where a force beyond the human capability is needed to achieve it. The MAN vehicles, in common with many modern vehicles are fitted with an electronic handbrake that releases automatically when the vehicle is commanded to move from stationary. Thus, if the engine speed is increased to provide hydraulic power to the winch to attempt to pull something towards the vehicle, the self-recovery winch interlocks will automatically release the handbrake as the engine is revved and pull the vehicle towards it!

The self-recovery winch interlocks prevent its operation for other than self-recovery operations by only enabling winch operation when the vehicle is able to move, for example the winch will not operate with the handbrake applied or with P (park) or N (neutral) selected the automatic gearbox.

Figure 9.5 below shows a partial model of the SX vehicles self-recovery winch function. The blue connections represent 'intended' ('designed-for') ME(I) transfers necessary to achieve the self-recovery function, and the two red connections the inherent transfers that could potentially allow the self-recovery function for load haulage.

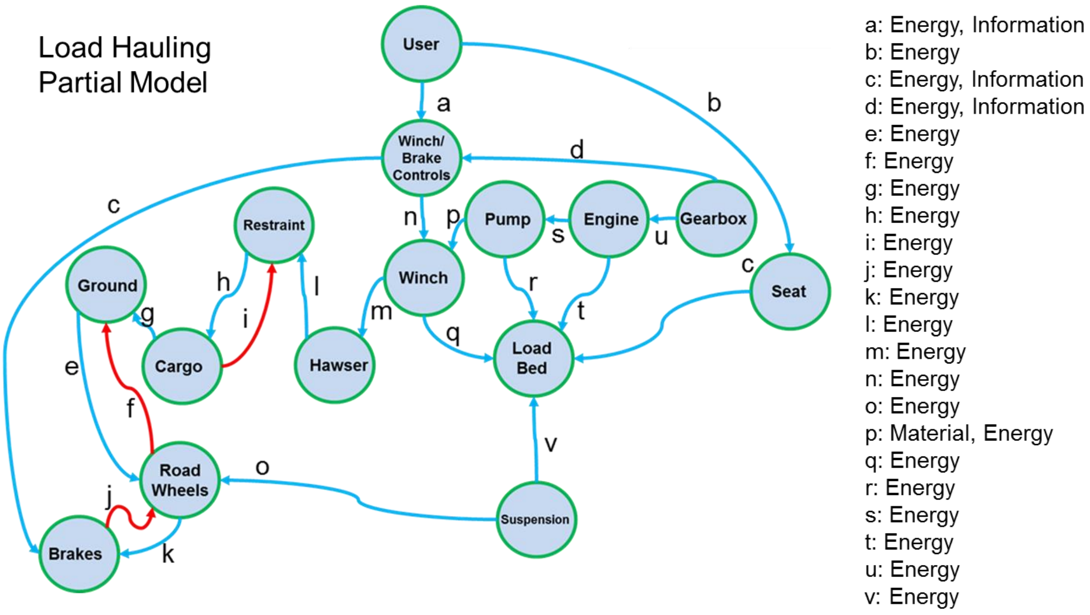


Figure 9.5: Partial TCA model of SX self-recovery winch function

This RLC case study revealed instances that can be abstracted as the notion that ME(I) transfers are vector rather than scalar quantities. 'Intended' and 'inherent' ME(I) transfers are directional, and the directions of 'intended' and inherent ME(I) transfers may not be the same, and this was incorporated into the TCA method.

9.3 Chapter Summary

The NTIS case-study typified a project whose characteristics meant that the TCA analysis method would not be of sufficient benefit to warrant its use, which reinforces the need for appropriate usage of analysis methods

The RLC case-study described instances of undesirable emergent properties that were readily apparent to the personnel close to the point of the systems employment, but not so apparent to the system supplier. Had the system suppliers had the benefit of the more complete view of their systems provided by the TCA analysis method, this may have (at what would have been undoubtedly a very busy time) brought into their focus of attention unintentional ME(I) sources, sinks and bearers, superimposed onto a model of their familiar, designed-for ME(I) transfers. These unintended ME(I) SSBs that had the potential to cause problems or provide opportunities for product enhancement could have stimulated whatever action the system supplier considered appropriate in a timely and economic manner to obviate or mitigate problems in the future.

10 Concept Validation Case Studies

This chapter describes a validating concept demonstrator in the form of a concept model utilising PC-based application programmes. A carrier vessel forming a major part of a large SoS was modelled in the form of a case study. Secondly a validation case study of part of a fast-jet aircraft fuel system is described which was undertaken by an M.Eng. student who applied the TCA technique to a current project at a major defence manufacturer as their final-year individual project.

10.1 Concept Demonstrator Case Study: Aircraft Carrier

This case study is not a functional implementation but a concept demonstrator intended to substantiate the approach to an automated implementation. Substantiation of this approach is not dependant on recorded data (which was unavailable) hence the concept demonstrator was able to be produced using generated data. The concept demonstrator provides a point-of-departure for industrial systems suppliers wishing to implement a functional automation of the TCA method using their preferred IT applications. Such a bespoke TCA implementation would then be an engineering design activity able to be seamlessly integrated as part of their PLM process. The concept demonstrator illustrates two things: firstly how the TCA method might inform system fit-for-purpose maintainers by revealing hidden potential problem causes so they can be addressed before they exhibit problematic symptoms downstream; and secondly how the TCA method described theoretically might 'look and feel' when implemented using IT applications and incorporated into an industrial PLM system such as Thales' CHORUS2. The subject of the case study has been confirmed by Thales to be representative of a complex system a prime contractor such as Thales would supply as a major constituent of a large SoS.

10.1.1 Overview of case study

It is not practicable in the scope of this research to manually capture all the 'intended', 'inherent' and 'independent' sources, sinks and bearers of material, energy and information extant in such a complex system; indeed the quantity of information for all but the simplest of systems would be so large that manual capture would be impractical; the process has to be significantly automated, and this might be achieved in concept is described in this section. For the purpose of this case study a selection of high level subsystems central to the role of a carrier vessel are shown, with their 'intended' ME(I) transfers constrained to the fundamentals of structure, power supply, control and status signals, these being sufficient to enable staff working on engineering processes or product design and development to visualise what a TCA method integrated into a PLM system might look like.

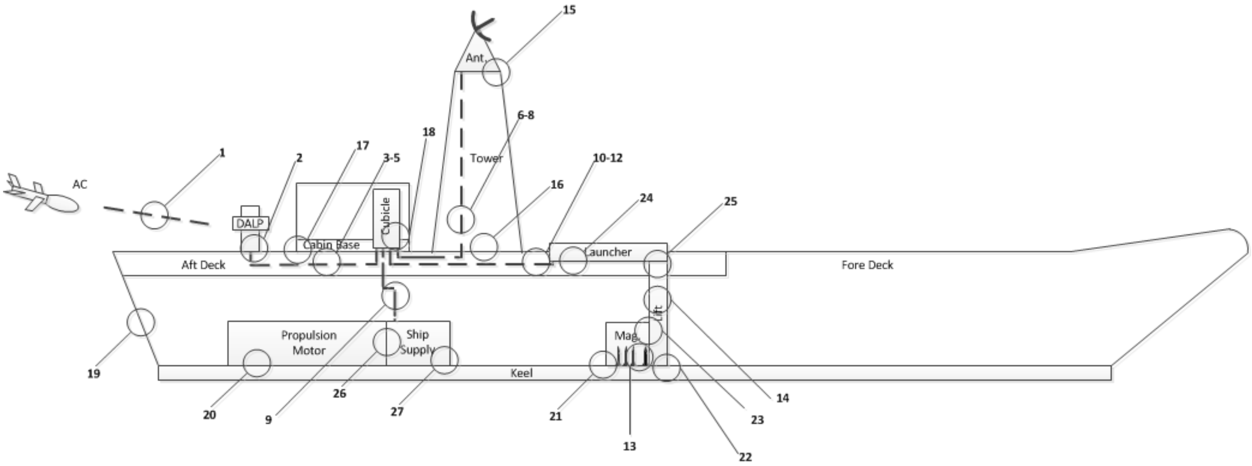


Figure 10.1: Simple model of a carrier vessel as a SoS constituent.

The type of depiction in Figure 10.1 above is drawn from the general assembly modelling package part of the integrated modelling environment that holds the top-level product design information as part of the PLM system. The principal subsystems and 'intended' ME(I) transfers are listed below:

1 WO Signal
2 DALP Structural Support
3 DALP Status
4 DALP Power
5 DALP Command Radar Data
6 Radar Status
7 Radar Power
8 Radar Command
9 Cubicle Power
10 Launcher Status
11 Launcher Power
12 Launcher Command
13 MissMag2Missile Push
14 MissLift2Missile Push
15 Ant Structural Support
16 Tower Structural Support
17 Cabin Structural Support
18 Cubicle Structural Support
19 AftDeck Structural Support
20 PropMotor Structural Support
21 MissMag Structural Support
22 MissLift Structural Support
23 MissMag Misslift Structural Support
24 Launcher Structural Support
25 MissLift Launcher Structural Support
26 ShipSup Drive
27 ShipSup Structural Support

Figure 10.2: Simplified carrier vessel principal subsystem ME(I) transfers

<u>Abbreviations</u>

WO: Wave-Off lamp.

DALP: Deck Approach Light Projector

MissMag: Missile Magazine

MissLift: Missile Lift

Ant: Multifunction RADAR Antenna

PropMotor: Propulsion Motor

ShipSup: Ship's power Supply

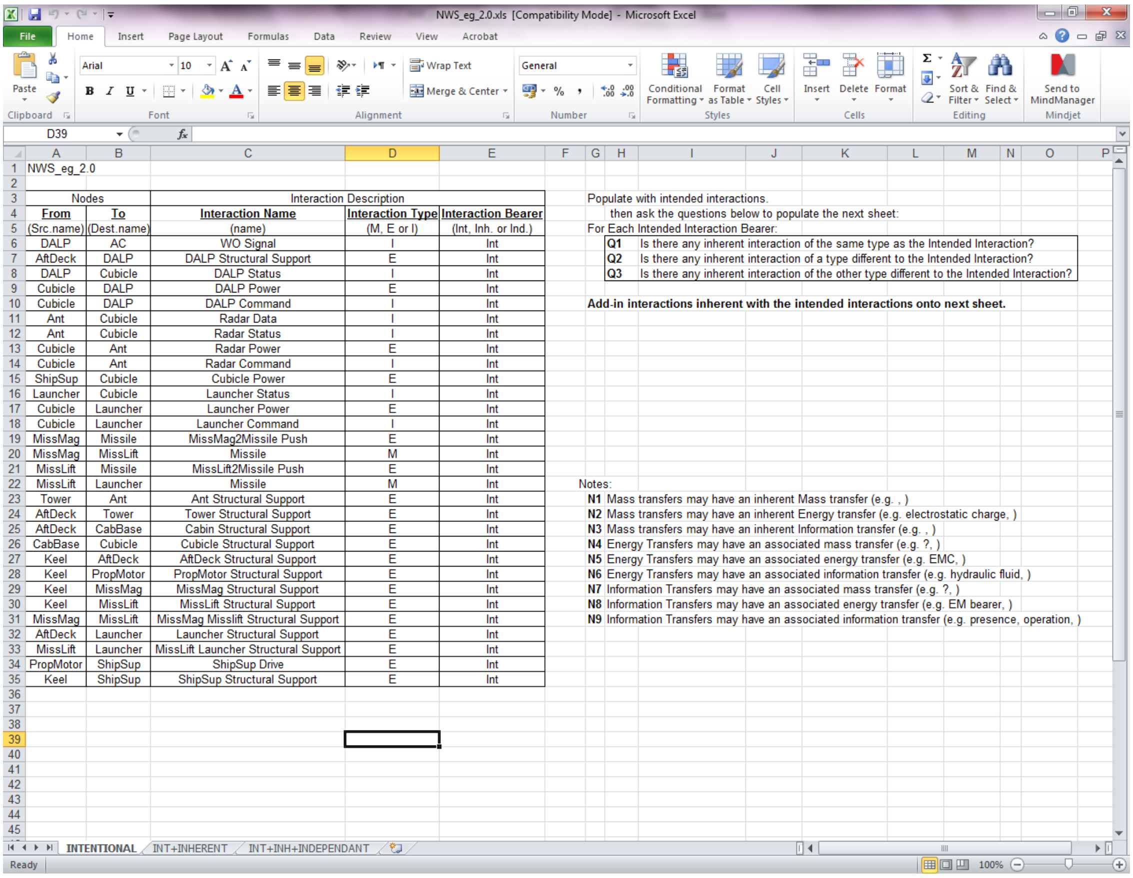
10.1.2 Research method

A stage of the sequential exploratory strategy used in this research as part of the concurrent triangulation strategy is “interpreting the findings of a quantitative study”. It was recognised that large amounts of data would be generated by analysing a SoI to determine its inherent and independent ME(I) transfers so it was considered that some exploration into how the manipulation and visualisation of the data might be automated to gain some insight into its feasibility and to provide guidance for a bespoke integration into an industrial system suppliers PLM system.

10.1.3 Approach adopted

A systems supplier incorporating TCA into their PLM system and engineering processes would require it to appear to be part of an integrated whole, with the same human interface as their existing processes familiar to the workforce. It was considered that the best return on investment for this case study would be to use widely available PC based applications to construct a concept demonstrator able to illustrate how the TCA processes can be implemented in an IT environment to inform an adopting system supplier adding an TCA implementation into their own bespoke PLM environment, rather than use research resources to create a fully functional demonstrator for a development exercise that would be of limited use to an industrial systems supplier.

This case study used the EXCEL spreadsheet application to capture ME(I) SSBs as illustrated in Figure 10.8 below, and Cytoscape, an open-source visual analytics application program originally designed for biological research but now finding wider application for complex network analysis and visualisation.



NWS_eg_2.0

Nodes		Interaction Description		
From	**To**	**Interaction Name**	**Interaction Type**	**Interaction Bearer**
(Src.name)	(Dest.name)	(name)	(M, E or I)	(Int, Inh. or Ind.)
DALP	AC	WO Signal	I	Int
AftDeck	DALP	DALP Structural Support	E	Int
DALP	Cubicle	DALP Status	I	Int
Cubicle	DALP	DALP Power	E	Int
Cubicle	DALP	DALP Command	I	Int
Ant	Cubicle	Radar Data	I	Int
Ant	Cubicle	Radar Status	I	Int
Cubicle	Ant	Radar Power	E	Int
Cubicle	Ant	Radar Command	I	Int
ShipSup	Cubicle	Cubicle Power	E	Int
Launcher	Cubicle	Launcher Status	I	Int
Cubicle	Launcher	Launcher Power	E	Int
Cubicle	Launcher	Launcher Command	I	Int
MissMag	Missile	MissMag2Missile Push	E	Int
MissMag	MissLift	Missile	M	Int
MissLift	Missile	MissLift2Missile Push	E	Int
MissLift	Launcher	Missile	M	Int
Tower	Ant	Ant Structural Support	E	Int
AftDeck	Tower	Tower Structural Support	E	Int
AftDeck	CabBase	Cabin Structural Support	E	Int
CabBase	Cubicle	Cubicle Structural Support	E	Int
Keel	AftDeck	AftDeck Structural Support	E	Int
Keel	PropMotor	PropMotor Structural Support	E	Int
Keel	MissMag	MissMag Structural Support	E	Int
Keel	MissLift	MissLift Structural Support	E	Int
MissMag	MissLift	MissMag Misslift Structural Support	E	Int
AftDeck	Launcher	Launcher Structural Support	E	Int
MissLift	Launcher	MissLift Launcher Structural Support	E	Int
PropMotor	ShipSup	ShipSup Drive	E	Int
Keel	ShipSup	ShipSup Structural Support	E	Int

Populate with intended interactions.
then ask the questions below to populate the next sheet:
For Each Intended Interaction Bearer:

Q1	Is there any inherent interaction of the same type as the Intended Interaction?
Q2	Is there any inherent interaction of a type different to the Intended Interaction?
Q3	Is there any inherent interaction of the other type different to the Intended Interaction?

Add-in interactions inherent with the intended interactions onto next sheet.

Notes:
N1 Mass transfers may have an inherent Mass transfer (e.g. ,)
N2 Mass transfers may have an inherent Energy transfer (e.g. electrostatic charge,)
N3 Mass transfers may have an inherent Information transfer (e.g. ,)
N4 Energy Transfers may have an associated mass transfer (e.g. ?,)
N5 Energy Transfers may have an associated energy transfer (e.g. EMC,)
N6 Energy Transfers may have an associated information transfer (e.g. hydraulic fluid,)
N7 Information Transfers may have an associated mass transfer (e.g. ?,)
N8 Information Transfers may have an associated energy transfer (e.g. EM bearer,)
N9 Information Transfers may have an associated information transfer (e.g. presence, operation,)

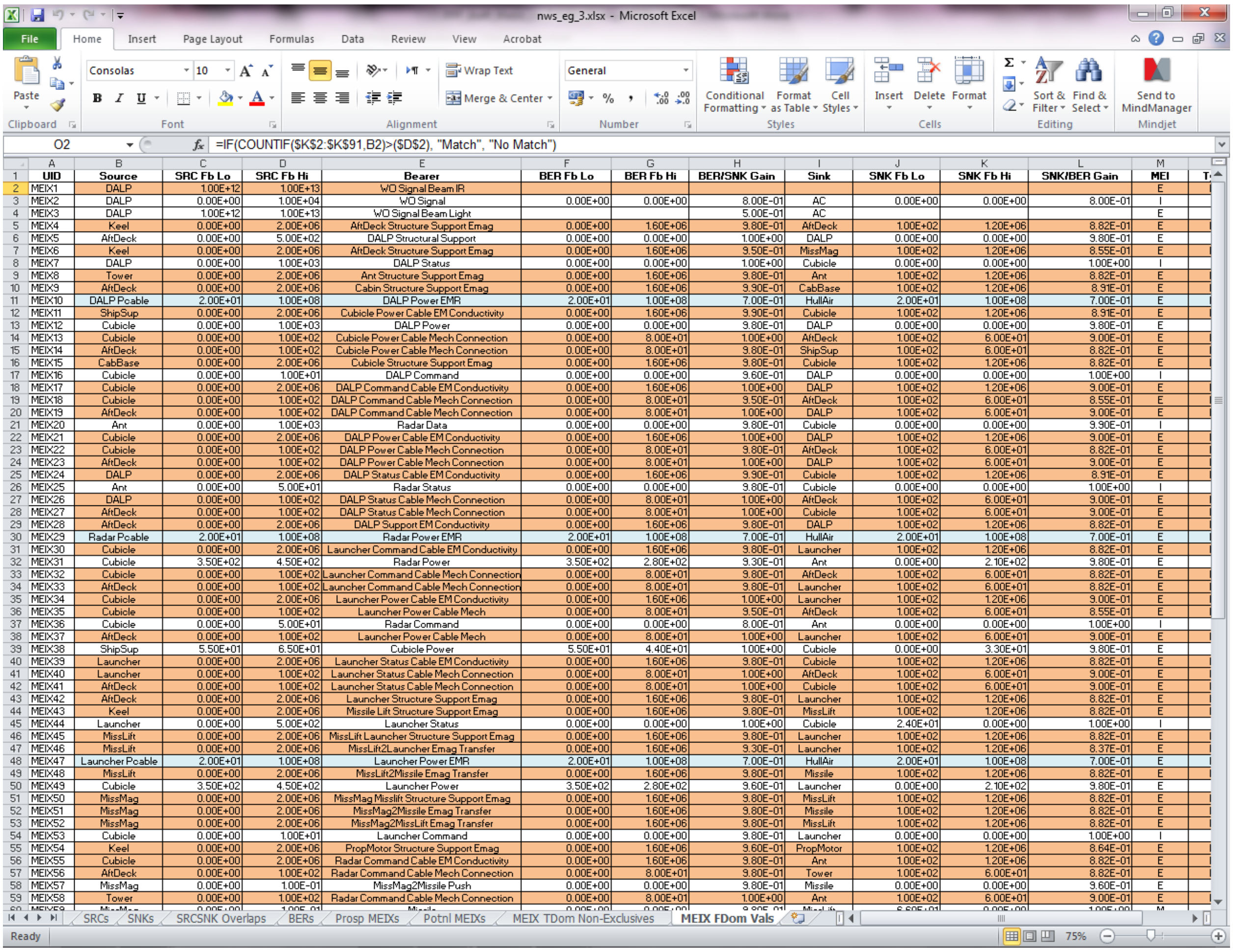
Figure 10.3: Intentional ME(I) Transfers captured in EXCEL

Intentional ME(I) transfer information comes from the Master Interface Schedules captured by product design information technical data pack artefacts in the PLM system. Once the 'intended' ME(I) transfers are captured, an initial analysis firstly identifies their SSB components, then the 'Inherent' and 'Independent' ME(I) SSBs, again captured in EXCEL. This is achieved (in generic terms) by

- Examination of the Intentional SSBs with their chosen implementations and determination of the associated inherent SSBs within the SoI.
- Identification of ME(I) bearers that cross the SoI boundary with their transfer characteristics (attenuation or amplification), spectral capabilities and temporal availability to conduct ME(I).
- Capture of ME(I) sources and sinks with outputs and admittances outside the SoI boundary spectra and availability overlap with those of the boundary-crossing bearers.

Figure 10.4 below is included here to illustrate how relatively large amounts of data are generated by a relatively simple system. Figure 10.4 shows the Intended (white rows), Inherent (orange rows) and 'Independent' (blue rows) SSB frequency domain analysis spreadsheet of the TCA method EXCEL workbook, showing the bandwidth break frequencies and bearer transmission characteristics for each SSB used to determine SSB combinations with the ability for ME(I) transfer (prospective ME(I) transfers).

Companion spreadsheets in the workbook contain the SSB time domain analysis and sink susceptibilities to determine which prospective ME(I) transfers will have the opportunity for transfer and additionally are not insignificant. Specialist engineers examine these potential ME(I) transfers to decide if they are likely to be either problematic or exploitable as enhancements to the SoIs affordance for ME(I) transfer.



UID	Source	SRC Fb Lo	SRC Fb Hi	Bearer	BER Fb Lo	BER Fb Hi	BER/SNK Gain	Sink	SNK Fb Lo	SNK Fb Hi	SNK/BER Gain	MEI
MEIX1	DALP	1.00E+12	1.00E+13	WO Signal Beam IR								E
MEIX2	DALP	0.00E+00	1.00E+04	WO Signal	0.00E+00	0.00E+00	8.00E-01	AC	0.00E+00	0.00E+00	8.00E-01	I
MEIX3	DALP	1.00E+12	1.00E+13	WO Signal Beam Light			5.00E-01	AC				E
MEIX4	Keel	0.00E+00	2.00E+06	AftDeck Structure Support Emag	0.00E+00	1.60E+06	9.80E-01	AftDeck	1.00E+02	1.20E+06	8.82E-01	E
MEIX5	AftDeck	0.00E+00	5.00E+02	DALP Structural Support	0.00E+00	0.00E+00	1.00E+00	DALP	0.00E+00	0.00E+00	9.80E-01	E
MEIX6	Keel	0.00E+00	2.00E+06	AftDeck Structure Support Emag	0.00E+00	1.60E+06	9.50E-01	MissMag	1.00E+02	1.20E+06	8.55E-01	E
MEIX7	DALP	0.00E+00	1.00E+03	DALP Status	0.00E+00	0.00E+00	1.00E+00	Cubicle	0.00E+00	0.00E+00	1.00E+00	I
MEIX8	Tower	0.00E+00	2.00E+06	Ant Structure Support Emag	0.00E+00	1.60E+06	9.80E-01	Ant	1.00E+02	1.20E+06	8.82E-01	E
MEIX9	AftDeck	0.00E+00	2.00E+06	Cabin Structure Support Emag	0.00E+00	1.60E+06	9.90E-01	CabBase	1.00E+02	1.20E+06	8.91E-01	E
MEIX10	DALP Pcable	2.00E+01	1.00E+08	DALP Power EMR	2.00E+01	1.00E+08	7.00E-01	HullAir	2.00E+01	1.00E+08	7.00E-01	E
MEIX11	ShipSup	0.00E+00	2.00E+06	Cubicle Power Cable EM Conductivity	0.00E+00	1.60E+06	9.90E-01	Cubicle	1.00E+02	1.20E+06	8.91E-01	E
MEIX12	Cubicle	0.00E+00	1.00E+03	DALP Power	0.00E+00	0.00E+00	9.80E-01	DALP	0.00E+00	0.00E+00	9.80E-01	E
MEIX13	Cubicle	0.00E+00	1.00E+02	Cubicle Power Cable Mech Connection	0.00E+00	8.00E+01	1.00E+00	AftDeck	1.00E+02	6.00E+01	9.00E-01	E
MEIX14	AftDeck	0.00E+00	1.00E+02	Cubicle Power Cable Mech Connection	0.00E+00	8.00E+01	9.80E-01	ShipSup	1.00E+02	6.00E+01	8.82E-01	E
MEIX15	CabBase	0.00E+00	2.00E+06	Cubicle Structure Support Emag	0.00E+00	1.60E+06	9.80E-01	Cubicle	1.00E+02	1.20E+06	8.82E-01	E
MEIX16	Cubicle	0.00E+00	1.00E+01	DALP Command	0.00E+00	0.00E+00	9.60E-01	DALP	0.00E+00	0.00E+00	1.00E+00	I
MEIX17	Cubicle	0.00E+00	2.00E+06	DALP Command Cable EM Conductivity	0.00E+00	1.60E+06	1.00E+00	DALP	1.00E+02	1.20E+06	9.00E-01	E
MEIX18	Cubicle	0.00E+00	1.00E+02	DALP Command Cable Mech Connection	0.00E+00	8.00E+01	9.50E-01	AftDeck	1.00E+02	6.00E+01	8.55E-01	E
MEIX19	AftDeck	0.00E+00	1.00E+02	DALP Command Cable Mech Connection	0.00E+00	8.00E+01	1.00E+00	DALP	1.00E+02	6.00E+01	9.00E-01	E
MEIX20	Ant	0.00E+00	1.00E+03	Radar Data	0.00E+00	0.00E+00	9.80E-01	Cubicle	0.00E+00	0.00E+00	9.90E-01	I
MEIX21	Cubicle	0.00E+00	2.00E+06	DALP Power Cable EM Conductivity	0.00E+00	1.60E+06	1.00E+00	DALP	1.00E+02	1.20E+06	9.00E-01	E
MEIX22	Cubicle	0.00E+00	1.00E+02	DALP Power Cable Mech Connection	0.00E+00	8.00E+01	9.80E-01	AftDeck	1.00E+02	6.00E+01	8.82E-01	E
MEIX23	AftDeck	0.00E+00	1.00E+02	DALP Power Cable Mech Connection	0.00E+00	8.00E+01	1.00E+00	DALP	1.00E+02	6.00E+01	9.00E-01	E
MEIX24	DALP	0.00E+00	2.00E+06	DALP Status Cable EM Conductivity	0.00E+00	1.60E+06	9.90E-01	Cubicle	1.00E+02	1.20E+06	8.91E-01	E
MEIX25	Ant	0.00E+00	5.00E+01	Radar Status	0.00E+00	0.00E+00	9.80E-01	Cubicle	0.00E+00	0.00E+00	1.00E+00	I
MEIX26	DALP	0.00E+00	1.00E+02	DALP Status Cable Mech Connection	0.00E+00	8.00E+01	1.00E+00	AftDeck	1.00E+02	6.00E+01	9.00E-01	E
MEIX27	AftDeck	0.00E+00	1.00E+02	DALP Status Cable Mech Connection	0.00E+00	8.00E+01	1.00E+00	Cubicle	1.00E+02	6.00E+01	9.00E-01	E
MEIX28	AftDeck	0.00E+00	2.00E+06	DALP Support EM Conductivity	0.00E+00	1.60E+06	9.80E-01	DALP	1.00E+02	1.20E+06	8.82E-01	E
MEIX29	Radar Pcable	2.00E+01	1.00E+08	Radar Power EMR	2.00E+01	1.00E+08	7.00E-01	HullAir	2.00E+01	1.00E+08	7.00E-01	E
MEIX30	Cubicle	0.00E+00	2.00E+06	Launcher Command Cable EM Conductivity	0.00E+00	1.60E+06	9.80E-01	Launcher	1.00E+02	1.20E+06	8.82E-01	E
MEIX31	Cubicle	3.50E+02	4.50E+02	Radar Power	3.50E+02	2.80E+02	9.30E-01	Ant	0.00E+00	2.10E+02	9.80E-01	E
MEIX32	Cubicle	0.00E+00	1.00E+02	Launcher Command Cable Mech Connection	0.00E+00	8.00E+01	9.80E-01	AftDeck	1.00E+02	6.00E+01	8.82E-01	E
MEIX33	AftDeck	0.00E+00	1.00E+02	Launcher Command Cable Mech Connection	0.00E+00	8.00E+01	9.80E-01	Launcher	1.00E+02	6.00E+01	8.82E-01	E
MEIX34	Cubicle	0.00E+00	2.00E+06	Launcher Power Cable EM Conductivity	0.00E+00	1.60E+06	1.00E+00	Launcher	1.00E+02	1.20E+06	9.00E-01	E
MEIX35	Cubicle	0.00E+00	1.00E+02	Launcher Power Cable Mech	0.00E+00	8.00E+01	9.50E-01	AftDeck	1.00E+02	6.00E+01	8.55E-01	E
MEIX36	Cubicle	0.00E+00	5.00E+01	Radar Command	0.00E+00	0.00E+00	8.00E-01	Ant	0.00E+00	0.00E+00	1.00E+00	I
MEIX37	AftDeck	0.00E+00	1.00E+02	Launcher Power Cable Mech	0.00E+00	8.00E+01	1.00E+00	Launcher	1.00E+02	6.00E+01	9.00E-01	E
MEIX38	ShipSup	5.50E+01	6.50E+01	Cubicle Power	5.50E+01	4.40E+01	1.00E+00	Cubicle	0.00E+00	3.30E+01	9.80E-01	E
MEIX39	Launcher	0.00E+00	2.00E+06	Launcher Status Cable EM Conductivity	0.00E+00	1.60E+06	9.80E-01	Cubicle	1.00E+02	1.20E+06	8.82E-01	E
MEIX40	Launcher	0.00E+00	1.00E+02	Launcher Status Cable Mech Connection	0.00E+00	8.00E+01	1.00E+00	AftDeck	1.00E+02	6.00E+01	9.00E-01	E
MEIX41	AftDeck	0.00E+00	1.00E+02	Launcher Status Cable Mech Connection	0.00E+00	8.00E+01	1.00E+00	Cubicle	1.00E+02	6.00E+01	9.00E-01	E
MEIX42	AftDeck	0.00E+00	2.00E+06	Launcher Structure Support Emag	0.00E+00	1.60E+06	9.80E-01	Launcher	1.00E+02	1.20E+06	8.82E-01	E
MEIX43	Keel	0.00E+00	2.00E+06	Missile Lift Structure Support Emag	0.00E+00	1.60E+06	9.80E-01	MissLift	1.00E+02	1.20E+06	8.82E-01	E
MEIX44	Launcher	0.00E+00	5.00E+02	Launcher Status	0.00E+00	0.00E+00	1.00E+00	Cubicle	2.40E+01	0.00E+00	1.00E+00	I
MEIX45	MissLift	0.00E+00	2.00E+06	MissLift Launcher Structure Support Emag	0.00E+00	1.60E+06	9.80E-01	Launcher	1.00E+02	1.20E+06	8.82E-01	E
MEIX46	MissLift	0.00E+00	2.00E+06	MissLift2Launcher Emag Transfer	0.00E+00	1.60E+06	9.30E-01	Launcher	1.00E+02	1.20E+06	8.37E-01	E
MEIX47	Launcher Pcable	2.00E+01	1.00E+08	Launcher Power EMR	2.00E+01	1.00E+08	7.00E-01	HullAir	2.00E+01	1.00E+08	7.00E-01	E
MEIX48	MissLift	0.00E+00	2.00E+06	MissLift2Missile Emag Transfer	0.00E+00	1.60E+06	9.80E-01	Missile	1.00E+02	1.20E+06	8.82E-01	E
MEIX49	Cubicle	3.50E+02	4.50E+02	Launcher Power	3.50E+02	2.80E+02	9.60E-01	Launcher	0.00E+00	2.10E+02	9.80E-01	E
MEIX50	MissMag	0.00E+00	2.00E+06	MissMag Misslift Structure Support Emag	0.00E+00	1.60E+06	9.80E-01	MissLift	1.00E+02	1.20E+06	8.82E-01	E
MEIX51	MissMag	0.00E+00	2.00E+06	MissMag2Missile Emag Transfer	0.00E+00	1.60E+06	9.80E-01	Missile	1.00E+02	1.20E+06	8.82E-01	E
MEIX52	MissMag	0.00E+00	2.00E+06	MissMag2MissLift Emag Transfer	0.00E+00	1.60E+06	9.80E-01	MissLift	1.00E+02	1.20E+06	8.82E-01	E
MEIX53	Cubicle	0.00E+00	1.00E+01	Launcher Command	0.00E+00	0.00E+00	9.80E-01	Launcher	0.00E+00	0.00E+00	1.00E+00	I
MEIX54	Keel	0.00E+00	2.00E+06	PropMotor Structure Support Emag	0.00E+00	1.60E+06	9.60E-01	PropMotor	1.00E+02	1.20E+06	8.64E-01	E
MEIX55	Cubicle	0.00E+00	2.00E+06	Radar Command Cable EM Conductivity	0.00E+00	1.60E+06	9.80E-01	Ant	1.00E+02	1.20E+06	8.82E-01	E
MEIX56	AftDeck	0.00E+00	1.00E+02	Radar Command Cable Mech Connection	0.00E+00	8.00E+01	9.80E-01	Tower	1.00E+02	6.00E+01	8.82E-01	E
MEIX57	MissMag	0.00E+00	1.00E-01	MissMag2Missile Push	0.00E+00	0.00E+00	9.80E-01	Missile	0.00E+00	0.00E+00	9.60E-01	E
MEIX58	Tower	0.00E+00	1.00E+02	Radar Command Cable Mech Connection	0.00E+00	8.00E+01	1.00E+00	Ant	1.00E+02	6.00E+01	9.00E-01	E

Figure 10.4: 'Intentional', 'Inherent' and 'Independent' ME(I) SSBs captured in EXCEL

Spectral and duty analyses of all the ME(I) source emissions, bearer capabilities and sink admittances will identify the prospective SSB combinations that have the potential for significant ME(I) transfer. This achieved by:

- Grouping ME(I) SSBs that have overlapping source emissions, bearer capabilities and sink admittance spectra then determining bandwidth overhead of groups as Prospective ME(I) transfers.

- Identifying the prospective ME(I) transfers that are contemporaneously operational and their temporal headroom and promoting those with the opportunity to transfer ME(I) to Potential ME(I) transfers.
- Determination of those Potential ME(I) transfers that could feasibly transfer amounts of ME(I) that exceed the sink's lowest significant output threshold. This threshold is considered to be the lowest level non-intentional transfer capable of affecting the SoI.
- From the above decide if each non-insignificant Potential transfer is either likely to be troublesome or has potential for exploitation to enhance the SoIs affordance for ME(I) transfer.

With the amount of data that will be generated from the analysis of all but the most trivial systems it is considered that visual analytics will be necessary to assist comprehension of the 'Intended', 'Inherent' and 'Independent' ME(I) transfers and their component SSBs.

An illustration of how a network analysis and visualisation tool uses graph theory algorithms to highlight network characteristics often not readily apparent. Figure 10.10 below shows the initial visualisation of the 'Intended', 'Inherent' and 'Independent' SSBs by Cytoscape (Cytoscape.org 2016) that were captured in the EXCEL spreadsheet above. Part of the spreadsheet appears in the lower right-hand pane of the Figure 10.10 below.

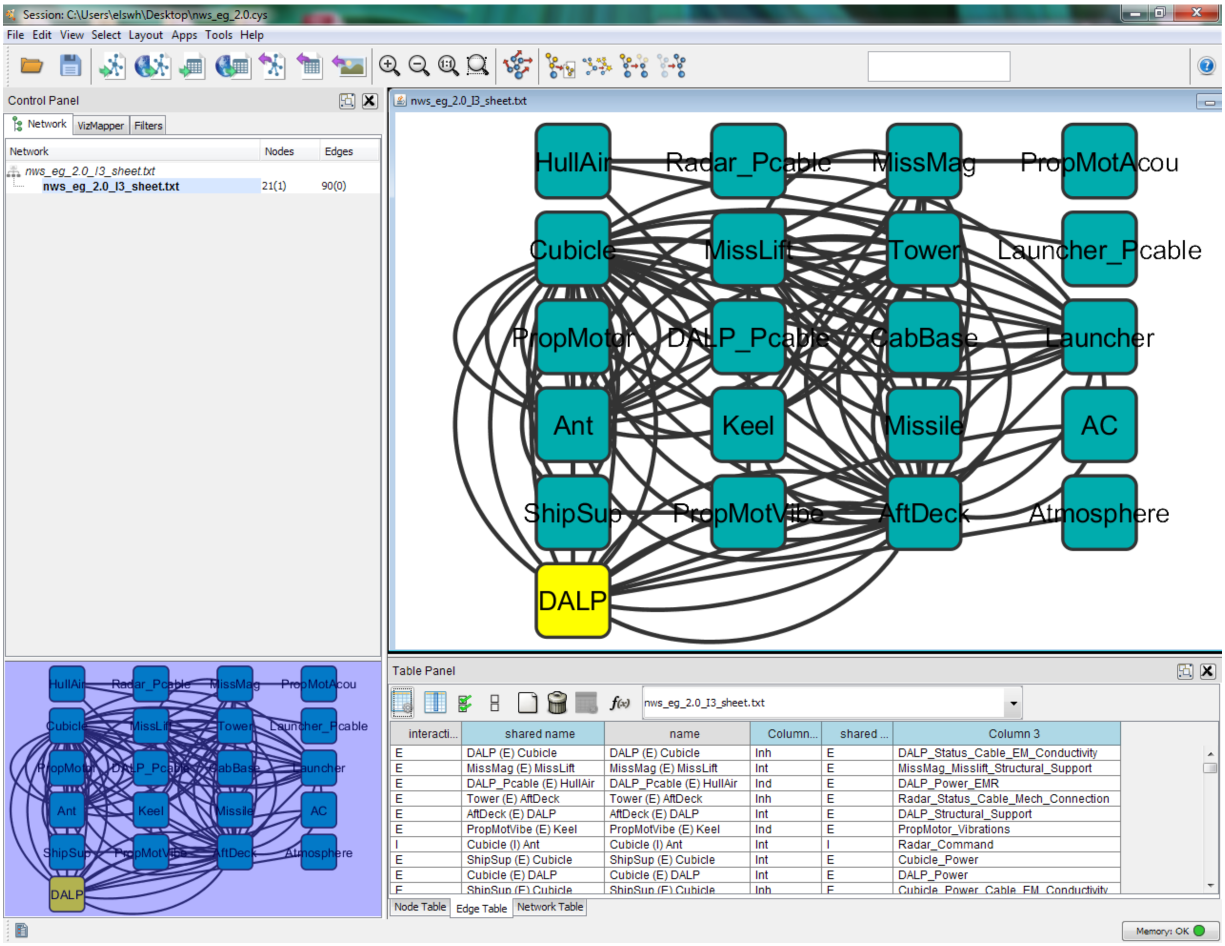


Figure 10.5: Visualisation of 'Intentional', 'Inherent' and 'Independent' ME(I) transfers

Figure 10.6 below shows a spatial redistribution of the SSBs from the application of an algorithm that identifies independent networks within the network captured. It has revealed an independent network with the potential for unintended energy transfer in part of the vessel's hull space.

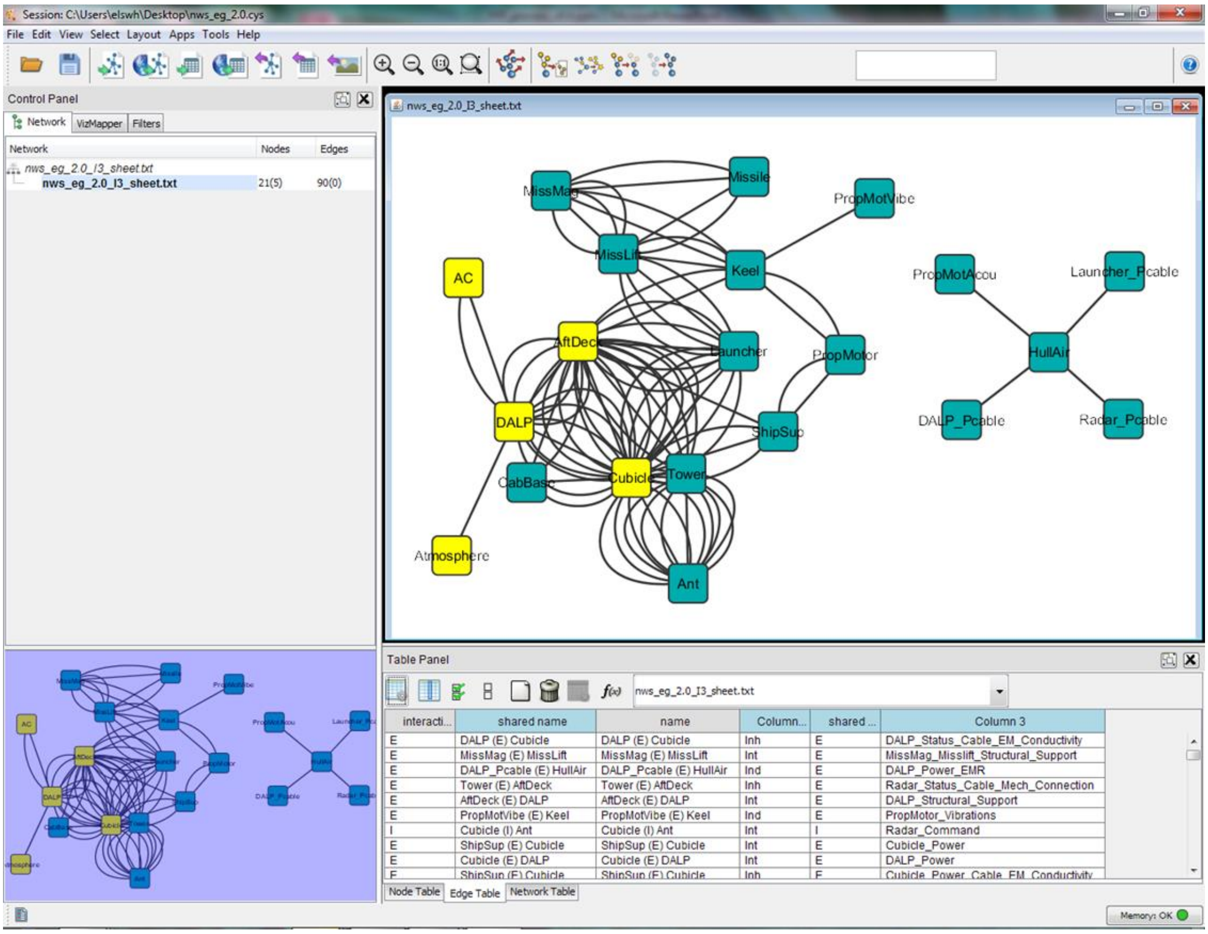


Figure 10.6: CytoScape visualisation of independent network.

The captured SSBs have been previously identified as having the potential to realise energy transfer, so those forming the highlighted independent network having the potential for Inherent and Independent energy transfer between electrical cables and propulsion motor signatures (e.g. crosstalk) in the cable duct under the aft deck within the hull space need further examination to determine if they could be either problematic or an opportunity to enhance useful energy transfer affordance. There are many other network analysis and visualisation algorithms, either built-in to Cytoscape, available as Cytoscape apps or bespoke algorithms that could be used to find and highlight other network characteristics and provide alternative visualisations that an adopter could choose to suit individual analysis applications.

10.1.4 Contribution of the case study to development of TCA process

This case study developed the TCA process by constructing an IT based concept demonstrator which acted to a degree like a virtual prototype for an instantiated TCA process that would form part of an engineering process. Recalling the experience of the roles of process and product engineers to appreciate the demands and constraints placed upon them as part of their 'day job' and considering their approach, perceptions of value and return-on-investment whilst constructing the demonstrator fed back insights to refine the TCA thought processes, analysis activities and their application sequence to be more amenable with how the TCA method would be implemented and who would implement it in an industrial exploiter's PLM system, and similarly the how and who of applying the implemented TCA processes to an engineering project to create and develop a product in accordance with them. This concept demonstrator successfully provided a point-of-departure for the creation of a functional automation of the TCA method/process.

10.2 Case Study: Aircraft Fuel System Project Trial

During the development of the TCA process, a BAE Systems sponsored student used the TCA method for his final year MEng advanced project to produce a ME(I) meta-model of part of a fast jet fuel system.

The first six sub-sections of this section draw upon the MEng final year advanced project deliverables produced by the LU undergraduate student Mr. M. Fishwick to meet the requirements of the systems engineering MEng course at Loughborough University. His evaluation report of the TCA Method and Process appears in Appendix A5.

10.2.1 Overview

A turbojet engine can be thought as consisting of three connected coaxial parts; firstly a frontal compressor stage which compresses the intake air prior to combustion, secondly a combustion chamber in the centre which introduces atomised fuel into the compressed air and ignites the fuel/air mixture, and lastly a turbine at the rear which is driven by the high pressure hot gas generated by combustion. Engine surge occurs when the turbine blades in a turbojet engine stall and hence stop forcing air through the engine. The resulting pressure drops in the frontal compressor and rear turbine allow the high pressure hot gas generated in the combustion chamber to exit in an uncontrolled manner from the engine intake and exhaust, resulting in a dramatic loss of thrust which in extreme circumstances can endanger the aircraft.

To approach optimal thrust and efficiency it is desirable to operate the engine close to conditions where surge might occur, but with an adequate margin for safe operation under the conditions at the time. BAE Systems considered that a particular aircrafts engine surge margin under certain conditions could be improved by a modification to the fuel system implemented by altering the valve control logic governing air bleed from the engine.

10.2.2 Research method

This case study took up an opportunity to introduce this research to a second major systems supplier and get feedback from an individual attempting to utilise it for the first time.

10.2.3 MEng Case Study Approach

The MEng case study evaluation took the engine surge improvement task and assessed it using the TCA method. The approach focused on the potential impact of the improvement modification and looked at the potential for undesirable effects and uncontrolled beneficial effects. This allowed a set of recommendations to be produced for the MEng case study owner.

The MEng case study considers a modification to the valve control logic which controls bleed air from the engine. The modification would increase the amount of air tapped from the engine in certain conditions. Air bleeding will reduce the pressure ratio, leading to an increased surge margin at the given air flow. This does reduce performance although the actual performance loss is considered negligible under the flight conditions where the surge margin is to be improved. The valve can be used to direct bleed air from the engine to the Air Cooled Fuel Cooler (ACFC) or alternatively to the thrust reversers. The proposed modification involves changing the operating logic of the valve, such that it remains open at conditions where it would currently be closed. This would then lead to an increased surge margin at the specified operating conditions.

Figure 10.7 below shows Fishwick's meta-model for the 'intended', 'inherent' and 'independent' ME(I) transfers. The focus whilst generating the data which led to the creation of this meta-model was on systems whose behaviours may be indirectly altered as a result of the proposed modification. The boxes filled by red represent the independent SoS constituents and the red lines shows the flow of 'independent' ME(I) transfers. Whilst it would have been possible to consider the wider aircraft system in this analysis, this was constrained to ensure that the scope of the project was achievable within the constraints of the MEng advanced project.

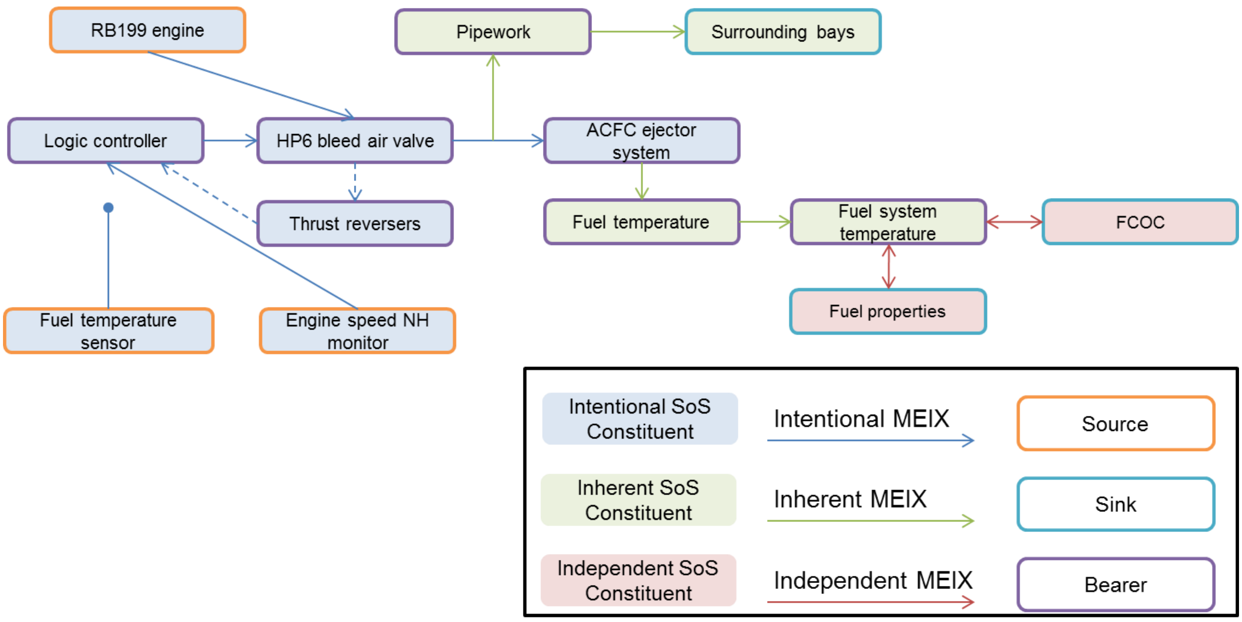


Figure 10.7: Fuel System Modification ME(I) Meta-Model

The student's TCA method generated four statements on the potential impact of the proposed modification. These were:

- Malfunction of the logic controller: It is theorised that the removal of the fuel temperature link in the logic controller will reduce the risk of malfunction or erroneous data being used. This may lead to increased reliability of the logic controller, meaning that it will perform better than required.
- Fuel type change: The US Air Force changed their primary fuel type from JP-8 to Jet A with additives in 2014. Whilst it is not clear if this is the case, if the UK follows the US in making this change, then the effects of the HP6 bleed air valve logic change may be worsened or improved.
- Engine surge: The proposed modification may have a positive or negative impact on the engine's ability to recover from an engine surge. (N.B. The proposed modification is intended to increase the surge margin; what happens if it does surge is outside the scope of this work.)
- Fuel Cooled Oil Cooler (FCOC): an increase or decrease in the average fuel system temperature could increase or decrease the capability of the FCOC, and potentially impact the average oil temperature.

10.2.4 TCA Method Key Evaluation Points

The student identified the following five key evaluation points based on his approach used for applying the TCA method to the MEng case study:

- The outputs generated using the TCA method would be difficult to replicate as different users would be expected to focus on different aspects depending on their knowledge of the system or SoS.
- The TCA method is highly reliant on qualitative opinions and did not appear to contain a means of ensuring that 'everything' is considered. This may indicate that the process needs to be tailored for each application prior to actual use.
- There was no clear-cut way of identifying 'independent' ME(I) transfers which were relevant to the system. Whilst the definition and importance of ME(I) transfers is clear, the student found it extremely difficult to identify 'independent' ME(I) transfers beyond those already highlighted as having potential by the MEng case study owner.
- It seems that the 'intended' and 'inherent' ME(I) transfers would be best captured by those already familiar with the system. However, it is likely that 'independent' ME(I) transfers

would be best captured by those slightly removed from the SoI (i.e. in the same way that Design Reviews are conducted by those in other parts of the same organisation).

- Based on the analysis conducted, it appears that the TCA method does provide a more complete understanding of the SoI. However, if the TCA method was used for a larger SoI, it appears that it would significantly increase the effort required to produce a similar output. This is because the system addressed in the MEng case study was relatively simple and a larger system would almost inevitably be more complex, necessitating additional time and resources.

10.2.5 MEng Student's Recommendations for the TCA method

The student made five recommendations for the ongoing TCA development. These were:

- A more detailed process, including definitions and examples of the terminology is required to ensure a consistent application of the process by different users. This would help to ensure that results could be reproduced (allowing conclusions to be verified) by ensuring that the meaning of different steps are less open to individual interpretation.
- Guidance on how to tailor the TCA method, in particular for complex systems or SoS, is required in order to ensure that the process can actually be applied using a reasonable amount of time and resources. Based on the small SoI considered for the MEng case study, it is not expected that the TCA method could reasonably be applied to an entire system or SoS. As such it would be helpful to include guidance on how to select areas where the complete process could be applied based on a more top level application of the process.
- From the results of the MEng case study and the difficulties experienced of identifying 'independent' ME(I) transfers, it is recommended that some consideration is given to the type of people who should use the TCA method. It is anticipated that the 'intended' and 'inherent' ME(I) transfers could be best identified by those closely involved with the system. However, it is anticipated that the 'independent' ME(I) transfers could be best identified by those not closely involved with the system as they would be more likely to think of issues which could be considered as being outside of the SoI.
- It appears that the TCA method could be used in part to analyse the agility of a system or a SoS. One interpretation of the TCA method is that it can be used to maintain a system of system's fitness for purpose by analysing its agility; that is the ability of a system to adapt to rapid, unexpected or unknown change from its environment.

- It may be useful to look at how an iterative approach can be taken using the TCA method. This could take the form of a similar but separate process which can be used to assist with the iteration of the process.

10.2.6 MEng Student's advice for the TCA User

The student provided three advice points for the potential TCA user. These were:

- In theory, the TCA method could be applied to a large and complex SoS. However based on the MEng case study conducted by the student, this would require a large amount of time and resources, even if the required information was readily available and in a suitable format. As such, the author recommends that an engineering judgement be made on how the SoI is determined. This should focus on areas where there is clear potential for issues to arise (or where issues could lead to serious problems) as opposed to analysing the entire system or SoS.
- The TCA method should be used by at least two users: one with in-depth knowledge of the SoI and one with relevant engineering knowledge but not in-depth knowledge of the system under consideration (e.g. from another domain or different project). The first user is likely to be best placed to identify the 'intended' and 'inherent' ME(I) transfers, whereas the second user would be well placed to identify additional 'inherent' ME(I) transfers as well as the 'independent' ME(I) transfers.
- Users of the TCA method should take note of Hinsley's statement that the process is "Not a substitute for wisdom & expertise" [12]. Based on the student's experience of conducting a MEng case study using the TCA method, it seems that relevant engineering experience and knowledge of the SoI is likely to be required in order to realise any benefits from using the process.

10.2.7 MEng Student's Case Study Conclusions

The following conclusions were made by the student:

The student acknowledges that there are limitations to the approach adopted, details of which can be found in in the TCA documentation provided. Nonetheless, the five key areas which emerged from the MEng case study evaluation have resulted in recommendations for the TCA method as well as advice on using the TCA method.

The MEng case study owner envisaged that the TCA method had potential benefits in analysing the performance of increasingly complex systems of systems. However he stated that the MEng case study chosen for this paper is relatively simple and not considered suitable for anything more than a demonstration of the TCA method. On this basis, the student recommends that the TCA method is applied to a more complex MEng case study in order to validate the method. The recommendations and advice provided in this paper should prove useful in this regard.

In conclusion, it is apparent from the evaluation of the TCA method that in addition to its stated purpose, it can also be used in part to analyse the agility of a system or a SoS, that is, "…the ability of a system… to adapt to rapid, unexpected or unknown change from its environment."

10.2.8 Contribution of the MEng case study.

One of the benefits of TCA is its aim to stimulate thoughts in, and subsequent actions by its users that might avoid or mitigate problems later in the project lifecycle and identify potential opportunities that are not obvious from the current viewpoints of the SoI. It is likely that the points raised would be detected by specialist engineering staff in the course of the normal design process, but such people are in great demand and may not always be available, especially where seemingly minor tasks are undertaken. TCA provoking these considerations in a broader set of the engineering community must be to the benefit of both the project and the business as a whole.

The student did not have the benefit of the automation concept demonstrator subsequently developed, the functional version of which would have provided a quantitative assessment and ensured repeatability of outputs, and would have utilised the specialist knowledge to generate 'independent' SSBs. The author agrees that specialist knowledge will be required to decide if unintended SSBs and ME(I) transfers are opportunities or risks and what appropriate action to take, which has been considered necessary from the outset. In addition it is accepted that the TCA analysts may be ideally those with some SoI knowledge similarly to those that would be chosen for design reviews.

The enhancement of terminology and definitions has been strengthened as suggested (See Definition of Terms page ii). The tailoring of the TCA method is best done by project staff on a case-by-case basis to ensure an acceptable return on the expenditure of their resources on TCA. The TCA method could conceivably be used to assess, and perhaps provide a 'Before and After Action' measure of agility, or re-configurability. This could be considered an aspect of iteration as suggested.

Use of the TCA method by staff with different levels of SoI familiarity is part of it is envisaged usage. The staff with an overall appreciation could use TCA to determine unintended SSBs, whilst specialist engineers would determine if any were problematic or an opportunity for enhancement, and what action was appropriate.

10.3 Chapter Summary

This chapter firstly described a case-study of a constituent of a complex socio-technical system that validates the TCA concept and method as a feasible means of revealing covert ME(I) transfer components inherent in a system design.

This case study can only provide generic guidelines for IT based implementation to assist the reader who may utilise the TCA method offered by this research. The criteria used to create the collection of 'Intended', 'Inherent' and 'Independent' ME(I) SSBs and assess their impact on the SoI can only be effectively determined in a quantitative form by the project engineering staff with the relevant domain knowledge and specialist expertise on a case-by-case basis.

Secondly this chapter has described another case-study which was an independent confirmation of the TCA concept validity by an M.Eng. Final-year individual project that focussed upon a major sub-system of a fast-jet military aircraft. This case-study was undertaken at a major systems building and integration company not involved with this research.

The independent industrial staff considered TCA had the potential in analysing complex systems-of-systems, and considered the MEng. Case study had demonstrated this. They felt that a more complex case study would be required to reinforce this. Any significant level of complexity would require the development of the generic automation concept demonstrator described in this thesis into a bespoke version tailored to the adopting industrial system suppliers PLM system to effectively and efficiently use the design artefacts in accordance with it by a project. Creation of a bespoke tool is outside the scope of, and would require resources beyond those available to this PhD.

11 PART A Summary

Part A of the thesis has described the research activities undertaken to investigate the problem of maintaining fitness-for-purpose of systems-of-systems constituents in the event of unforeseen events. The research has created a TCA technique and method that provides a more complete view of a system by revealing covers ME(I) SSBs inherent with the system design that could be opportunities to provide personnel close to the point of a systems employment 'something to work with' so the delivered system could be maintained as 'Fit-For-Purpose' should unforeseen events preventing the achievement of the system purpose occur. In addition to this, the research has shown that revealed ME(I) SSBs may be also be risks as possible causes of undesirable emergent properties, which can be effectively and economically taken to avoid or mitigate against them when revealed at an early lifecycle stage.

This chapter has shown case studies having undesirable emergent properties in SoS constituents which were discovered when in-service. These might have been obviated early in the lifecycle, or had their adverse effects mitigated at design opportunities occurring during the in-service phase by the use of the TCA method. A TCA concept demonstrator built on commercially available IT applications has provided an example of how TCA implemented on an industrial systems suppliers' bespoke PLM system might 'look and feel', demonstrated initial feasibility of an automated solution and also provided a point of departure for the development of a functional demonstrator.

As a footnote to this part, the author attended the 2016 INCOSE International Seminar in Edinburgh to present a paper on his work. During a panel session "Systems-of-Systems, Cyber-Physical Systems Internet of Things" in the "Future of Systems Engineering" stream, an ex-US forces attendee spoke of the introduction of Kevlar helmets to replace the in-service steel helmets that illustrated human resourcefulness and ingenuity utilising inherent functionality, saying that infantrymen could no longer use their helmets as a bowl for small laundry, washing, shaving, heating soup and other uses.

PART B: Exploitation.

This part of the thesis describes the industrial viewpoint from senior staff of the industry partner THALES, and how the TCA technique may be exploited by them and systems suppliers generally. Case studies illustrate the incorporation of research outcomes into a system suppliers ‘creating system’ of processes and procedures, and also into their created products and services (Hitchins 2005), illustrating the benefit of using the TCA analysis method as part of the design process. The viewpoints of THALES staff on how they and their customers perceive the problem of TCA maintenance are examined, and the viewpoints of THALES staff with the responsibility for engineering products and processes on the application and potential benefits of the TCA analysis method generally and related to current projects are examined. A functional demonstrator validates the feasibility of realising the TCA analysis method into a tool designed to be integrated as part of a PLM system. This part ends with guidance for industrial suppliers exploiting the TCA analysis method created by this research and recommends topics for consideration.

12 System Example, User and Supplier Problem Corroboration

This chapter firstly provides an example of a scenario where a major sub-systems ability to transfer ME(I) is enhanced and how this enhancement is capitalised upon to restore the capability to its host SoS after an unforeseen event. Secondly it describes the viewpoints of industrial stakeholders on their experiences and on the adoption of TCA: both the engineering practitioners who would use TCA to benefit their products and their engineering staff, the engineering process owners who would have to integrate TCA with their existing PLM system, and the customers of the system suppliers.

12.1 Industrial Exploitation

The TCA method and process was created to allow scalable application to both created and creating systems. The author considers that few suppliers of complex socio-technical systems are likely to have a homogeneous design and manufacturing system with a truly integrated modelling environment that would allow the integration of a TCA process able to autonomously create a ME(I) meta-model of a supplied system. It is recommended that a supplier adopting TCA should take an incremental approach starting with an exploration of how their supplied products and services have developed and been used over their lifecycles and how different degrees of TCA adoption might have been of benefit to them, taking account of the future direction of the business. In parallel to this, the PLM system and engineering design artefacts produced for projects should be examined to determine factors such as the machine readability of design documentation at the ME(I) transfer level and the level of integration of system models. The goal of these activities is to baseline the 'Where we are now' and 'Where we want to be' in terms of both the systems supplier's created and creating systems from the viewpoint of TCA adoption. The knowledge gained would be used to introduce the TCA concept and perceived benefits using language terms and examples familiar to engineering managers, project managers and project chief engineers, perhaps in the form of a short course as has been previously suggested by both academic and industrial partners This should be immediately followed by a meeting that produces an TCA adoption route-map with 'quick win' milestones between the points of departure and the desired end state that is considered to deliver the best return-on investment from TCA adoption from the budget available. An early and cost-effective intervention would be the addition of TCA oriented questions in the review checklists for preliminary and critical design reviews. A second step, dependant on the level of machine-readable design information available, might be the automated generation of a ME(I) meta-model of the 'intended' ME(I) transfers.

12.2 Exploitation Potential of Unintended ME(I) SSBs

As said earlier, the motivation for this research came from the desire to enable personnel engaging with systems close to their point of employment to be able to more readily adapt them to address a new need, after experiencing unpredictable changes in operation, internal and/or external factors. The new, more complete viewpoint provided by the TCA method could be exploited by these personnel to adapt their system by changing the 'intended', inherent and perhaps 'independent' ME(I) SSBs to stop existing transfers, create new transfers, increase or decrease the volume or frequency of transfers. The suppliers of SoS constituents could similarly do so, but additionally (and more importantly) they could make provisions for these changes to be done in the future. These provisions could be designed to benefit future system enhancements or be used to inform implementation of Product Line Architectures (PLAs).

Suppliers could use the viewpoint to identify single or combinations of ME(I) SSBs that could lead to undesirable system behaviour that otherwise may not be identified until system integration, or later when the system is composed with others into a SoS. Another supplier exploitation might be to act as a pathway to innovation, providing stimulation for thoughts as to how the SoI might be enhanced; not only in terms of function and performance, but also in maintenance, support and other through-lifecycle activities by utilising inherent ME(I) SSBs to support these type of activities.

12.3 TCA as an Innovation Enabler

The TCA method provides a novel viewpoint of an engineering system by showing its capacity to source, transport and sink ME(I), and to what extent this capacity is utilised. This viewpoint provides a pathway for innovation to enhance and adapt systems by exploitation of their existing ME(I) SSB infrastructure, and to do this in an efficient cost-effective manner by incorporating improvements into the system at naturally occurring opportunities throughout its lifecycle, to the depth and breadth that individual projects consider can be accommodated and provides best return-on-investment for their particular case at the time.

The TCA viewpoint of ME(I) SSBs may assist problem solving in SoS constituents. Often when addressing a problem we have the feeling that there is a 'piece missing from the jigsaw'; this 'piece' may well be an obscured connection between functional pieces that the TCA method would make visible.

The TCA viewpoint may be utilised by additive manufacturing close to the point of SoS constituent employment. The TCA identification of potential ME(I) transfer enhancements to address the occurrence of an unforeseeable problem could be used to determine what physical artefacts are required to implement the new ME(I) transfers, and instruct a local 3D printer to manufacture these required mechanical components, couplings, electrical connectors, adaptors, hardware, etc. necessary to instantiate the necessary transfers.

12.4 System Example: Obsolescence Resolution of Deck Approach Light Projector (DALP)

The previous case study in section 10.1 illustrated how the TCA method might be incorporated into system suppliers PLM engineering processes in an automated manner using existing project design artefacts to minimise the impact of adoption on staff and resources. This case study is intended to illustrate how a design intervention resulting from a TCA perspective might be incorporated into a system suppliers' product in an affordable manner by taking advantage of an opportunity to enhance its affordance for ME(I) transfer.

12.4.1 Overview

To assist aircraft landing on a carrier, an array of lights on the deck project beams towards the pilot to indicate the movement of the ship and their aircrafts deviation from the ideal approach angle and landing point.

A 'Wave-Off' (WO) lamp in the array illuminates if it is necessary for an approaching aircraft to abort the landing attempt. Figure 12.1 below shows a photograph of a DALP equipment fitted to a carrier, which is reproduced courtesy of www.netmarine.net under creative commons (https://commons.wikimedia.org/wiki/File:FS_CdG_Optics.jpg).

Figure 12.1: Deck Approach Light Projector (DALP)
Photo courtesy of www.netmarine.net under creative commons https://commons.wikimedia.org/wiki/File:FS_CdG_Optics.jpg)

12.4.2 Research method

This case study explores how the interpretations of “the findings of a quantitative study” might be practically exploited by an industrial systems supplier. As was mentioned in the summary of the literature review in section 3.12 previously there appeared to the author to be a paucity of this information to assist prospective industrial beneficiaries of research.

12.4.3 Approach

Obsolescence of some of the original equipment filament bulbs provided an opportunity to reduce downtime and maintenance cost by capitalising on advances in LED technology. No explicit enhancements to the DALP equipment have been requested at the time of the obsolescence resolution exercise, so the TCA method is applied ‘Open-Loop’, i.e. not in response to a function or performance upgrade requirement. The TCA method shows that enhancement of the DALPs ability to transfer ME(I) can be done in parallel with obsolescence resolution at little extra cost.

12.4.4 Enhancement Design Integration

The DALP WO ME(I) transfer affordance is a lamp that when flashed at 1Hz. instructs the pilot of an approaching aircraft attempting to land that they should abort. The TCA analysis method determines the potential for ME(I) transfer enhancement of the DALP’s ME(I) affordances and SSBs, and identifies the potential of the WO affordance for enhanced information transfer.

The on/off and off/on response time of a LED is much faster than that of a conventional incandescent lamp which requires a finite time to heat up and cool down, so the faster switching characteristic of a LED lamp could provide an opportunity to enhance information transfer of the WO affordance, by modulating its output. The enhanced WO affordance would provide the carrier an available, non-broadcast, secure, low-latency and jam-resistant communications link to an approaching aircraft.

The new WO LED lamp requires a new driver circuit. It has a switching input that is able to be connected to the DALP data bus. (Note: circuit is for illustration purposes only). The new circuitry required for the new LED lamps is shown on the left-hand side of the Figure 10.13 below.

The new LED WO lamp driver circuit has a modulation input added to it. The modification to the new lamp driver circuitry is shown circled on the right-hand side of Figure 10.13 below.

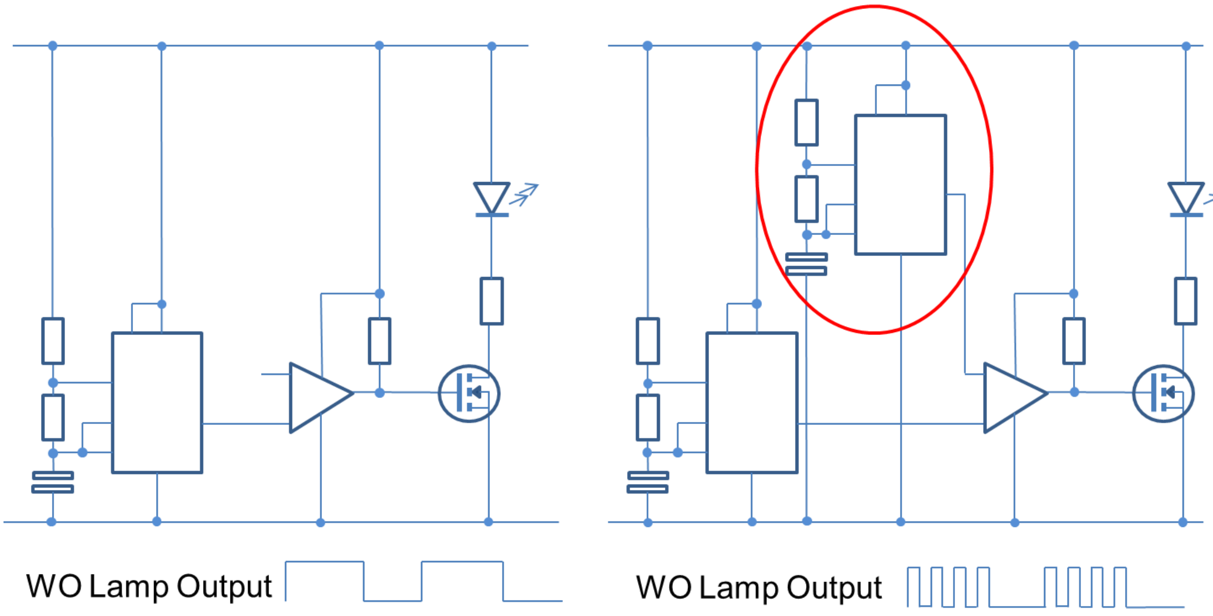


Figure 12.2: LED Driver Circuit Enhancement

The ME(I) transfer (in this case Information) enhancement facilitates a new, secure, un-jam-able data transmission from the carrier to an approaching aircraft. The carrier houses extra functionality not occupying processor and memory space on the aircraft where it is at more of a premium.

12.4.5 Contribution of this case study to TCA development

This case study contributed an insight into how an TCA perspective might prove beneficial, and where the benefit from it might be outweighed by the cost of implementation into engineering processes and enhancement of products. In this case study the enhancement costs are small, as in this instance the equipment and associated documentation is already scheduled to be modified, and the number of DALPs in-service is small. The enhancement above does not significantly increase component count and type, and in this case should not significantly impact costs from bought-out materials, testing, equipment support publications, training etc.

In a higher volume, lower margin environment the FFP risk identification element of TCA may be seen as worthwhile as the cost of recall and rework in this situation may be intolerable, whereas it is considered likely that the cost burden of making provision for the future in such an environment would be prohibitive. It is the system supplier who has to decide what level of intervention in their products best suits them on a case-by-case basis, for example by considering aspects such as easement to product line architecture or in-service enhancement of delivered systems enabled without return to manufacturer.

The WO enhancement modification is incorporated into the design actions forming part of the DALP project plans and documentation in accordance with the company lifecycle management process.

The earlier RLC case study contained an instance where the user exploited an inherent ME(I) transfer affordance that was not recorded or controlled by the system design definition artefacts in the PLM system. The TCA method exploiters need to decide if there is merit at a design opportunity such as the DALP obsolescence recovery task in analysing both the 'before' and 'after' situations. Here the move to LED lamps reduced then WO lamp energy transfer by a significant reduction in the IR region. This meant that although the new lamps retained the NVG and FLIR visibility of the old lamps, the inherent IR energy transfer of the LED lamps was insufficient to prevent ice build-up in artic conditions, and a de-icing provision had to be made that was fulfilled by the inherent IR output of the old filament lamps.

12.5 System Example: ME(I) transfer Affordance Enhancement Exploitation

12.5.1 Research method

This case study adds to the guidance for systems suppliers for the practical implementation of ME(I) transfer affordance into their products by an illustrative example of how an 'open-loop' enhancement might be practically utilised.

12.5.2 Overview

The carrier is a central part of SoS (a carrier group of vessels) that is conducting military operations in a littoral scenario, whose purpose is to provide ISTAR capability to friendly forces ashore. An unforeseen change in the political situation around the carrier groups operations meant that some military tasks being achieved by manned aircraft became untenable. As a consequence of the external change the carrier group was no longer fit for the purpose of providing an ISTAR capability.

12.5.3 Approach

Candidate solutions were examined to determine their feasibility, impact and timeliness on both the problem and the capabilities available from the SoS resource, which included the necessary changes and enhancements to the ME(I) transfers. A preferred solution of UAV operations was chosen from a candidate set. Available UAVs have a core capability of operating from land, but do not have the ability to operate from a carrier. The UAV's are normally landed by a human pilot under remote control, but the latency in the control loop is too large to enable the remote pilot to compensate and make adjustments for the movements of the carrier at sea. The enhanced carrier to aircraft information transfer via the light projector is exploited to provide a command link to an unmanned aircraft (UAV) via its panoramic Infra-Red/Thermal Imaging (IR/TI) camera, auto-tracker and flight control system to provide a low-latency minor control loop to relieve the pilot of compensating for the movements of the vessel, enabling him to apply the flight commands to the UAV landing on the carrier much as he would do for a landing on the ground.

The provision made by the supplier during the DALP obsolescence recovery task was brought on-line whilst the carrier group was on-station, and enabled the available UAVs to be operated from the carrier, thus maintaining fulfilment of the necessary ISTAR tasks without placing pilots, and expensive aircraft containing sensitive intellectual property in harm's way.

12.5.4 Contribution of this case study to TCA development

This case study illustrates the exploitation of an enhancement to the affordance for ME(I) transfer of a system (the DALP) to maintain a capability of its higher SoS (the carrier), and hence maintain the fitness-for-purpose (to provide ISTAR capability in littoral operations) of the next higher SoS (the carrier battle group) in the event of an unforeseen change (social and political acceptability).

12.6 TCA Exploitation: Product Engineering Perspective

Sections 12.6 to 12.9 below contain the outcomes of presentations, meetings and semi-structured interviews with Thales staff responsible for the whole of Thales' engineering activities (the operational viewpoint, section 12.6.1), senior engineering staff members responsible for engineering projects/products; the 'Created System' (perspectives from the product engineering viewpoint, section 12.6.2 et al), their perception of their customers viewpoint, (the customers perspective, section 12.7) and staff responsible for business processes; the 'Creating System' (perspectives from the process engineering viewpoint, section 12.8). Section 12.9 summarises salient points from the engagements with Thales staff. The précis of Thales engagement appears in Appendix A6.

All meeting attendees and interviewees were given pre-meeting material in the form of a PowerPoint presentation and a short paper that described the research aims and the TCA method together with application illustrations and applications to existing systems. At the start of each interview queries were answered and the context set for the discussion, including a description of the TCA technique as a method and process facilitating the maintenance of a system as fit-for-purpose by identifying its inherent abilities to transfer Material, Energy and Information (ME(I)) to be either suppressed to reduce the risk of them giving rise to undesirable emergent properties, or exploited to enhance its affordance to transfer ME(I) to overcome a shortfall caused by an unforeseen event.

Confidentiality prevents the author from identifying Thales personnel or specific systems.

12.6.1 Overall Engineering Authority Interview

This subsection is a précis of a telephone interview and subsequent discussion between the person with overall engineering authority at Thales and Steve Hinsley (SH) of Loughborough University, held on 09/09/15.

- The TCA method will need to be a largely automated process and will need to mine existing PLM and design artefacts held in CHORUS2 to minimise its impact of adoption.
- Autonomous vehicles may be a domain that would benefit from the TCA method: requirements can be met, but this does not guarantee fitness-for-purpose.
- The 'untangling' of complex systems and exposure of covert characteristics to engineering staff in a timely manner as might be done by an automated process provided by an integrated IT based TCA method package.
- Incorporation of facilities for future development in the underwater domain have been successful in the past, taking advantage of convenient opportunities to add them.
- Thales maritime autonomy group would be interested in TCA research. Unmanned platform projects may have parallels and common ground that TCA might address to the benefit of both. The example of carrier based UAV operations example is pertinent to Thales' work in the UK.
- What is the necessary amount of 'man in the loop' to be fit-for-purpose is a common question within rail public transport, autonomous automotive applications and naval surface ships. The design of vehicles often currently includes a facility to house a person, which is not optimal for an autonomous platform design. The current regulatory regime is complex and unclear on responsibilities and definitions which are acting as a blocker to unmanned operations and vehicle development.

12.6.2 SoS Architect telephone discussion 1

Procurement was seen as a factor that could enable or inhibit exploitation of latent capability, as could the other components of capability typified by the UK MoD Defence Lines of Development (DLoD).

The systems architect could see TCA as a cross-discipline analysis informing Critical Design Reviews (CDRs) by identifying unintended ME(I) transfers that may cause undesirable emergent properties, and hence identify the need mitigating action early in the lifecycle. The systems architect thought the TCA method may also facilitate incremental paradigm change that would be more amenable to customers by identifying latent capabilities of legacy SoS constituents to be used at interim stages. SH added that the words "Maintain FFP" was used in the title of the research to reinforce that it was not something for use at the initial design stage of the lifecycle only.

The systems architect thought that TCA did bring something to the analysis of design by identifying both the risks and the opportunities created by revealing otherwise covert inherent ME(I) transfers and give the benefit of early hindsight. The architect mentioned the separation of operational and enabling functionality, with a focus on the former causing the latter to be more ad-hoc, exemplifying this with the need for power supply conditioning to enable sonar to detect low level returns. SH said that the TCA method could promote enabling functionality to be on par with operational functionality as a Failure Modes Effects and Criticality Analysis (FMECA) does where root causes of a failure have equal weighting. Parallels were drawn between FMECA and TCA method, where TCA added the exploitation opportunity viewpoint. The systems architect thought this may be a familiar departure point to introduce TCA, also envisioning a ‘Opportunity Tree’ equivalent to the fault trees produced by a FMECA.

The systems architect thought there may be an issue in the exploitation of inherent headroom in that the exploitation may result in operation of the system outside its safety case or certification boundaries. How this could be accommodated as part of headroom exploitation could be cited as an opportunity for further TCA research. The existing Urgent Operational Requirement (UOR) procedures may provide an existing mechanism or a point-of-departure for this further work.

12.6.3 SoS Architect discussion 2

This subsection is a précis of a telephone conversation following on from a previous telecon on 18/09/15 between a Thales SoS architect and Steve Hinsley (SH) of Loughborough University. SH had supplied the architect with a synopsis of an earlier telecon and questions on 23/09/15 previously.

The procedure and management of acceptance for use of enhanced systems, by exploitation of latent capability through the TCA method or otherwise will need to be addressed. The MoD customer has responsibility for the Provision of Use for Equipment at Work (PURE), and a system supplier such as Thales would have to provide a safety case and have responsibility for the FFP enhanced system delivered. There may be caveats in terms of operation, duration, limitations of use and removal of modifications as with systems modified in response to a UOR. Incremental certification was used to accept the addition of air-conditioning for vessels to be employed in extreme temperature environments, and that the Additions and Alterations (A&A) process is well-established for large, long service life platforms to ensure that the overall capability of a platform was not compromised where its role, partnering systems and utilised technology may well change dramatically over its service life. There are existing mechanisms in defence procurement and governance of which UOR and A&A are examples that may be able to accommodate FFP modifications.

Design for Mutation could be enabled and informed by ‘A More Complete View’ provided by the TCA method. There appears to be an implicit disposition that provided solutions will be immutable, with the result that Material/Energy/Information (ME(I)) transfers between the constituents of a solution are often hidden from external view and in a form not readily usable outside the solution boundary. A simile might be made with the differing philosophies of Apple and IBM upon user accessibility to internal data within the Apple Mac computer (very limited) as opposed to the IBM PC (mostly accessible).

An ME(I) meta-model (not currently a part of a solution's technical definition) would expose transfers between the product block constituents of a system and provide a 'big picture' view of the 'intended' and 'inherent' ME(I) connections with other blocks. This ME(I) meta-model should provoke consideration of future mutation at design time, stimulate new questions and assist identification of possible axes of mutation that can be supported. To facilitate system reconfiguration blocks need to be loosely coupled and connected by open interfaces so they are amenable to reconfiguration and that transfers between them are made accessible. Additionally the ME(I) meta-model would provide an enhanced view at the system-of-systems level of what could be provided by individual systems and their constituents to reveal latent capability and inform its practical exploitation.

Projects focus on 'intended' ('designed-for') ME(I) transfers. Taking a wider view, informed by a ME(I) meta-model created from project information held in artefacts such as Interface Control Documents, System and Sub-system design documents, CADCAM and 3D models. The meta-model may reveal risks and opportunities not otherwise apparent. Partial views of inherent ME(I) transfer, both internal and external to a system of interest boundary can exist in some specialist disciplines such as platform spectrum management, shock and vibration analysis and platform signature management, but are not drawn together as a single point of reference to be holistically visible to all engineering disciplines. Approaches used in specialist domains such as underwater systems may be usefully utilised in other domains and disseminated as best practice.

It was noted that reconfiguration may well have a knock-on effect upon other LoDs: complementary adjustments to operational procedures may be required to realise tactical advantage for the user from the exploitation of latent capability. The architect cited the effect on logistics of the adoption of a new land vehicle under a UOR that could not be supported by other systems for transport, maintenance and repair and other LoDs to varying degrees.

12.6.4 Semi-Structured Interview Questions

This subsection contains the set of questions used to focus and stimulate discussion among the subjects of the semi-structured interviews and also in the attendees of meetings with Thales staff. A précis of the answers to the questions provided by Thales personnel appears below. Questions are denoted by a “Qn” and answers to them by “An”. Multi-part questions and their answers are denoted by a lower-case letter suffix.

Q1: What do you see as impediments and enablers to the adoption of the TCA method by the Thales Product Lifecycle Management (PLM) system from the viewpoints of …

a) Projects?

A1a: Project Impediments: Projects are focussed tightly on efficiently satisfying customer requirements, and are reluctant to apply resource on anything that does not deliver against a project requirement or reduce risk. Projects are also understandably keen to avoid anything that will adversely affect attaining contract closure.

A1a: Project Enablers: Use of configured product blocks to create a solution to a requirement. Examples of product blocks to be assembled into a solution might be Communications / Command & Control / Consoles / Processing / Image exploitation / Payload. Project engineering would integrate blocks and conduct Validation & Verification of the solution.

The partitioning of the development of product blocks from projects. This should allow the scope of analysis of product blocks to be widened as they need to be applicable to as many solutions as possible. Product blocks will probably have more interfaces and functionality that any one solution requires from it. This allows bottom-up push from blocks into solutions to provide capability not envisaged by the solution team. Block interfaces need to be standardised. Need to decouple a block’s data model from its interface technology, e.g. by use of adaptors. This provides modularity in block functionality and interface. Solutions can be enhanced by exploiting inherent product capability and exchanging / adding product blocks. This is probably easier to achieve in software than hardware. A software application would need to expose the rich data set available provided by the block. The maximum block size will be governed by its most constrained application (solution). Over-specification may not be cost effective; a cross-project cost/benefit analysis would best be done by product block creators and should be extended across all the Lines of Development: e.g. logistics, training, infrastructure, doctrine etc.

A1b) PLM / Engineering Governance?

PLM/ Engineering Governance Impediments: Separation of functions for security. E.g. a vessel command system containing sensitive data is separated from other less sensitive functions. Locking down may inhibit connections. Impact on support arrangements; Boundaries. Handbooks. Multiple operating modes and procedures.

PLM / Engineering Governance Enablers: Bring questions into design review checklists. Would benefit staff professional development and products by reinforcing thoughts of how blocks and solutions fit into the wider system/ SoS that integrates them with other constituents. SoS thinking at all levels and taking a wider view than just equipment. May promote ethos and culture of systems thinking and contribute to staff development.

Q2: What do you feel your customers might see as impediments and enablers to them benefiting from latent capability realised by exploitation of inherent (i.e. not 'designed-for') Material, Energy and Information (ME(I)) transfers?

A2: (See section 12.8 below).

Q3: What examples do you have of where problems were caused by the lack of complete, timely and correct ME(I) transfer?

A3: To be advised. (Currently unsupplied)

Q4: Which of the problems in response to Q3 can you envisage might or might not have been alleviated by inherent ME(I) transfer suppression of exploitation, and why?

A4: To be advised. (Currently unsupplied)

Q5: What percentage of sufficiency for a TCA method do you feel a typical project has in terms of ME(I) source, sink and bearer characteristics …

Q5a) stored digitally in its project technical data pack?

A5a: Inside scope of supply boundary sufficient for project needs, but focussed on the designed-for functionality. Information transfer is probably the most comprehensive, then Energy, then Material. Externally, information is held between interface stakeholders, who may be affected by reconfiguration.

Q5b) stored digitally in a format that conceivably an automated TCA method could access?

A5b: This is some way off yet.

12.7 TCA Exploitation: Customer Perspective

This section contains Thales' perception of their customer's viewpoint, followed by problems they perceive that the TCA method might alleviate.

Q2: What do you feel your customers might see as impediments and enablers to them benefiting from latent capability realised by exploitation of inherent (i.e. not 'designed-for') Material, Energy and Information (ME(I)) transfers? (This is a précis of discussion with several individuals).

Thales' MoD customers are asking for enablers to release latent capability. Bodies with a cross-IPT view such as the Naval Combat System Integration Authority are beginning to have a positive effect. Reduced budgets can act as an enabler: more 'Bang per Buck' is required, greater re-use, solution convergence (many similar requirements fulfilled with solutions with a high degree of commonality, ideally to the level of form, fit and function, used on differing platforms).

Impediments to the successful exploitation of latent capability as identified by the TCA method include the MoD customers Integrated Project Teams (IPTs) being structured to look after the interests of their own capability blocks. Procurement bodies seemingly always see competition as a good thing, whereas sometimes cooperation might deliver better benefits and capitalise on synergies between systems and capabilities. Stove-piped procurement structures inhibit the flow of information between them and make re-use and trade-offs to achieve best benefit difficult. Determination of risk ownership may be less clear-cut where solutions cross structure boundaries. The lack of commonality of sub-assemblies across the fleet may limit re-use of TCA meta-models and hence increase the NRE burden on projects.

12.8 TCA Exploitation: Process Engineering Perspective

Interest in TCA is mainly seen by Thales to be as ‘Internal Benefits’: ‘Benefits Realisation Management’. TCA may sit within Model Based Systems Engineering (MBSE) activities and contribute to Product Line Architecture development. The CHORUS2 PLM and Product Line Engineering activities are not completely joined: TCA could straddle these. As well as MBSE, elements of TCA could be incorporated into the Decision Analysis Review (DAR) process that should look at candidate solutions as well as the preferred solution as part of the Design, Development and Quality Solution (DDQS) activity. What and where TCA components are placed in CHORUS2 needs to be assessed by Thales. Parts of TCA fit with product variability management activities. A TCA adoption routemap could provide at least a point of departure for TCA research exploitation and would assist TCA integrators when proof of concept was established. TCA could be taught as a short course for continuing professional development; this has been similarly suggested previously at Loughborough University as a taught module constituent of LU postgraduate systems engineering tuition.

12.9 Points arising from engagement with Thales staff.

12.9.1 ‘Minimum Scope’

There is a pervading school of thought orienting the solution designer towards producing the minimum to meet the requirement at hand. This approach has some merits, and is likely to be efficient and cost-effective (in the short term at least), possibly more so in industries where both problems and solutions are well-known, clearly bounded and deterministic. This situation is less likely to be the case for suppliers of complex socio-technical systems often forming part of a system-of-systems as are many of those supplied by Thales, and hence may have detrimental effects in the medium and longer term, for example upon selection by customers for follow-on orders and on company reputation. However, recently there is movement towards generic, reusable system constituents having a degree of functional and performance scalability built into them, such as the 'System on a Chip', which may be facilitated by new organisational initiatives such as design centres and innovation hubs undertaking early concept work.

12.9.2 Operational Appreciation

Although an aside to the research topic, it has been the author's experience that a designer's appreciation of the operational usage of their SoI is such a positive influence on achieving fit-for-purpose products that it warrants inclusion into this thesis. 'Not-fit-for-purpose' occurrences encountered in several product areas were due to misalignment between the product and how the interacting humans operated; a human integration problem concerning the link between the delivered system and humans. One project that met all its requirements was not considered fit-for-purpose by the users as its advanced design and increased complexity made it difficult for users to operate in the traditional way to which they were accustomed, which necessitated changes to the information displays. In common with the author's personal experience, the opportunities for designers to gain an appreciation of their system-of-interest's operational usage have reduced significantly since the mid-1980s due to the difficulty in quantifying return-on-investment in both time and cost to the business. For example opportunities for engineers new to the defence industry to spend a week with a tank regiment on exercise, enrol on doctrine, tactics and weapon system appreciation courses, observe at live firing demonstrations and customer acceptance trials and engage with training and maintenance personnel in the armed forces at their place of work are much reduced. It is the author's opinion that the lack of insight from such first-hand experience adversely affects both the skill and motivation of the staff and the perceived worthiness of the products they design.

12.9.3 Unstipulated Requirements

An often-heard question is 'It meets the requirements but is it fit for purpose?' and it is felt that current metrics are all around the 'known'. Covert characteristic measurement and design for whole life are potential candidates where TCA might help. How the TCA method might output its findings is an area to be explored for further work. It could be as simple as 'Red/Amber/Green': Even this level would be very useful. Currently some aspects similar to this are decided by experience… also known as 'Gut Instinct'. There is eagerness to explore fit-for-purpose in more complex cases where meeting the requirement would not deliver something that is fit-for-purpose. It was thought that maritime autonomy might be exactly in this space: for example the constraints upon unmanned system solutions to a requirement may so great such that it's 'easier' to use a manned solution.

12.9.4 Capability Growth

Defence Mission Systems in the Maritime domain expressed an interest in fit-for-purpose as over the last 3-4 years there was a need for Thales' products to do more than originally planned, which they express as the 'release of latent capability'. They could relate collaborative Underwater Unmanned Vehicle (UUV) scenarios to the Deck Approach Light Projector (DALP) example, and described a designed-in expansion capability example of a 'Guest Processor' in a UUV to be used for capability growth at some time after initial delivery (designed-in expansion capability in TCA terms is 'Intended Headroom'). A main goal of the TCA research is to stimulate risk and opportunity thinking; 'Inherent Headroom' in TCA terms is analogous to 'latent capability'.

12.10 Chapter Summary.

This chapter has captured viewpoints from the industrial partner (Thales') from commentaries on the adoption of TCA by both CHORUS2 owners and project team users.

System architectures receptive to reconfiguration used to facilitate the need for agility, robustness and resilience against foreseeable events would also support exploitation of TCA revealed 'inherent' and 'independent' ME(I) Sources, Sinks and Bearers (SSBs).

Exploitation of a systems headroom would enhance ME(I) transfer at the system level and may improve capability at the System-of-Systems level should the enhanced ME(I) transfer ability have a role in SoS capabilities.

The interviews, discussions, meetings and presentations generated the following salient points:

- A 'design for minimum' policy coupled with a lack of operational appreciation can cause fitness-for-purpose shortfalls as all that is necessary to produce a fit-for-purpose solution is not in the explicit requirements, and may necessitate rework in later lifecycle stages.
- TCA would help identify 'latent capability' and fit into CHORUS2 perhaps as a practice, in the Decision Analysis Review and could bridge the PLM/product Line engineering activities
- The cost/benefits of TCA should be assessed from a cross-project viewpoint to align with the move towards generic reusable system constituents.

In summary, Thales projects have had instances that suggest some adoption of TCA might have been beneficial, and the engineering staff interviewed could see benefit from adoption at some level, for example starting with a 'TCA Thinking' short course to establish the mind-set in staff involved in both the 'Creating and 'Created' systems. An investigation of historical projects might provide evidence and broader buy-in for TCA adoption, which the author suggests would be an incremental process perhaps starting with a pilot project which could be in-service equipment due for a mid-life improvement. The direction and emphasis of TCA adoption would be informed by feedback and the experience gained over time in order to provide Thales with the most cost-effective form of TCA adoption for them.

13 Process Gap, Solution Environment and Solution Requirements

This chapter describes the gap in existing PLM process that lets unintended and independent ME(I) SSBs in a SoI remain hidden. This is followed by a brief description of the THALES PLM environment and some of the processes within it. This is followed by a description of the cardinal point requirements for a TCA analysis solution able to be integrated in such a hosting PLM environment.

13.1 PLM Process Gap

The considerations of engineering specialists started from the author's formulation of the question 'What design artefact (for example a model, specification, drawing etc.) in a product's 'technical data pack' accounts for the inherent characteristics of the design solutions?' For example, what artefact considers the mechanical characteristics of electrical elements, electrical aspects of mechanical structures, what information is implicitly transferred with material or energy transfers? From this came the thought that snippets of this information may exist in some form from activities in mainstream engineering and as outputs of specialist engineering discipline; control engineers may consider the mass, inertia and centre-of-gravity of electrical cables carrying power to motors on moveable structures, mechanical engineers consider galvanic corrosion caused by the junction of dissimilar materials, electrical engineers consider the current-carrying capability of mechanical structures under fault conditions, platform signature management consider the multispectral emissions of platform subsystems, similarly to the considerations of EMC/RFI engineers managing conducted and radiated electromagnetic noise.

13.2 Solution Environment: PLM and CHORUS2

13.3 Chorus 2 Global Management System

CHORUS2 is the name given to the Thales global management system that provides a common and efficient way of working across the globe, of which PLM is a part. The previous common management system Chorus 1 had many variants and local procedures, many as legacies from companies in the defence, electronics and optics sectors from which Thales was formed, from company acquisitions over a number of years. CHORUS2 provides a multinational common reference and operational architecture at both the country and group levels that has few local variations.

CHORUS2 encompasses governance, processes/rules, methods, roles and a glossary to provide a reference for Thales businesses and staff distributed across several countries, enabling businesses to work together effectively in partnership. Using CHORUS2, businesses share and use the same vocabulary to describe their activities. Projects and personnel have a reference for roles and responsibilities, a driver for collective improvement and ultimately a common culture that mobilises staff to succeed.

CHORUS2 processes are divided into three parallel channels of activities that connect customer needs with customer satisfaction. The Steering channel activities define company strategy, manage and control the company finances, risks, policy, workload, capacity, competencies and continuous improvement. The Operational channel has parallel activities that manage bids, projects, design, development and qualification of solutions, in addition to activities that source or make solution constituents and prepare and deliver customer service. The Support channel activities support operational processes such as health and safety, export control, security, information systems, human resources etc. An overarching “Govern and Organise” activity parallels the three channels.

TCA method would form part of the “Design, Develop and Quantify the Solution” activity in the operational channel. Three key elements of this are the:

- PRS: Process Reference System that defines ‘what’ needs to be done
- TRS: Technical Reference System that defines how things are done, and contains engineering tools and processes (‘What with’)
- PIVS: Process Implementation and Verification System containing the audit process.

The scope of CHORUS2 activities and artefacts are tailored to suit individual projects on a case-by-case basis, as would be the scope of TCA activity. Tailoring is a key activity to ensure that activities efficiently and effectively add value to individual projects. The ‘What needs to be done’ contained in the PRS and the ‘How it needs to be done’ in the TRS is being changed to a process versus practice arrangement using a new reference artefact called an “eTUP” (a definition of engineering practice) to support a condensed PRS. TCA would appear to fit within the TRS, sitting as a practice rather than a process, with an associated TCA ‘tool’ in the relevant part of the TRS. An eTUP for TCA appears in Appendix A7.

13.4 Functional Demonstrator Cardinal Point Requirements

The functional demonstrator functionality shall be demonstrated using the same simplified example of a major SoS constituent as used by the concept demonstrator.

The functional demonstrator shall use EXCEL and Cytoscape PC applications for the capture, analysis and visualisation of ME(I) transfers and SSBs as used by the concept demonstrator.

The functional demonstrator shall use frequency and time domain analysis as used by the concept demonstrator to tag groups of ME(I) SSBs as either Prospective or Potential ME(I) transfers respectively.

The functional demonstrator shall use sensitivity analysis to flag if potential ME(I) transfers may be either a risk or an opportunity.

The functional demonstrator user will be able to interrogate the ME(I) SSBs captured in EXCEL and filter them by any captured characteristic to display ME(I) SSBs with a characteristic commonality.

13.5 Chapter Summary.

This chapter has outlined the industrial partner (Thales') PLM system CHORUS2 and described the process gap that lets unintended and independent ME(I) SSBs in a SoI remain hidden. A brief description of the THALES PLM environment and some of the processes within it is followed by a description of the cardinal point requirements for a TCA analysis solution able to be integrated in such a hosting PLM environment.

14 Feasibility Validation: Functional Demonstrator

This chapter describes a final-year individual project of a B.Eng student who developed a functional demonstrator from the concept demonstrator and the cardinal point requirement specification.

14.1 Functional Demonstrator

During the development of the TCA process, a BEng. student took up a final-year project proposal (Appendix A8) to develop a TCA functional demonstrator from the concept demonstrator.

The sub-sections of this section draw upon the BEng final year advanced project deliverables produced by the LU undergraduate student Mr. N. White to meet the requirements of the systems engineering BEng course at Loughborough University. He was provided with a cardinal point requirements specification (Appendix A9). The BEng project report and TCA functional demonstrator user guide appear in Appendix A10.

14.1.1 Research method

This case study took up an opportunity to verify the feasibility of an automated data manipulation and visualisation by someone unfamiliar with the research, by using the concept demonstrator as a point-of-departure for its development.

14.1.2 Concepts to Functions.

The student was provided with TCA research reports, presentations, a cardinal point specification for the functional demonstrator and the concept demonstrator software as the point-of-departure for his project. The functional demonstrator is realised using EXCEL and CytoScape as is the concept demonstrator, and has a user-friendly operator interface. The functional demonstrator (based on the aircraft carrier system) part-automates the functions necessary to determine the 'inherent' and 'independent' ME(I) SSBs that form potential ME(I) transfers that might be problematic or provide an opportunity for exploitation to enhance a systems affordance for ME(I) transfer. The functional demonstrator is based on the three-stages of the TCA process. The structure of the functional demonstrator is shown by the students' functional diagram appearing as Figure 10.15 below.

Figure 14.1 shows the use of user-entered ME(I) connections from the users 'kinematic' analysis of the 'intended' ME(I) transfers and 'unintended' ME(I) SSBs. Firstly an algorithmic determination of the frequency domain commonality of all ME(I) SSBs generates a list of prospective ME(I) transfers which have the ability to transfer ME(I). Secondly, from these prospective transfers a list of potential ME(I) transfers is generated. These potential ME(I) transfers are those prospective ME(I) transfers that also have SSBs that are synchronously active, that is they have the opportunity to transmit, receive and transport ME(I) during certain periods in time; they have both the ability and opportunity for ME(I) transfer. Thirdly the ME(I) transfer capacity of the potential ME(I) transfers is determined to identify those that have the capacity to transfer quantities of ME(I) that are not insignificant (that is have the capacity to affect system function to a perceptible degree). The ME(I) transfers that have the ability, opportunity and capacity to affect system operation can then be examined to determine what action is to be taken to either reduce the risk of undesirable unintended ME(I) transfer to an acceptable level or to exploit the opportunity they provide for enhanced ME(I) transfer.

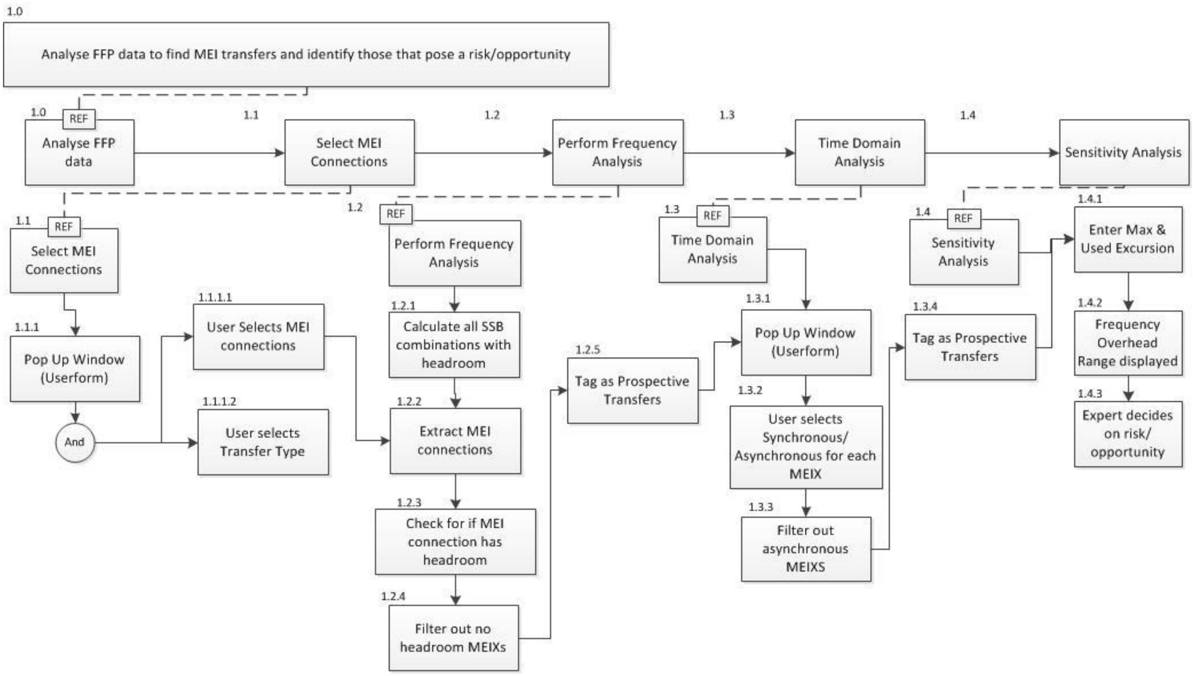


Figure 14.1: TCA Functional demonstrator functional diagram

The students' time constraints did not allow the incorporation of sensitivity analysis data which would use the same mechanism as the frequency domain analysis. An illustrated operator manual which includes sources of further information (within Appendix A10) was provided that showed by example the use of the functional demonstrator, which itself contains references to the manual.

14.1.3 Contribution of the BEng Example.

The creation of the functional demonstrator and user handbook demonstrated some opportunities for misunderstanding of the TCA method leading to implementation issues that an exploiting systems supplier may have in integrating the TCA method into their PLM system. TCA implementation should include;

- Consistent use of defined terminology

Definitions of ME(I) transfers and their components at different stages of maturity needs to be in terms used exclusively and consistently to avoid misunderstanding; similar to the use of 'reserved words' in strongly-typed software languages such as ADA.

- Unmatched ME(I) connections and retention with unconnected ME(I) SSBs

A connected set of ME(I) SSBs that lacked commonality in frequency or time domains was not named. A connected set was subsequently termed as a ‘ME(I) transfer connection’. The importance of retaining these along with characterised unconnected SSBs in an implementation of the TCA method was reinforced, so that the implementation could show what effect any changes would have on ME(I) transfer affordance and hence the risk/opportunity of the altered affordance subsequently assessed.

- Overhead quantification

The units of measurement of an ME(I) transfer in terms of bandwidth, duty and capacity differ between M, E and I and also within a transfer of any one type. Hence with this generic implementation headroom is considered as a relative measure; that is as the percentage of the maximum available not used by design. It is realised that the engineer looking to reduce risk from, or exploit the headroom of a particular ME(I) transfer having been shown a headroom percentage that interests them will subsequently use the absolute measure of the particular ME(I) transfer to inform any action they consider necessary.

14.2 Chapter Summary.

This chapter has described a functional demonstrator from the concept demonstrator and the cardinal point requirement specification. It has validated the conceptual TCA analysis method by demonstrating that using the concept demonstrator as a starting point a functional TCA analysis artefact can be made that could form part of a systems supplier’s suite of design tools.

15 Adopting the TCA Method

This chapter describes how the TCA method might be visualised as an engineering process and how it might be applied by an engineering company such as Thales on an engineering project. Section 15.1 expands upon the TCA concept described in Chapter 8. It does this by revisiting the TCA method's correlation to the systems engineering 'Vee' model, and goes on to describe how the TCA method visualised as a transform chain relates SoS capabilities to SoS constituent ME(I) transfer affordances outlined earlier. Section 15.2 describes two methods of applying the TCA method, from which a system supplier can decide a TCA application with the balance and proportion best suited to their needs on a case-by-case basis. Section 15.3 describes a chronological process that offers a foundation for adoption into a company's Product Lifecycle Management (PLM) system.

15.1 TCA Method

The TCA method is a transform cascade, as shown previously in Chapter 8 and in Figure 15.1 below. What follows is an explanation to assist in the implementation of the TCA method as a process (or practice) into an existing PLM system. Although Figure 8.3 in chapter 8 suggests a waterfall process, there will be iteration and feedback between the transformations, as is usual, for example, during the requirements and design engineering activities on the left-hand slope of the 'Vee' model also illustrated in Figure 15.1 below (The V Lifecycle Model © INCOSE UK Ltd, reprinted with permission).

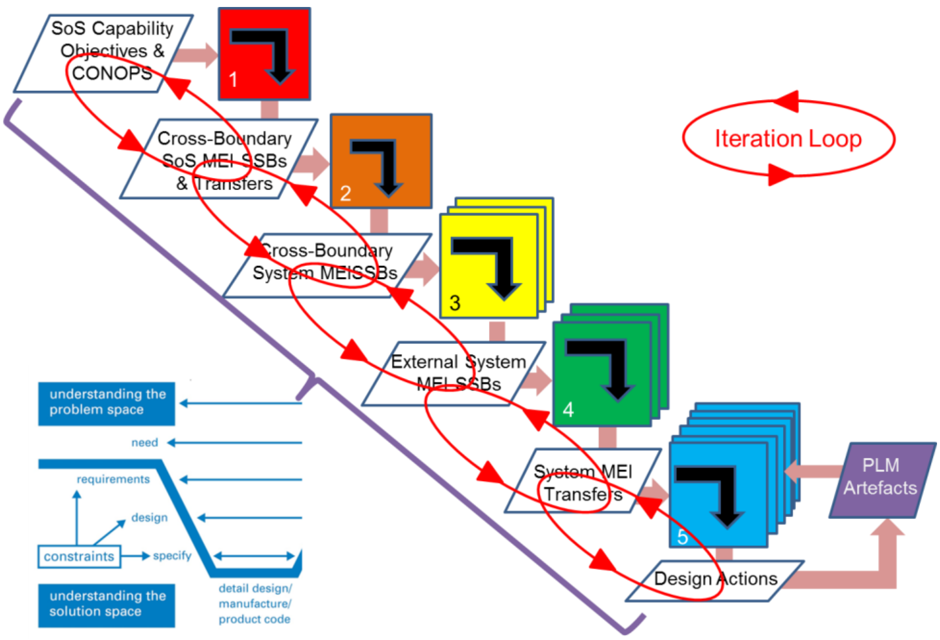


Figure 15.1: Left-side of 'Vee' model and TCA transforms

The method facilitates changes in SoS constituent system capability necessary to address the effects of the occurrence of an unforeseeable change. It does this by identifying candidate improvements or expansions to the ability of a SoS constituent system to transfer Material, Energy and Information. The incorporation of ME(I) transfer affordance enhancements at a 'design opportunity' (for example a mid-life improvement, repair, refurbishment or an obsolescence recovery task) is achieved by additional design actions incorporated into the PLM artefacts containing the design actions required by the design opportunity. The ME(I) transfer enhancements at the lower levels combine to provide additional System and SoS capability at higher levels, just as functionality created at the lower levels to meet specified requirements builds to provide System and SoS capability up the right-hand side of the 'Vee' diagram as shown in Figure 15.2 below (The V Lifecycle Model © INCOSE UK Ltd, reprinted with permission). Again this will be an iterative process, but iteration loops have been omitted for clarity.

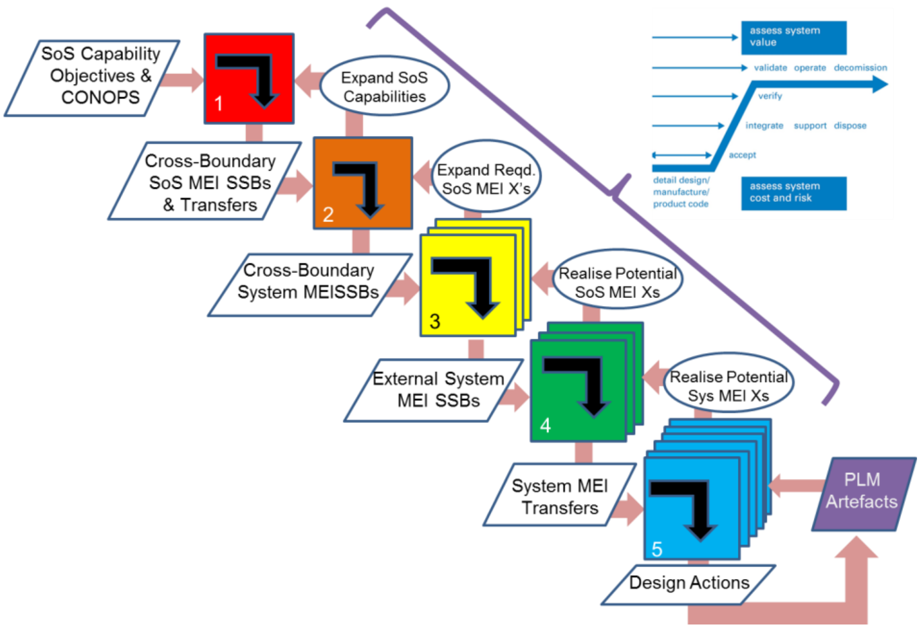


Figure 15.2: Right-side of 'Vee' model and TCA transforms

The human element in a complex socio-technical system decides what ME(I) transfer enhancements are required to maintain the SoS constituent system fit-for-purpose in the event of an unforeseeable change when they experience it. Changes may affect fitness-for-purpose at the SoS constituent system level only, requiring reconfiguration to restore a constituent system to satisfactorily perform system level tasks, or affect the SoS fitness-for-purpose which will drive down to SoS constituent levels, or be a combination of both.

Figure 15.3 below combines both the downward flow shown in Figure 15.1 earlier and the upward flow shown in Figure 15.2 above to illustrate a needed SoS capability augmentation being fulfilled by a ME(I) transfer at the SoS level using the TCA method. Candidate SoS ME(I) transfer enhancements are generated, analysed and decomposed into a sub-set of feasible lower-level

ME(I) transfer enhancements, then design actions implement the preferred ME(I) transfer affordance enhancements, which combine to provide the SoS level ME(I) transfer enhancement enabling the SoS capability augmentation needed. Figure 15.3 shows a more detailed version of that shown earlier in Figure 6.3.

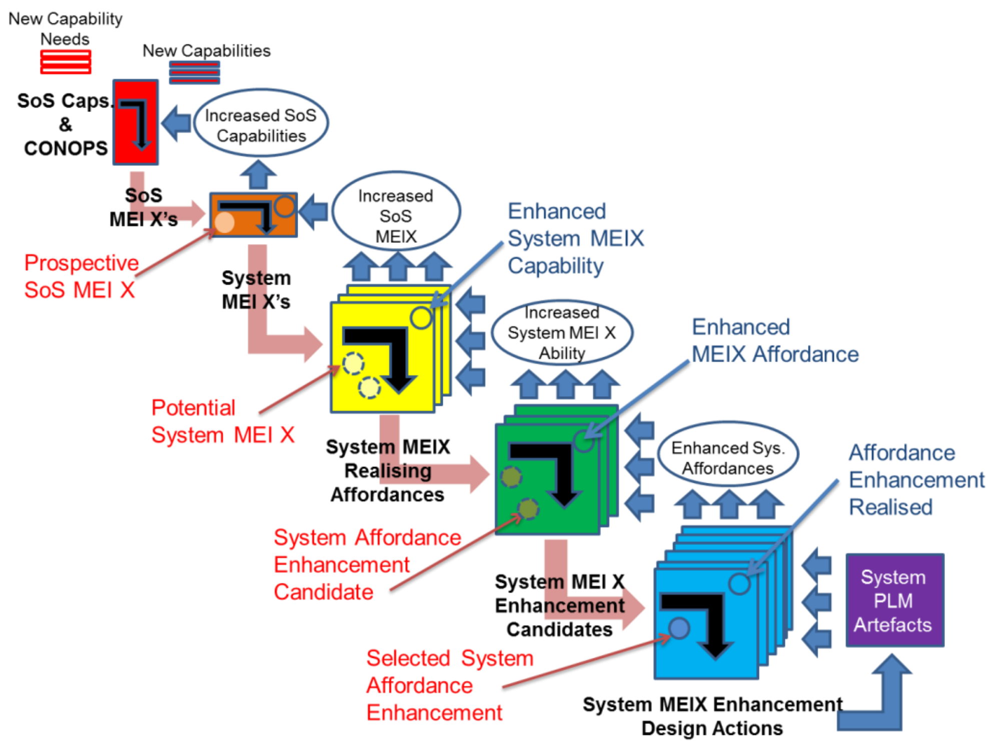


Figure 15.3: TCA Method

With reference to Figure 15.3 above:

Transform 1 (Red Box) relates the SoS capabilities in the context of its operational concepts, to the ME(I) transfers across its boundary that realise the SoS' capabilities.

Transform 2 (Orange Box) in the cascade is a similar transformation to the first transform, but at the SoS constituent system level.

Transform 3 (Yellow Box) groups all the prospective SoS constituent system ME(I) transfers into a set of system affordances for ME(I) transfer and identifies the major subsystems of interest. This better enables examination and assessment of ME(I) transfer enhancement from a subsystem viewpoint.

Transform 4 (Green Box) analyses the realising affordances for ME(I) transfer and determines a sub-set as candidates for enhancement, by assessment at the system / subsystem level by the relevant specialist discipline engineers.

Transform 5 (Blue Box) associates system design actions with the system ME(I) transfer enhancement candidates, guided by the original system design actions and any others that will be concurrent with subsystem ME(I) transfer enhancement.

The purple “System PLM Artefacts” box represents the Project Lifecycle Management documents, drawings, models etc. into which the enhancement design actions are integrated.

The blue arrows correlate to the upward right hand side of the ‘Vee’ model, showing how ME(I) transfer enhancements fulfil the new or improved system capabilities necessary to address the effects of the unforeseeable change occurring.

15.2 TCA Method Application

The TCA method is applied using one of two approaches, analogous to “Open-Loop” and “Closed-Loop” control systems (Levine 2000).

An open-loop system is driven directly by the input demand for output, which is therefore purely a function of the input. A closed-loop system compares the output with the input demand and uses the difference to drive the system, so its output is a function of the error between the input demand and the output. This is illustrated in Figure 15.4 below.

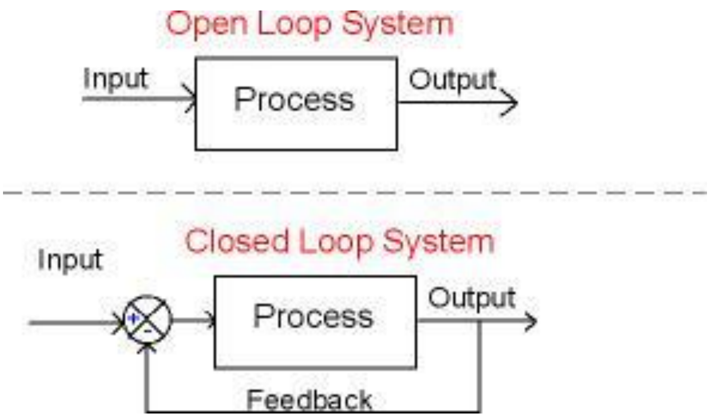


Figure 15.4: Open Loop / Closed Loop

The open-loop approach takes advantage of a design opportunity to provide some technical credit that may be utilised to enhance the SoI’s affordance for ME(I) transfer at some future time. Without a target outcome, enhancements are not focussed to a goal, but provide exploitable enabling facilities. The closed-loop approach is taken where there exists some measure of known agreed purposes and hence the designers have a degree of knowledge and desired outputs, that allow error-driven corrective actions by using the difference between desired fitness-for-purpose and fed-back actual fitness-for-purpose (‘fitness-for-purpose error’) to drive actions correcting fitness-for-purpose deficiencies.

15.2.1 Time and Frequency Domain Responses

This section is a simple explanation of time and frequency domains and corresponding measurements of a dynamic system in these domains for those readers who are unfamiliar with them. The time domain and the frequency domain are respectively temporal and spectral viewpoints of a dynamic system. They are complementary and provide visualisations of the behaviour of a dynamic engineering system of interest. The time response is a measurement of how long it takes a dynamic system to do something as a function of time. A mechanical example could be how many seconds it takes a cranes jib to slew from on position through ninety degrees to another position or an electrical example might be how long a high-efficiency light bulb takes to achieve its rated luminosity. The frequency response is a measurement of how fast a dynamic system is as a function of frequency, for example how many times per minute can a crane jib slew to ninety degrees and back again, or what frequency of light (perceived as colour) a bulb emits. As electrical systems tend not to involve the movement of mass, they are able to respond more quickly than dynamic mechanical systems; for example an audio amplifiers output voltage can slew between limits and oscillate at frequencies much higher than a loudspeakers cone can replicate.

15.2.2 Open-Loop

This approach will examine candidate SoS constituents to firstly identify their 'intended', 'inherent' and 'independent' SSBs, and secondly to determine each SSB's characteristics. From these, frequency domain analysis will identify any prospective affordances formed by them. Some of these prospective affordances will be promoted to potential affordances by time domain analysis. The assembly of ME(I) SSBs into prospective affordances, the recognition of some as potential affordances, and the subsequent identification of these as either risks of undesirable ME(I) transfer or implementations into the SoI at some level will be continually assessed for feasibility, unintended consequences and RoI in terms of increased SoS fitness-for-purpose likelihood. Taken to the extreme this approach would allow any useful connection of matter, energy and information sources, sinks and bearers.

15.2.3 Closed-Loop

This approach uses what degree of agreed purpose is known to examine the perceived fitness-for-purpose shortfalls of an existing SoS, and then decompose these into ME(I) transfer deficiencies of its constituents. Each SoS constituent's 'intended', prospective and potential affordances for ME(I) transfer will be examined and the conversion of the potential affordances to 'intended' will be assessed for feasibility and RoI in terms of fulfilling the perceived SoS fitness-for-purpose resilience shortfalls. This approach will only create affordances for ME(I) transfer that directly contribute to correcting a known fitness-for-purpose shortfall.

15.3 TCA Method in Practice

The TCA method is an instantiation of the TCA technique for use with industrial PLM systems. CHORUS2 is the Thales reference system that provides a common and efficient way of working across the globe. A common approach enables work to be shared across distributed teams, and then seamlessly brought together into complex solutions. By embracing best practice, including the requirements of the Capability Maturity Model Integrated (CMMI), CHORUS2 contributes to risk reduction and achievement of cost and schedule performance (Thales 2009). The embedded TCA process will accommodate both open and closed loop application, integrate with CHORUS2 processes and utilise PLM project documentation familiar to Thales engineering staff. It is envisaged that there will be overlaps in method and process development from iterative concurrent development.

The five transformation functions in the method could be realised by one of several options, such as operational analysis models, SySML models, Functional models (e.g. Context diagram, function-flow diagram, Flow Dictionary, Functional specs), Behavioural Models etc. dependant on the Line-of-Development (LoD) and the particular case being examined. Ideally these transformation models will be abstractions of the requirements, design and development models, documents and simulations originally created under the company lifecycle management processes to reduce the opportunity for error and maintain fidelity with the project / SoI. The abstracted model may essentially be a type of functional model: Functional Flow Diagrams, Flow Dictionaries and Functional specifications.

In systems oriented engineering companies, the product design process is often the systems engineering process, one common representation of which is the systems engineering 'Vee' diagram shown in Figure 8.1 earlier.

The artefacts produced at each stage of this process by different company's implementations are functionally similar, but tailored to their individual needs and constraints.

The following subsections illustrate how the TCA method would be applied by engineering staff in an industrial environment with the aid of function-flow diagrams. As this process is essentially repeated for each transform, only the top two (SoS and System) are illustrated here.

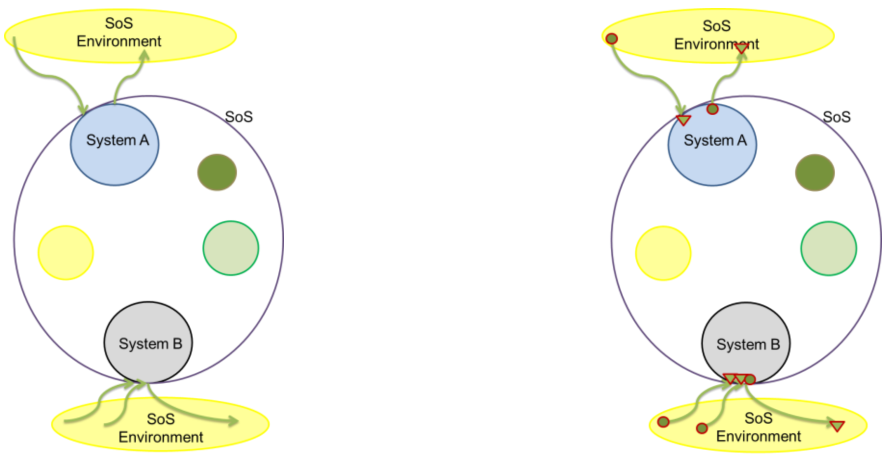
15.3.1 Transform 1: SoS Capabilities and ME(I) transfers

Transform 1 is achieved by determination of the ME(I) transfers that occur when the SoS uses a capability to fulfil a need described in concept documents. There are typically three related concept documents that capture a concept as it is developed. The content of these conceptual documents varies around common themes described here as:

- Concept of Employment (CONEMP). This document describes how a capability (not physically envisaged in terms of physical entities, such as equipment) will be employed in scenarios and on operations.
- Concept of Use (CONUSE). This document describes how a physical entity such as a piece of equipment is to be used in a range of operations and scenarios.
- Concept of Operations (CONOPS). This document describes the operational characteristics of a physical entity such as a piece of equipment.

The concept descriptions, requirements documents and design artefacts of the individual SoS constituents contained in the respective design authorities PLM system are examined to determine the intentional ('designed-for') ME(I) transfers that cross the SoS boundary when the capabilities fulfilling the needs specified by the CONEMP / CONUSE / CONOPS are exercised.

See Figure 15.5 below. The 'Intended' ME(I) transfers to and from the SoS are firstly identified. This is illustrated by the left-hand diagram in Figure 15.5, which shows a bounded SoS containing heterogeneous constituent systems. The right-hand diagram illustrates the determination of the design of the 'intended' ME(I) transfers SSB components. Two of the SoS constituent systems make 'intended' transfers of ME(I) across the SoS boundary. The right-hand diagram has red-outlined symbols that represent the 'intended' SSBs implementing the 'intended' ME(I) transfers.

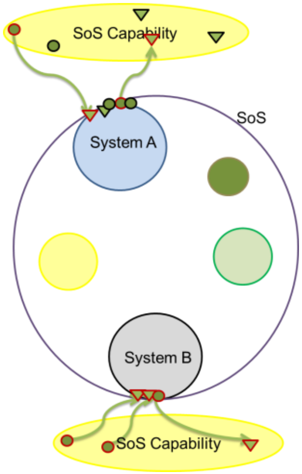


Determine 'intended' SoS ME(I) transfers Identify SSB Components of ME(I) transfers

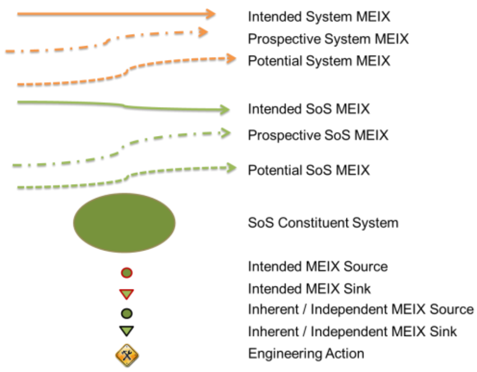
Figure 15.5: TCA Process Transform 1 operations

See Figure 15.6 below. The left-hand diagram illustrates the 'Inherent' ME(I) SSBs that are intrinsic with the design of the 'intended' ME(I) transfers that have been implemented are identified, and any 'Independent' ME(I) SSBs outside the SoS boundary that, although independent of the SoS, are thought to have an effect on the SoS that is considered not insignificant. Both 'inherent' and 'independent' SSBs are indicated by black outlined symbols.

A diagram key for all the bubble diagrams in this section is the right-hand diagram of Figure 15.6.



Identify the Inherent & ‘independent’ ME(I) SSBs

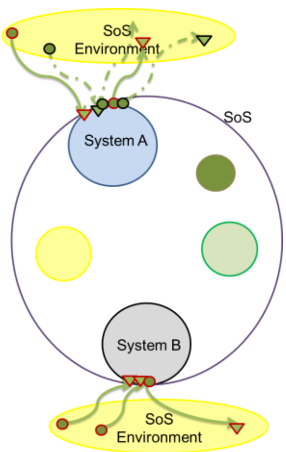


Key to Figures

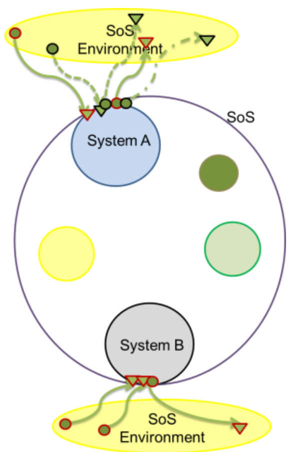
Figure 15.6: TCA Process Transform 1 operations (cont.)

See Figure 15.7 below. The left-hand diagram shows the ‘Intended’, ‘Inherent’ and ‘Independent’ SSBs with common frequency-domain characteristics grouped into prospective ME(I) transfers. Prospective ME(I) transfers are formed from SSBs that are compatible in the frequency domain and might either already form unintended ME(I) transfers or be able to be engineered to form ME(I) transfers without breaking physical or legislative laws, but may require significant effort to engineer them into intentional ME(I) transfers within the constraints of the SoS.

The right-hand diagram illustrates the result of a subsequent time-domain and sensitivity analysis of the prospective ME(I) transfers to inform the promotion of some them to potential ME(I) transfers. These potential ME(I) transfers are assessed by engineering staff as either potentially troublesome or as opportunities to enhance ME(I) transfer affordance and hence produce a set of ‘intended’ (does transfer ME(I)), prospective (has the ability to transfer ME(I)) and potential (has both the ability and opportunity to transfer ME(I)) SoS capability level ME(I) transfers.



Identify SSBs forming prospective ME(I) transfers



Identify SSB potential ME(I) transfers

Figure 15.7: TCA Process Transform 1 operations (cont.)

See Figure 15.8 below. The red ovals on the left-had side diagram illustrates the examination of the potential SSBs forming potential ME(I) transfers to determine the risk and opportunity associated with them by asking (i) ‘Are any of these likely to cause problems?’ (Crosstalk, Unexpected behaviour, Undesirable emergent properties etc.) and (ii) ‘Can any of these be exploited?’ (Enhanced ME(I) transfer, Enhanced functionality, Technical credit etc.). The right-hand side diagram illustrates with tool symbols engineering activities reducing the likelihood of problems caused by two potential ME(I) transfers making unintended ME(I) transfers to an acceptable level.

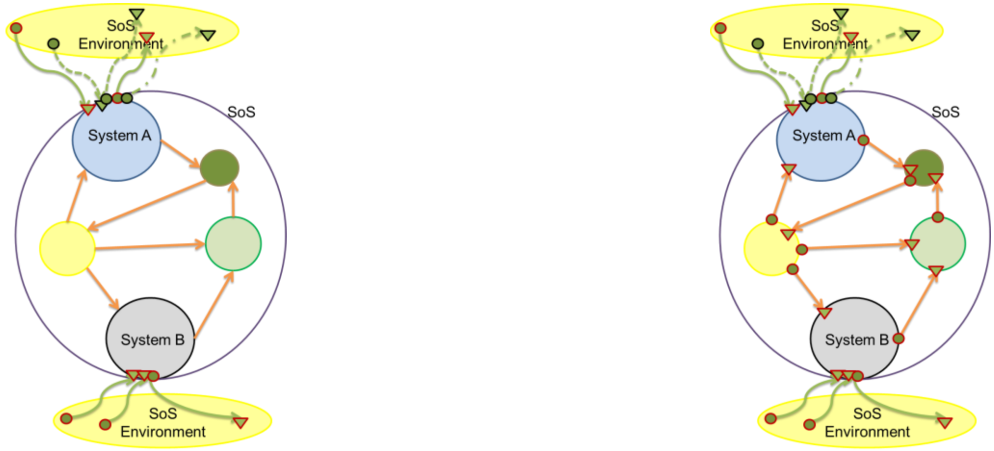
It is worthwhile noting here that in design definitions that have not had the benefit of the TCA method, ‘Inherent’ & ‘Independent’ ME(I) SSBs almost certainly won’t appear, therefore these SSBs and any formed ME(I) transfers will not be controlled or managed. In addition to the risk or opportunity questions in the above paragraph, a third, perhaps knottier question arises: are they being utilised by some stakeholders such as users and maintainers unbeknown to the system design authorities?

Decide if Potential ME(I) transfers are opportunities or risks… and Engineer them appropriately!

Figure 15.8: TCA Process Transform 1 operations (cont.)

15.3.2 Transform 2: SoS Constituent system ME(I) transfers

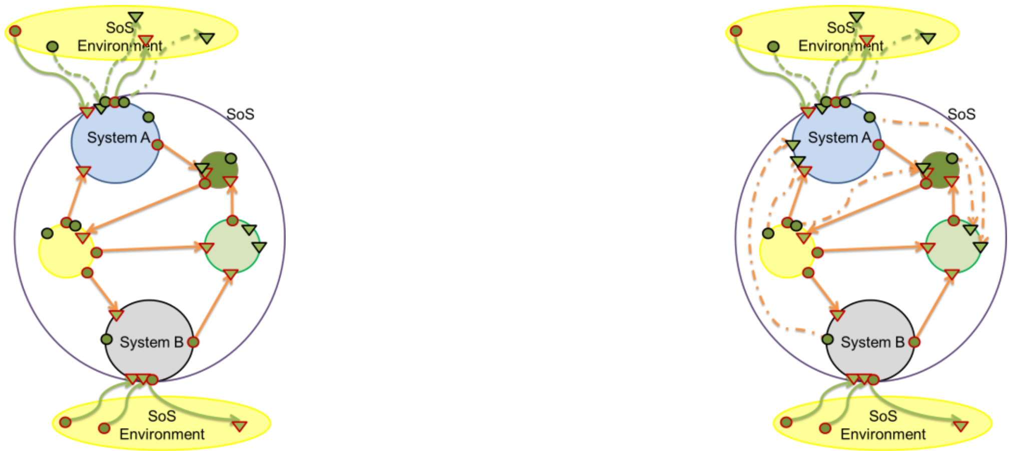
The process for SoS constituent systems is similar to that used at the SoS level, so the following description of the system level process is less detailed. See Figure 15.9 below. Similar to Transform 1 at the SoS level, Transform 2 produces a ME(I) meta-model but at the SoS constituent (system) level. From this the user of the TCA method can make an informed decision as to what action to take to engineer potential ME(I) transfers to reduce undesirable effects to an acceptable level or exploit them to the preferred degree. The left-hand diagram of Figure 15.9 illustrates the identification of the SoS constituent systems ‘intended’ ME(I) transfers and the right-hand side diagram illustrates the determination of their SSB components.



Determine ‘intended’ System ME(I) transfers Identify System ME(I) transfer SSB Components

Figure 15.9: TCA Process Transform 2 operations

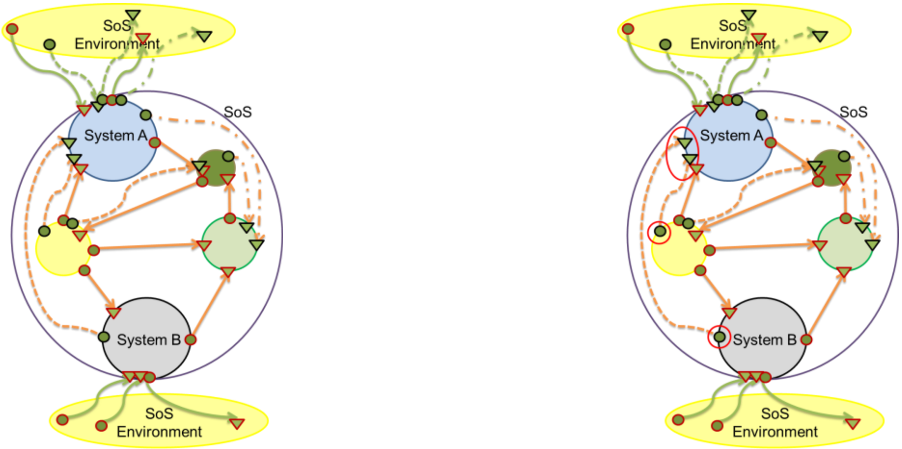
See Figure 15.10 below. The left-hand side diagram illustrates the identification of the inherent and ‘independent’ SSBs and the right-hand side diagram illustrates the determination of the prospective ME(I) transfers formed by them.



Identify Inherent and ‘independent’ system SSBs Determine Prospective System ME(I) transfers

Figure 15.10: TCA Process Transform 2 operations (cont.)

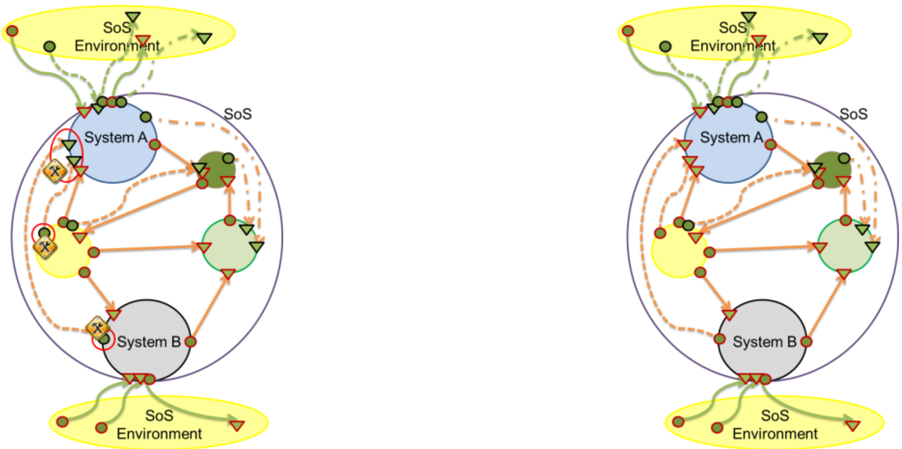
See Figure 15.11 below. The left-hand diagram illustrates the analysis of the Prospective ME(I) transfers SSBs, and the promotion of those with the ability and opportunity to transfer ME(I) to ‘Potential’ ME(I) transfers. Three prospective ME(I) transfers were promoted to Potential (dot/dashed bearers to dashed bearers). The right-hand diagram indicates with red ovals the Potential ME(I) transfer SSBs considered to require engineering action to reduce risk and/or exploit an opportunity. In this diagram one Potential ME(I) transfer was deemed not to require further action.



Determine Potential System ME(I) transfers Decide if Potential's are opportunities or problematic

Figure 15.11: TCA Process Transform 2 operations (cont.)

See Figure 15.12 below. The left-hand diagram illustrates the engineering of the two prospective ME(I) transfers SSBs to either reduce the risk of those thought might be problematic to an acceptable level, or exploit those thought to be an opportunity to enhance the systems affordance for ME(I) transfer to the preferred degree. The right hand diagram illustrates a case where the SSBs of two potential ME(I) transfers (highlighted by red ovals) were engineered to provide a ME(I) transfer enhancements able to be activated whilst the systems are operational (whilst fulfilling their own commitments and contributing to the fulfilment of those of the SoS) when required at a future time. The disabled state is shown by the dotted (indicating Potential) lines connecting the sources and sinks. Note this action also changed the SSBs from 'Potential' (black outlined SSB symbols) to 'Intended' (red outlined SSB symbols).

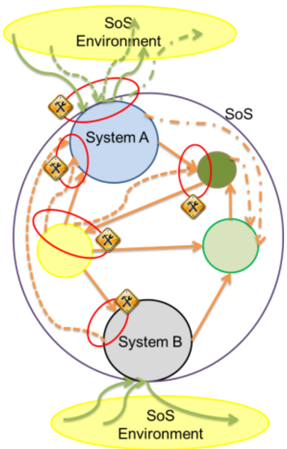


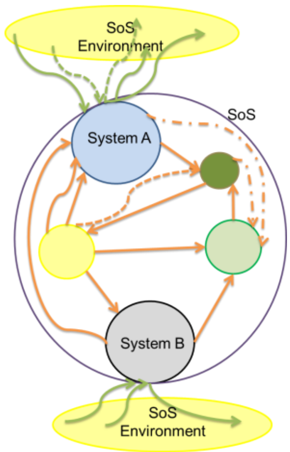
Engineer potential System ME(I) transfers… into ME(I) transfer enhancements (disabled)

Figure 15.12: TCA Process Transform 2 operations (cont.)

15.3.3 Enhancing ME(I) Transfer

See diagram 15.13 below. The left-hand diagram illustrates the action that enables (highlighted by red ovals) a ME(I) transfer enhancement whilst the systems are operational (whilst fulfilling their own commitments and contributing to the fulfilment of those of the SoS) to make the ME(I) transfers necessary for the systems to address an unforeseen internal, external or duty change. Note this action changed the two ME(I) transfers from ‘Potential’(dotted lines) to ‘Intended’ (solid lines), and that the third revealed Potential ME(I) transfer remains dotted as a record for possible future use.





Change necessitates enhancement enabling transfers

Enhancements enabled as ‘intended’ ME(I)

Figure 15.13: TCA Process Transform 2 operations (cont.)

15.4 A Candidate Process for TCA Method

Part A describes how the TCA analysis method may be applied to system of system constituents using case studies of practical examples. This section offers a process to realise the TCA method.

It is acknowledged that the TCA process will require some additional resource, minor changes to the existing design process and possibly digitisation of parts of the technical data pack for legacy products. The suggested process below to create the complete ME(I) SSB viewpoint of a SoI ‘meta-model’ is expected to be tailored by individual systems suppliers to best suit their own PLM systems in order to minimise the impact of adoption and maximise their return-on-investment.

15.4.1 Intended ME(I) Transfers Process

- Capture ‘intended’ source and sink nodes.
- Capture ‘intended’ bearers and connections.
- Map-out an ‘intended’ ME(I) transfer kinematic (unquantified) baseline.
- Record ‘intended’ source transmission capacities and utilisation profiles as a spectrum.
- From ‘intended’ source duties determine constant and temporary unutilised transmission capacity.

- Record ‘intended’ sink admittance capacities and utilisation profiles as a spectrum.
- From ‘intended’ sink duties determine constant and temporary unutilised reception capacity.
- Record ‘intended’ bearer transport capacities and utilisation profiles as a spectrum.
- From ‘intended’ bearer duties determine constant and temporary unutilised transport capacity.
- Collate ‘intended’ source, sink and connecting bearer spectra and duty to analyse and assess the ability, opportunity and likelihood of unintended transmission, transport and reception affordance that could be undesirable or be potentially exploitable ME(I)X enhancement.
  Notes: This process creates an initial ‘kinematic’ model, subsequently populates it with ‘intended’ ME(I) transfer loadings to identify unintended interaction and potential capacity for enhancement.

This part of the process creates an initial designed-for ‘kinematic’ model, subsequently populates it with ‘intended’ ME(I) transfer characterisations (Frequency-domain analysis) and loadings (time-domain analysis) to identify ‘headroom’ that can be a mechanism for unintended interaction and/or a capacity for potential ME(I) transfer affordance enhancement.

15.4.2 Inherent ME(I) transfers Process

This is essentially a repeat of the ‘Inherent’ process on inherent transfers similarly identified by engineers familiar with the SoI on a case-by-case basis.

- Examine the ‘intended’ ME(I) transfers to identify inherent source and sink nodes.
- Visualise inherent bearers.
- Visualise inherent source transmission activity and capacity profiles as a spectrum.
- From inherent source duties determine constant and temporary unutilised transmission capacity.
- Visualise inherent sink admittance activity and capacity profiles as a spectrum.
- From inherent sink duties determine constant and temporary unutilised reception capacity.
- Visualise inherent bearer transport utilisation and capacity profiles as a spectrum.
- From inherent bearer duties determine constant and temporary unutilised transport capacity.
- Create a combined ‘intended’ & inherent ME(I) transfer map.

- Collate 'intended' source, sink and connecting bearer spectra and duty to analyse and assess the likelihood of undesirable unintended interaction and potential exploitation for ME(I)X enhancement.

*Notes: Bearers may be found that have less than two terminations. Bearers may not always be transporting.

This process creates a characterised ME(I) transfer model incorporating both 'intended' and 'inherent' ME(I) transfers and interchanges between the two types. Both 'Intended' and 'Inherent' source and sinks can be connected by any type of bearer.

This part of the process extends the model, by repeating the detection and identification process used for the 'intended' ME(I) transfers on the ME(I) SSBs that are inherent with the implementations of the 'intended' ME(I) transfers to reveal further ME(I) transfer risks and enhancement opportunities.

15.4.3 'Independent' ME(I) transfers Process

This is essentially a repeat of the 'Inherent' process on inherent transfers, similarly identified by engineers familiar with the SoI on a case-by-case basis.

- Examine the 'intended' ME(I) transfers to envision 'independent' source and sink nodes.
- Visualise 'independent' bearers.
- Envision 'independent' source transmission activity and capacity profiles as a spectrum.
- From 'independent' source duties determine constant and temporary unutilised transmission capacity.
- Envision 'independent' sink admittance activity and capacity profiles as a spectrum.
- From 'independent' sink duties determine constant and temporary unutilised reception capacity
- Envision 'independent' bearer transport activity and capacity profiles as a spectrum.
- From 'independent' bearer duties determine constant and temporary unutilised transport capacity.
- Create a combined 'intended', 'inherent' and 'independent' ME(I) Transfer map.
- Collate 'intended' source, sink and connecting bearer spectra and duty to analyse and assess the likelihood of undesirable unintended interaction and potential exploitation for ME(I)X enhancement.

*Notes: Bearers may be found that have less than two terminations. Bearers may not always be transporting ME(I).

This process creates a characterised ME(I) transfer model incorporating 'intended', 'inherent' and 'independent' ME(I) transfers and interchanges between the three types. Any type of source and sink can be connected by any type of bearer.

This part of the process further extends the model, accounting for 'independent' ME(I) SSBs as was done above for Inherent SSBs.

15.5 Chapter Summary.

This chapter has shown how the TCA technique might be exploited by an industrial systems integrator/manufacturer. It has described methods of application, a TCA analysis method, shown a stepwise application of the method to a SoS using simple function-flow diagrams and suggested a basic implementing process as text.

16 TCA Method Implementation Considerations and Exploitation Guide

This chapter provides guidance for systems suppliers adopting the TCA method into their engineering processes, describes the fundamental structure of lifecycle management stages and aspects of TCA analysis/PLM integration. The chapter ends with points for consideration by an industrial adopter of the TCA technique and its implementation as an automated part of an existing PLM system in an industrial environment.

16.1 TCA Process Considerations

In the course of the process, bearers may be found that do not connect a source to a sink. Bearers may not always be transporting. The whole process creates a characterised ME(I) transfer meta-model incorporating 'intended', 'inherent' and 'independent' ME(I) SSBs ('Connected' AND 'Floating') and ME(I) transfers between connected SSBs of any of the three types.

The process of identification and characterisation of the ME(I) SSBs needs to have a high degree of automation, ideally forming an extension of the industrial partners PLM system / Integrated Computer Technology (ICT) design tool suite, utilising design documentation and artefacts that are produced as part of the normal design and development process to maintain fidelity with the physical SoI and not have a significant impact on the workload of project staff.

The implementation of ME(I) SSB enhancements are scalable, and are implemented by the project to the degree that offers the preferred cost/benefit to them on a case-by-case basis. The implementations range from capture as a design note, Printed Circuit Board (PCB) layout, populated board but out-of-circuit, inhibited software modules, etc.

These enhancements are implemented at 'design opportunities' throughout the project lifecycle, not just early in the lifecycle at the initial design phase. Design opportunities are at times that are convenient and economically advantageous, for example incorporation of a risk mitigation or ME(I) transfer enhancement would be piggy-backed onto events such as workshop repair, refurbishment, major overhaul, service intervals, mid-life improvement, obsolescence recovery, upgrades etc. so that the logistic and overhead costs are not borne by the ME(I) SSB enhancement activity.

It is enlightening to think of ME(I) transfers are vectors: they are directional, and the direction of an 'intended' ME(I) 'flow' may oppose that of the inherent ME(I) transfer that the implementation of the 'intended' ME(I) transfer affordance creates. For example, a drain that allows egress of material may also act as a portal for the ingress of energy, for example where radio frequency interference is concerned.

Chapters 9, 10 and 12 provide case studies of practical examples of how the TCA process may be applied to system of system constituents.

The TCA method is able to bring benefit to the suppliers and users of systems at various junctures throughout the SoI's lifecycle. However as has been said earlier, TCA brings a novel viewpoint and new way of *thinking* to capability and systems suppliers that effectively and efficiently benefits both the "Created" and "Creating" (Hitchins, 2003) systems of systems supplier's enterprises. The process is not a 'magic wand' that if followed will guarantee flawless system integration: TCA addresses largely non-deterministic problems that confront systems engineers, who rarely have the comfort of certainty in the efficacy of the solutions they provide. The TCA process is not a substitute for wisdom and expertise. The potential exploiters need to decide upon the degree of intervention to suit the needs and constraints of their particular application to satisfy themselves that their return on investment, in terms of reputation and revenue, are worthwhile.

16.2 Product Lifecycle Management (PLM)

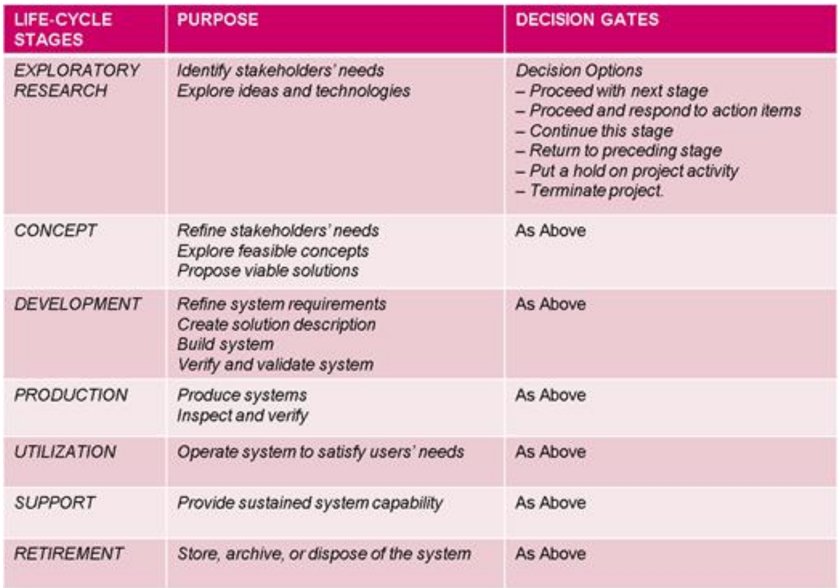
The TCA method will be implemented as part of the system provider's PLM system. This section provides an overview of PLM and describes the relationship between PLM and systems, lifecycle, and capability engineering.

16.2.1 System Lifecycle

Many systems engineering standards, such as IEEE 1220, EIA 632, CMMI, ISO 15288, and NASA incorporate lifecycle methodology. There are differences between these standards, some of which will suit one enterprise more than another, but essentially all are variations around a common theme of accepted good practice. Typical lifecycle stages are:

- Business Winning
- Design and Development
- Manufacturing
- Support
- Disposal

Figure 16.1 below taken from INCOSE Systems engineering handbook (Table 3-1) shows generic life-cycle stages, their purposes, and decision gate options. Stages begin at exploratory research, and flow through to retirement. It can be seen that decision options vary from "proceed" to "Abandon the Project!"



LIFE-CYCLE STAGES	PURPOSE	DECISION GATES
EXPLORATORY RESEARCH	*Identify stakeholders' needs* *Explore ideas and technologies*	*Decision Options* *– Proceed with next stage* *– Proceed and respond to action items* *– Continue this stage* *– Return to preceding stage* *– Put a hold on project activity* *– Terminate project.*
CONCEPT	*Refine stakeholders' needs* *Explore feasible concepts* *Propose viable solutions*	As Above
DEVELOPMENT	*Refine system requirements* *Create solution description* *Build system* *Verify and validate system*	As Above
PRODUCTION	*Produce systems* *Inspect and verify*	As Above
UTILIZATION	*Operate system to satisfy users' needs*	As Above
SUPPORT	*Provide sustained system capability*	As Above
RETIREMENT	*Store, archive, or dispose of the system*	As Above

Figure 16.1: INCOSE lifecycle stages, their purpose and decision gates (INCOSE 2015)

Table 3-1 from the INCOSE Systems engineering handbook (INCOSE 2015) shown in Figure 16.1 below compares the generic life-cycle stages to other life-cycle viewpoints.

Figure 16.2 below illustrates the similarities between the standards: for example it can be seen that the Concept Stage is aligned with the commercial project's Study Period and with the Pre-systems Acquisition and the Project Planning Period in the U.S. Departments of Defence and Energy, respectively.

Typical decision gates are presented in the bottom line.

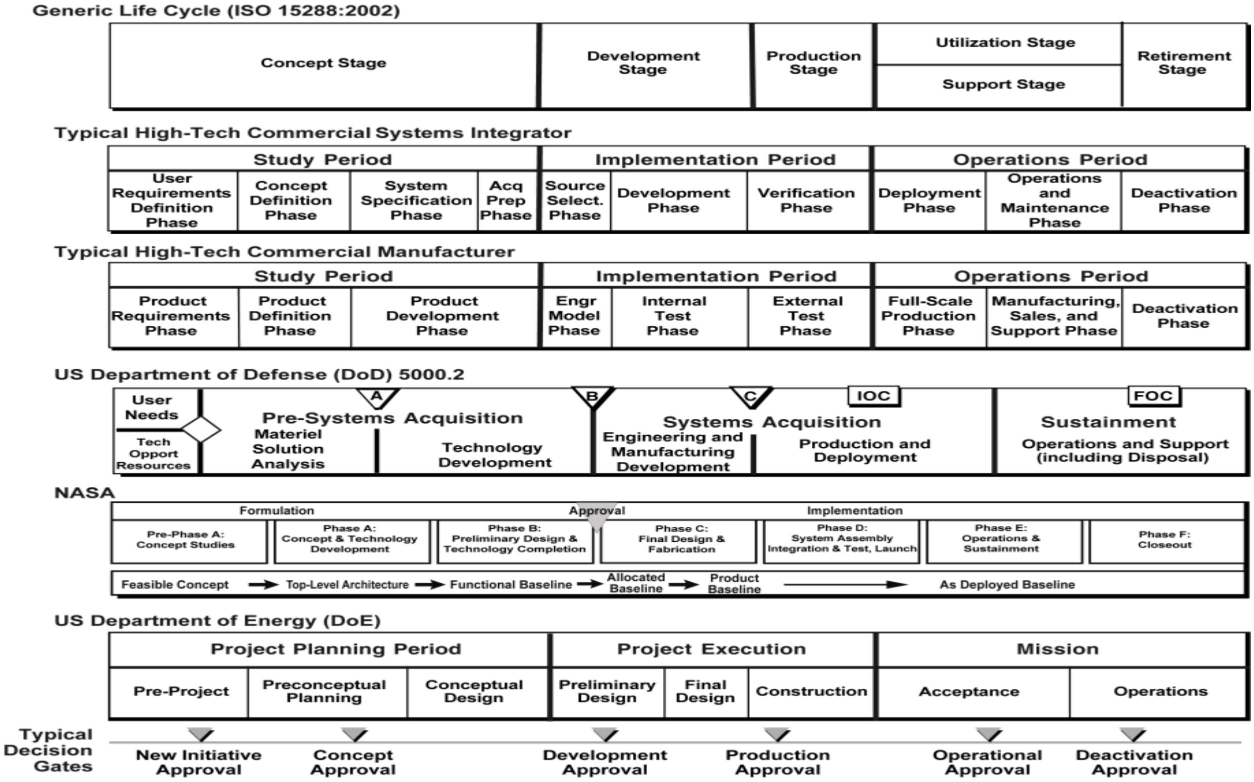


Figure 16.2: Generic lifecycle stages, tailored forms and decision gates (INCOSE 2015)

16.3 Aspects of TCA Integration into a PLM System

16.3.1 'Big Data'

As previously stated, a high degree of automation is required for any non-trivial application due to the large amount of data to be processed. To illustrate this, Figure 16.3 below shows an EXCEL spreadsheet (See Appendix A11 for a larger image) containing 91 prospective ME(I) transfers formed by a frequency domain analysis of the SSBs of the simple illustrative case study.

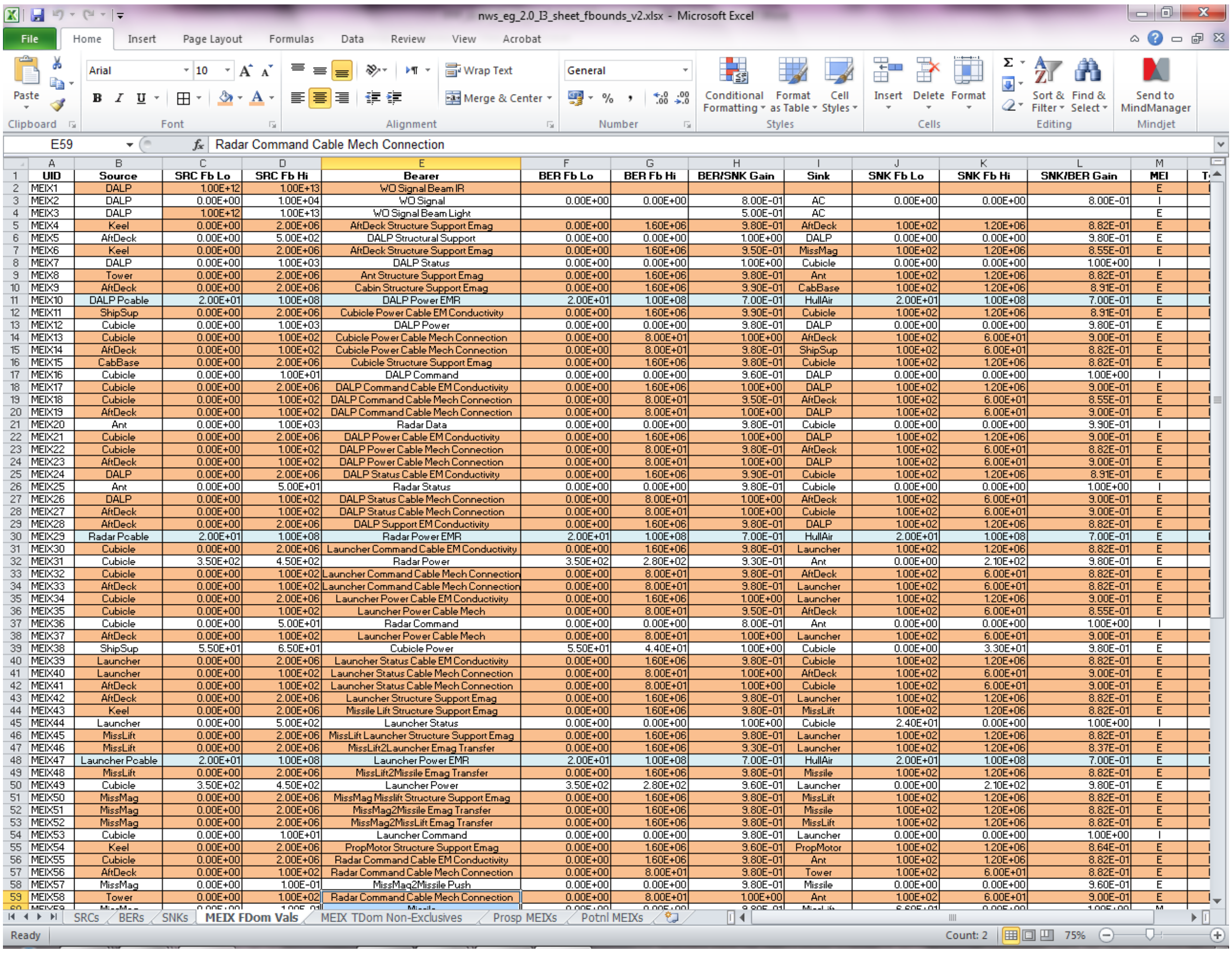


Figure 16.3: Illustrative EXCEL spreadsheet of carrier vessel case study.

The TCA extension to an adopting PLM system would need to generate, hold and manipulate large data arrays. It is envisaged that these data arrays would be 'living documents' updated with changes to the SoI and be used to show the impact of proposed changes on the unintended ME(I) transfers to inform the design decisions. The PLM system would need to populate the TCA arrays with data such as SSB frequency bounds, efficiencies, duty cycles and active periods from the design artefacts and component data sheets held in the PLM system.

16.3.2 Data Manipulation

In contrast with the data handling task, the operations on the TCA data set are relatively straight forward. The sequence of operations can be arranged to suit the characteristics of the embodying PLM system. A typical sequence might be:

- Identify SSB components of 'intended' ME(I) transfers.
- Identify 'Inherent' and 'Independent' SSBs.

- Characterise SSBs in the frequency domain to determine operational bandwidth (½ power points of each Source, Sink and Bearer).
- Form spectrally compatible source/sink/bearer combinations with the ability for non-trivial* ME(I) transfer (Prospective ME(I) transfers).
- Examine SSBs to determine and discard mutually exclusive (not allowed) combinations.
- Examine SSBs in the time domain to determine contemporaneous active status.
- Output a list of ME(I) SSB combinations (Potential ME(I) transfers that have been promoted from Prospective ME(I) transfers) i.e. those that have the ability and opportunity to make non-trivial transfers of ME(I) for examination by engineering staff and sentencing as either risks to be managed, opportunities to enhance the SoIs affordance for ME(I) transfer or neither a risk nor an opportunity.

16.3.3 Integration Summary

Integration with PLM systems. It is recognised that PLM systems are seldom a true integrated modelling environment where tracability is maintained from stakeholder needs to LRU throughout the lifecycle, and hence TCA integration would not be an insignificant task. However an TCA extension would capture in digital form information that otherwise would at best probably be held only tacitly and patchily distributed. A parallel to the potential benefits to a system supplier might be drawn by considering the advantages of the more complete view of a SoI that was gained thirty-plus years ago with the move of engineering data from paper based technical data packs to CAD/CAM systems.

As said earlier the success of an exploiter of this work will be predicated on good knowledge management: Capture is one aspect; easy availability for use by others in their situation is another.

The degree of TCA adoption by the creating PLM system can be scaled to suit individual exploiters, which is best decided upon on a case-by-case basis similar to the choice of level of ME(I) transfer affordance enhancement of created products.

Integration with systems/SoS being used. It is considered that requiring that the personell using and maintaining SoS constituent systems to have the knowledge and expertise to be able to reconfigure systems by exploiting TCA identified ME(I) transfer affordance enhancements without help is unfeasible. This is because when the personell working with the systems requiring reonfiguration will most likely need to reconfigure it, they will be in a stressful time-constrained situation in an arduous environment not conducive to finding a preferred solution from many options, and and implementing it. The most one could reasonably expect is that staff could follow instructions supported by knowledgeable guidance. Coupled with the complexity of sub-systems, the specialist knowledge required, the significant number of sub-systems on a sizeable SoS constituent system such as a ship or even a modern land vehicle, it is suggested a reasonable solution would be to ensure that staff have access to local information at a level comprehensible by them, and also to remote Original Equipment Manufacturer (OEM) level expertise as is currently implemented to support complex platforms whilst on operations.

A suggested knowledge management solution to in-service support for TCA is a layered approach, similar to the first, second and third line repair and maintenance regimes commonly established and integrating with the current support packages provided to the Royal Electrical and Mechanical Engineers (REME) of the British Army and other engineering officers . This may consist of inbuilt facilities (for example, similar to BITE) at first line, on-system (a product support and reference source on the system) at second line, for example an expert system, and remote access to subject matter experts at third line. The emphasis and content at each line would be commensurate with the facilities and resources currently within the existing support solution.

16.4 Considerations for the TCA Exploiter

16.4.1 TCA Process Techniques

The identification of prospective ME(I) transfers could be considered as a divergent thought process, in contrast to the more conventional convergent oriented activities that system and sub-system designers use to create a design response to a defined requirement. To assist designers, a ‘spectral sweep’ technique is offered. This asks the designer (most likely using an automated process implemented as part of TCA integration into their PLM system) to identify the ‘intended’ ME(I) transfers that enable the system capability that responds to the system requirement and the ‘Inherent’ and ‘Independent’ SSBs, then examine the interaction between each source/sink as a ‘seismic to light’ spectral analysis: that is from very low (below 10^0 Hz), to very high (up to 10^{25} Hz.) frequencies to show all interaction across the band. This is a process that identifies what of types of Material, Energy and Information that are potentially and actually transferred. For example, the previously related example of a steel wire armoured DC power cable that electrically connects two components will also conduct heat through its steel armour at the low-frequency end of the spectrum, and mechanical force, magnetic flux and AC currents at the higher frequency end of the spectrum, so as well as connecting the two components with DC electrical power, it also conducts AC and connects them thermally, magnetically and mechanically.

The TCA process will also contribute to the conventional design process, by identifying undesirable interactions, and what implicit interaction gains and losses are inherent with design decisions. For example, a submarine periscope used as an optical connection to conduct an image of the surface scene to the vessel’s command centre requires substantial mechanical connections to do so, and hence has a significant effect on the design of the whole vessel. A photonic mast uses an electrical connection with insignificant mechanical coupling, and allows the vessel designers a hugely increased solution space for the control room size, location and design.

One affordance for transfer may be used for several transfers: for example one information bearer such as a VHF radio may be used to conduct both voice and data to inform the down selection process as shown in transform 4 of Figure 8.3 in section 8.2.

Multiple transfers of a single affordance may have different response times: for example the transfers of energy and information by a signal lamp by a modulated signal lamp. Energy in the form of light is transmitted faster than the data carried by the modulation of it.

A ME(I) transfer affordance may transfer a combination of ME(I): the movement of material may also move information, for example instructions written on the packaging of material.

Assessment of ME(I) transfer enhancements will decide on the degree of implementation: i.e. the level of provision made for ME(I) transfer enhancement can be tailored on a case-by-case basis. In equipment hardware implementation for example, enhancement provision may range from design only, functional models, virtual prototypes, board layout, fitted components to live spares.

It is envisaged that the analysis processes used to populate the matrices will identify opportunities to realise affordances at design opportunities such as scheduled major maintenance intervals, obsolescence resolutions, Mid-Life Improvement (MLI) programmes and Improvement-Through-Spares programmes.

16.4.2 TCA Process Salient Points

The level of provision made for ME(I) transfer enhancement can be tailored to the needs of the business and the constraints of the project. It is neither an 'all or nothing' nor a 'one size fits all' enhancement to processes and products.

'Inherent' and 'Independent' ME(I) transfers almost certainly will not appear in the design definition, they will not be controlled or managed, but they may well be problematic: or being utilised by some stakeholders such as users and maintainers and thus cause problems when they change or are subconsciously withdrawn from the product due to through-life development and modifications.

ME(I) transfer enhancement requiring additional hardware, software etc. to achieve it may involve some additional cost, however it is an investment for the future which will reduce future implementation risk, reduce operational benefit latency and by taking the advantage of design opportunities reduce the overall cost of maintaining fitness-for-purpose by engineering system capability to current operational needs.

ME(I) transfer enhancement should provide returns similarly to other preparations for the future, such as product line architecture reduction, future spares provisioning and 'fitted-for-but-not-with' strategies. Commercial arrangements could share risk and benefit between customer and supplier.

Integration of the TCA method into a supplier's PLM system will benefit the "Creating" system by enhancing it to provide a more complete understanding of "Created" systems, by capturing information that previously may have only been tacit. This process also identifies the major subsystems that will be affected by ME(I) transfer affordance enhancement, and facilitates examination by specialist engineers organised into WBS subsystem teams that are familiar and experienced in their own areas. TCA embodied into a PLM system can examine a very large data set in a timely manner for 'inherent' and 'independent' ME(I) transfers than could be problematic or provide opportunities that would be totally impractical otherwise.

System designers incorporating enablers for ME(I) transfer enhancements that may be brought into play at some time in the future need to be aware of the capabilities and facilities available to those enabling the enhancement. At first line, close to the point where the SoI is utilised, personnel will have fewer resources than are available at second line (deployable support and repair, field maintenance) and similarly less than those at third line (base workshop).

An TCA goal is to stimulate thought that creates new design actions to realise a potential ME(I) transfer at the system and hence SoS level to enable a new SoS capability, or mitigate risks that may only be realised when products are fielded. The TCA method as it appears in this thesis is restricted to ME(I) spectra and duty: individuals may well be stimulated to think of other parameters that could be brought into the project definition to facilitate fitness-for-purpose maintenance. This thesis is not 'intended' to offer a universal and complete solution; it is a contribution that that provides a more complete view of a system which may well stimulate adopters to produce similar analyses tailored to best benefit their individual products and services.

Any TCA generated design actions need to harmonise with concurrent actions and existing processes and procedures. ME(I) transfer enhancement and risk mitigation design actions on the selected major subsystems should be incorporated with the company PLM system and able to be integrated with other concurrent design actions, for example those implementing Mid-Life Improvements (MLI)s, carrying out maintenance or repairs.

16.5 TCA Automation Considerations

An automated TCA process will require the bandwidth and duty (frequency of use over time) characteristics of the ME(I) SSBs in the system definition to be held digitally in the hosting PLM system. This data will exist as component libraries, engineering models and schematics generated by specialist engineering disciplines and systems design artefacts generated by the project system engineers. However, the ME(I) SSB characteristics may not all be in a machine-readable form. The potential industrial exploiter will need to do a trade study between the desired degree of TCA automation and the amount of machine-readable data currently in their PLM system with the work necessary to achieve the level of machine-readable data commensurate with the allocation of function (i.e. either manual, semi-automated or fully automated) that they consider best suits them.

The author considered that this work should provide some thoughts to assist those considering an automated implementation of the TCA method/process, and that a concept demonstrator would be achievable and most efficiently provide a useful enhancement to this illustrated description. A TCA concept demonstrator could convey a representative ‘form and feel’ of an automated implementation and could be used as a point of departure for either a functional demonstrator utilising common software applications, or for a prototype TCA analyser that utilised specialist applications used by the existing engineering processes within an industrial system providers PLM system.

An automated implementation of the TCA method/process was envisaged as having two main functions; firstly a data capture and manipulation function to capture and process the system ME(I) SSBs, and secondly a data visualisation and analytics function to visualise and rearrange the intended and unintended ME(I) transfer connections. These two functions are represented in the concept demonstrator using manually input ME(I) SSB parameters, rather than calculated parameter values that a functional demonstrator determines.

The TCA concept demonstrator developed by the author using a naval platform case study is described in earlier. The functional demonstrator developed from the concept demonstrator as a BEng. undergraduate final-year project.

16.6 Chapter Summary

This chapter has provided guidance for systems suppliers adopting the TCA method into their engineering processes by firstly describing the fundamental structure of lifecycle management stages and aspects of TCA analysis/PLM integration, then secondly points for consideration by an industrial adopter of the TCA technique and its implementation as an automated part of an existing PLM system in an industrial environment.

17 Part B Summary

This part of the thesis has shown by example how the TCA technique may be exploited to provide a ME(I) transfer affordance enhancement at a convenient 'Design Opportunity' to a major subsystem typical of those encountered by major systems integrators such as THALES. It has described the industrial viewpoints from senior staff with the responsibility for engineering products and processes at THALES, and drawn salient points from them. Practical examples have shown how TCA can be used to build-in 'technical credit' to a SoS constituent, and how it can be utilised to maintain fitness for purpose in the event of an unforeseeable change occurring that would otherwise render the capability ineffective in some capacity. The functional demonstrator has shown feasibility for realising the TCA analysis method into a tool designed to be integrated as part of a PLM system and has been supplied to the industrial partner. Points for consideration, recommendations and guidance for industrial suppliers exploiting the TCA analysis method created by this research were brought out with recommendations of topics for consideration to assist the developers of an industrial implementation beyond the work of this PhD.

.

PART C: Discussion, Conclusions and Further Work

18 Discussion

The first part of this chapter relates the journey taken by this research, then discusses the research topic and how the research outcomes might benefit a system supplier adopting the TCA method. The research itself is then discussed and what might have been done differently considered. This is followed by the potential benefits to systems suppliers and their stakeholders and ends with some considerations for the potential adopter.

18.1 The 'Cognitive Journey' of TCA Research

It was considered that the reader may benefit from a chronological description of the author's thinking over the course of the research. Consideration of aspects of this research with activities correlating to the set of general principles represented by the scientific method described earlier were generated, revisited and iterated throughout the research period, which makes the true sequence of events a rather convoluted and difficult to follow path. However, the thoughts in this section are in approximate chronological order, but they do not follow every iteration, twist and turn taken during the research.

The TCA research started with the experience of problems in the real world: the author observed problems that occurred during the development of engineering systems that formed part of a larger SoS, and also problems that only exhibited themselves during systems integration or operational employment. These systems had human constituents, for example to operate and maintain them throughout their life. These observed problems prompted the author to question 'Is it just me?' With hindsight, it could be said that a significant portion of these problems could have been avoided with improved design and development processes (and the resources to allow them to be effective), but others were not realistically foreseeable, and had to be dealt with using what was available when they revealed themselves.

Despite the fact that delivered systems were developed under a respected systems engineering oriented design process, problems in design, development and operation still occurred, especially with new products. This stimulated the question, "Why don't things work when put together?' Investigation into this admittedly loose question resulted in an equally loose answer of 'Because some 'thing' didn't get all the 'stuff' it needed to work: the 'stuff' was either incorrect, incomplete or late". As the research progressed it was appreciated that especially in overcoming operational problems experienced by the human elements in the system, their ingenuity, resourcefulness and adaptability were key to getting things to work. These attributes the author thought should be capitalised upon by product design; systems suppliers should provide them ‘something to work with’ as far as practicable the delivered system could be maintained as ‘Fit-For-Purpose’.

It was recognised that systems suppliers do design for adaptability, robustness, resilience, agility etc. which make some provision for foreseeable future events, but it is impractical to efficiently and effectively cater for all eventualities; and even less so for ‘unknown-unknown’ events that will occur throughout a systems lifecycle and cause problems that the systems human elements will most likely have to address. Provision for ‘unknown-unknown’ events and unforeseen problems was thought to be part of the gap in the design and development process.

The most informed view one ever gets of a project is hindsight: the fresher the better. One function of systems engineering and lifecycle management is the ‘left-shift’ of knowledge, or obtaining hindsight early. Unforeseen problems are most effectively and efficiently dealt with when they reveal themselves, that is they become known, and it would be indeed fortunate to have a solution to the revealed problem at hand at that time, or soon enough after to overcome or at least mitigate the effects of the problem to an acceptable level in a timely manner.

Systems suppliers, especially as they are likely to be remote in location and time to a revealed problem cannot realistically provide solutions to unknown problems. The personnel forming part of the system are those close to a revealed problem and are likely to be one of the first to perceive its effects and the urgency with which it ought to be addressed. Systems suppliers could provide help in the form of ‘pre-work’; that is components of solutions able to be put together by those close to the problem.

From the notion of ‘something to work with’ came the thought that system personnel have more than they think they have; they have “unknown-known” resources and capabilities. Revealing these capabilities would enable these covert resources to be ‘on the table’ for consideration for utilisation as part of a constructed solution. Identification of a systems latent capability and exploiting these latent capabilities with solution component provisions is another contribution to filling the design and development process gap.

The concept of ‘stuff’ was thought worthy of further exploration, which led to the assertion that systems that were not fit-for-purpose were so because they could not make the complete, correct and timely transfers of material, energy and Information necessary to achieve a desired result. From this came the concept of the systems designers ‘designing-in’ functionality that does implement the transfers necessary for the system to achieve its ‘known’ requirements: that is to have the ability to cause the desired effects.

The concept of latent capability was revisited. Initial thinking considered latent capability as decomposed in the terms of a collection of Material, Energy and Information transfers that were

'Inherent' with the design solutions chosen to implement the 'designed-for', or 'Intended' ME(I) transfers. Lower-level thinking and investigation of real-world systems and lower-level thinking into the components of a ME(I) transfer identified two implicit and erroneous assumptions; firstly that Source, Sink and Bearer components of an ME(I) might not be connected and thus able transfer ME(I), which also gave rise to the concept of 'Independent' MEI SSBs that were outside the system of interest as defined by the designed-for system boundary, and secondly that connected ME(I) sources may not necessarily be transferring ME(I). Thus, any analysis has to consider ME(I) transfer at the SSB level.

How the ME(I) SSBs might be visualised was considered. Engineering staff could appreciate a QFD-Style of transform cascade that related 'Whats' to 'Hows' from top-level system-of-system capability down through system constituents to sub-systems in terms of ME(I) transfers, rather than in terms of functionality as does the QFD. The Function-Flow Diagram seemed to have better traction with engineering staff, as it was more widely used and provided a more intuitive feel of 'how it all works'. The FFD visualisation was considered better as a vehicle to capture and collate the 'Intended', 'Inherent' and 'Independent' ME(I) SSBs as a ME(I) Meta-Model and provided a relatively familiar common reference for a variety of engineering disciplines, however it was understood that an TCA adopter would likely want to use a visualisation that integrated well with their existing PLM system, and that for all but the most trivial of practical systems there would be large amounts of ME(I) SSBs and ME(I) transfers to accommodate. This 'Big Data' issue also dictated that extensive automation would be necessary in a practical TCA method process used to analyse realistic systems.

The work and writings of others in the systems engineering domain and the considerations of engineering specialists that had resonance with the author's research were sought and a literature review conducted. The considerations of engineering specialists started from the author's formulation of the question 'What design artefact (for example a model, specification, drawing etc.) in a product's 'technical data pack' accounts for the inherent characteristics of the design solutions?' For example, what artefact considers the mechanical characteristics of electrical elements, electrical aspects of mechanical structures, what information is implicitly transferred with material or energy transfers? From this came the thought that snippets of this information may exist in some form from activities in mainstream engineering and as outputs of specialist engineering discipline; control engineers may consider the mass, inertia and centre-of-gravity of electrical cables carrying power to motors on moveable structures, mechanical engineers consider galvanic corrosion caused by the junction of dissimilar materials, electrical engineers consider the current-carrying capability of mechanical structures under fault conditions, platform signature management consider the multispectral emissions of platform subsystems, similarly to the considerations of EMC/RFI engineers managing conducted and radiated electromagnetic noise. The literature survey found several writings on the problem of and need for agility, robustness and resilience to address the known and the uncertain, a couple on ME(I) as consumables, and a paucity regarding solutions and their practical implementation; this latter gap resonating with the aim of this research and hence having an influence the content of this thesis.

Throughout the research the author has been aware that adopters of the TCA method will have to provide some resources to implement it, that they need to have some return on this investment, and that the level of implementation giving the preferred return will differ between adopters, thus examples of how TCA adoption can be scaled to benefit people, process and product are provided, together with issues adopters need to consider and examples where TCA might not yield sufficient benefit, such as overcoming a lack of will of the human elements of a socio-technical system, a clash with doctrine or where the reconfiguration of a highly-interconnected, balanced system would have unacceptable consequential effects or perhaps make the situation ‘different’ rather than ‘better’. Thoughts of future TCA development and research considered how adoption issues could be addressed, conducting independent trials and research into the extension of TCA automation to support system adaption to generate candidate options to address the effects of unforeseen events to support decision-making.

18.2 The TCA Method: A New Insight

‘Inherent’ & ‘Independent’ ME(I) transfers almost certainly will not appear in a product’s design definition: they will not be controlled or managed, but potentially they may well be either problematic or be utilised by some stakeholders such as users and maintainers and thus will cause problems when they change or without deliberate consideration are withdrawn from the product due to through-life development and modifications. For example, mechanical connections formed by electrical cables to a cabinet may transmit harmful shocks and vibrations to sensitive components within it. Specification compliant replacement components may not have the design margins of original components being exploited by operators and maintainers. One way of encouraging considerations of a system’s ‘Intended’, ‘Inherent’ and ‘Independent’ ME(I) transfers could be to make a TCA method part of a project’s Systems Engineering Management Plan.

As with systems engineering effort, ME(I) transfer enhancement may involve some additional cost, and the ‘how much is enough’ question has to be answered by the practitioners based on the cost-benefit to their particular case. However, it also is an investment for the future which will reduce future implementation risk, reduce operational benefit latency and, by taking the advantage of design opportunities, reduce the overall cost of maintaining fitness-for-purpose by engineering system capability currency to operational needs. ME(I) transfer enhancement should provide returns similar to other preparations for the future, such as product line architecture reduction, future spares provisioning and ‘fitted-for-but-not-with’ strategies. Commercial arrangements could share risk and benefit between customer and supplier, but the business case has to be assessed on a whole-life basis that includes the cost of upgrades.

The level of provision made for ME(I) transfer enhancement can be tailored to the needs of the business: it may range from design only, functional models, virtual prototypes, board layouts, installed components to live spares. These provisions could enhance ME(I) transfer enabling operational augmentation at the system level as well as at the SoS level.

Integration of the TCA method into a supplier’s PLM system will benefit the “Creating” system by enhancing it to provide a more complete understanding of “Created” systems by capturing information that previously may have only been tacit. This process also identifies the major subsystems that will be affected by ME(I) transfer affordance enhancement, and facilitates examination by specialist engineers organized into Work Breakdown Structure subsystem teams that are familiar and experienced in their own areas. TCA embodied into a PLM system can examine a very large data set in a timely manner for ‘inherent’ and ‘independent’ ME(I) transfers than could be problematic or provide opportunities that would be totally impractical otherwise.

An automated TCA process will require the bandwidth, operating period (duty) and sink susceptibility characteristics of the ME(I) SSBs in the system definition to be held digitally in the hosting PLM system. These characteristics will exist as component libraries, engineering models and schematics generated by specialist engineering disciplines and systems design artefacts generated by the project system engineers. However, the ME(I) SSB characteristics may not all be in a machine readable form. The potential industrial exploiter will need to do a trade study between the desired degree of TCA automation and the amount of machine-readable data currently in their PLM system with the work necessary to achieve the level of machine-readable data commensurate with the allocation of function (i.e. either manual, semi-automated or fully automated) that they consider most cost-effectively delivers the desired benefits from incorporating TCA into their engineering processes.

Designers incorporating enhancements into systems enablers for ME(I) transfers which may be brought into play at some time in the future need to be aware of the capabilities and facilities available to those enabling the enhancement. At first line, close to the point where the SoI is utilized, personnel will have fewer resources than are available at second line (deployable support and repair, field maintenance) and similarly less than those at third line (base workshop).

Any TCA generated design actions need to harmonize with concurrent actions and existing processes and procedures. ME(I) transfer enhancement and risk mitigation design actions on the selected major subsystems should be incorporated with the company PLM system and able to be integrated with other concurrent design actions, for example those implementing MLIs, carrying out maintenance or repairs.

A TCA goal is to stimulate thought that creates new design actions to realize a potential ME(I) transfer at the system and hence SoS level to enable a new SoS capability, or mitigate risks that may only be realized when products are fielded. The TCA method as appears here deals with ME(I) spectra, duty and capacity: potential TCA adopters may well be stimulated to think of other parameters that could be brought into the project definition to facilitate fitness-for-purpose maintenance.

TCA may appear to be a convoluted route to an end that could be achieved by talented, experienced engineering practitioners using alternative methods with which they are familiar. It is acknowledged that this might be the case, and furthermore that alternative methods to identify ‘Inherent’ and ‘Independent’ ME(I) SSBs will exist in some specialist engineering areas, but these may well be sporadic and dispersed. For example, those responsible for platform signature management and spectrum management will identify inherent energy sources and determine their ability, capacity for transmission and crosstalk. The mechanical characteristics of electrical components will be examined by those responsible for such aspects as centre-of-gravity management, mass and space claim budgeting, whilst the electrical characteristics of mechanical structures will be examined by mechanical engineers considering galvanic corrosion and also electrical engineers determining the paths of full-load fault currents and lightning strokes. Working with the assumption that a systems supplier operates using a tailored form of the systems engineering process as described by ISO 15288, INCOSE and others, TCA improves the “Integration with Specialist Engineering” activity by disseminating some aspects of the specialist technical skills as well as those commonly engaged during this activity such as security and human factors. Specialist technical skills like those described above are likely to be busy, scarce resources that may well not be available to systems engineers having a broader viewpoint, and brings these specialist engineering considerations together in one holistic picture.

Potential TCA adopters may well decide that TCA would not provide an acceptable return-on-investment if applied in areas where nearly all the transfers are of one type, such as data handling and information management or where there is little latitude for modification. Some solutions may appear not to be amenable to modification because of the high interconnectivity between their parts, or operate with low design margins meaning that changing one part affects many others and that all parts are working close to their maximum capacity. In this case TCA may confirm the inadvisability of modification and that replacement might be the preferred option, or perhaps reveal latent capability that could be exploited to provide a service life extension until a replacement was available.

This research is not intended to offer a universal and complete solution; it is a contribution that provides a more complete view of a system. If a system supplier considers that they would not profit from TCA as described here, they may well be stimulated to produce a variation tailored to best benefit their individual products and services.

18.3 The TCA Research

The initial impetus for this research was to help personnel in the field working as part of a socio-technical system to address previously un-encountered problems caused by unforeseen events. The author felt it negligent and unethical not to provide something to capitalise on the tenacity, resourcefulness and ingenuity of personnel working close to the point of employment of the systems to which he had contributed. Design for Agility, Robustness and Resilience coupled with rigorous Failure Mode Effects and Criticality Analysis (FMECA) accommodated foreseeable events, but to provide against the unforeseen is difficult and likely to be ineffective and inefficient. Risk and Opportunity analyses are a step towards identifying future problems and opportunities for improvement, but are often limited to 'designed for' aspects of the delivered system and its lifecycle management. The author felt that something was missing from the design process that could be used in the future to alleviate unforeseen problems.

Examination of real-world problems from the author's experience and from research activities did not find any that would have been troublesome if the right 'stuff' had been to hand when needed. This gave rise to the conceptual-world assertion that it was the inability to make the necessary correct, complete and timely transfers of Material, Energy and Information that prevented socio-technical systems achieving what was desired, which posed the question of how a systems affordance for the transfer of ME(I) could be enhanced such that when an unforeseen event occurred new ME(I) transfers necessary to address the unforeseen problem could be brought into play. Furthermore, systems had ME(I) transfers, and ME(I) transfer components (Sources, Sinks and Bearers) that were unintentional, that is not 'designed-in'; some were inherent with the means chosen to implement the conceptual solution functions required for it to fulfil its requirements, and others were 'independent', for example belonging to another system but having the potential to affect the system-of-interest under examination. 'Intended' ME(I) transfers had Inherent SSBs that were of the same and/or different types; for example an armoured DC power cable was able to also conduct energy as magnetic flux and mechanical force, and information such as 'supply and connections present / not present'.

Thoughts then were directed to a process that could reveal the ‘inherent’ and ‘independent’ ME(I) SSBs, and determine if they were either a risk because they may be likely to cause problems, or they provided an opportunity to enhance a systems ability to transfer ME(I).

As exemplified above, some specialist engineering disciplines do use methods that address some of the risk aspects of some of the ‘Inherent’ and ‘Independent’ ME(I) SSBs, but these disparate viewpoints are not currently drawn together in a ‘big picture’ view that is necessary to reveal what effect these SSBs might have at the system or SoS level, or what latent capability they may hold. The TCA meta-model appearing in this thesis is offered as one way of visualising a SoIs ME(I) transfer affordance ‘big picture’.

At the outset this research the author intended to carry out some of the preliminary activities required for TCA adoption using case-studies of deliverable solutions from the industrial partner, but none could be realised within the research timeframe. The case-study with the Royal Logistic Corps was valuable and contributed the benefit to the research that would have been obtained from an industrial case study, albeit not providing the industrial partner with information on their specific products. However a TCA pilot is still being sought by the industrial partner to provide an independent assessment of the TCA method, the impact of adoption and bespoke tailoring to provide the preferred cost/benefit.

A TCA process integral with the adopting industrial’s PLM system is envisaged to be used primarily by a range of engineering staff to reveal potential problems and prospective opportunities from unintended ME(I) SSBs, which will populate a ME(I) meta-model. Engineering staff include those working at the sub-assembly level up to those working at the SoS level, to benefit from their domain knowledge. The TCA process was designed to use tangible fundamental concepts (frequency, time and amplitude) with which most of them would be familiar, rather than a new abstract set of concepts that needed to be learned before the engineering staff could contribute.

The author considers that few suppliers of complex socio-technical systems are likely to have a homogeneous design and manufacturing system with a truly integrated modelling environment that would allow the integration of a TCA process able to autonomously create a ME(I) meta-model of a supplied system. The TCA method and process was created to allow scalable application to both created and creating systems. It is recommended that a supplier adopting TCA should take an incremental approach starting with an exploration of how their supplied products and services have developed and been used over their lifecycles and how different degrees of TCA adoption might have been of benefit to them, taking account of the future direction of the business. In parallel to this, the PLM system and engineering design artefacts produced for projects should be examined to determine factors such as the machine readability of design documentation at the ME(I) transfer level and the level of integration of system models. The goal of these activities is to baseline the 'Where we are now' and 'Where we want to be' in terms of both the systems supplier's created and creating systems from the viewpoint of TCA adoption. The knowledge gained would be used to introduce the TCA concept and perceived benefits using language terms and examples familiar to engineering managers, project managers and project chief engineers, perhaps in the form of a short course as has been previously suggested by both academic and industrial partners This should be immediately followed by a meeting that produces an TCA adoption route-map with 'quick win' milestones between the points of departure and the desired end state that is considered to deliver the best return-on investment from TCA adoption from the budget available. An early and cost-effective intervention would be the addition of TCA oriented questions in the review checklists for preliminary and critical design reviews. A second step, dependant on the level of machine-readable design information available, might be the automated generation of a ME(I) meta-model of the 'intended' ME(I) transfers.

Systems engineers need to appreciate the system-level consequences of specialist engineering design decisions, but the opportunities for them to gain experience with specialist engineers and those that interact with the systems they design over its lifecycle are arguably much fewer than might be considered adequate for them to develop the knowledge and expertise to prevent system problems early in the lifecycle before they exhibit themselves in later design phases such as systems integration, operational trials, customer acceptance and whilst in-service. This is an area where TCA can help.

18.4 Potential benefits of TCA

18.4.1 Benefit to the Industrial Adopters

ME(I) transfer enhancement should provide return-on-investment as other preparations for the future. Potential benefits to the sponsors include:

- Reduction in whole-life costs
- Reduction in system implementation and systems integration risk
- Expedited realisation of product adaption and extension
- Facilitation of 'what-if' demonstrations in operational environments with reversibility
- Reduce operational benefit latency
- The level of provision made for ME(I) transfer enhancement can be tailored to match the resources available on a case-by-case basis and by taking advantage of Design Opportunities reduce the overall cost of adoption.

18.4.2 Benefit to Thales

A new perspective on SoS and SoS constituent systems from the viewpoint of the transfers of M, E & (I) which identifies both inadvertent and potential transfer mechanisms associated with particular design solutions.

Benefits Include:

- An enhancement to the CHORUS2 engineering processes
- The introduction of a technique with the potential improving staff by increasing their awareness
- Stimulus for innovation from increased awareness of engaging staff
- Opening of new markets for existing products
- Contribute to Product Line Architecture design
- Enhanced reputation from greater product ‘usefulness’
- Easement of demonstrations using customer equipment

18.4.3 ‘Managed Futures’

ME(I) transfer enhancement should provide returns similarly to other preparations for the future, such as product line architecture reduction, future spares provisioning and ‘fitted-for-but-not-with’ strategies. ME(I) transfer enhancement will involve some additional cost, however it is an investment for the future which should reduce future implementation risk, reduce operational benefit latency and by taking the advantage of design opportunities reduce the overall cost of maintaining fitness-for-purpose by engineering system capability currency to operational needs. Commercial arrangements could share risk and benefit between customer and supplier. The TCA method might form part of the SoS component whole life cost model.

18.4.4 Where it fits in: the ‘Creating System’

The degree of incorporation into the engineering PLM Process is tailorable; for example the TCA method could be integrated with:

- Design Guide
- Design Review checklist
- Modelling Suite toolbox
- Automated CADCAM Function
- Mandatory Design Document

- Incremental adoption would harmonise with process improvement and staff development programmes

18.4.5 Where it fits in: the 'Created System'

The level of provision made for ME(I) transfer enhancement can be tailored: for example it may be as:

- Design only
- Functional models
- Virtual prototypes
- Mass and Space claim
- Cable Flooding / Board layout
- Fitted components
- Live spares

18.4.6 When it fits in: 'Design Opportunities'

"Maintaining" in the title of this research is there to highlight that TCA application isn't just an initial design phase activity, and can be employed at 'Design Opportunities' such as:

- Scheduled Maintenance
- Repair
- Refurbishment
- Improvement through Spares
- Mid-Life Upgrades
- In Service

18.4.7 Some TCA Adoption Considerations

The TCA method will generate large amounts of data for all but the most trivial of systems, and hence will need to be a largely automated process for real-world applications. How much design information is captured within IT systems, and how much is in machine-readable formats? Design information will often be as complete as suits the creator, which may be insufficient for wider usage. Are all the design information constituents coherent and at the current build state? How must supporting non-engineering disciplines (Commercial, Finance, Legal, Business) change to realise the benefits? Consider the design and management strategy necessary for certification and safety cases for mutable products.

18.5 Chapter Summary.

This chapter began by relating how the end-point of the research was arrived at, followed by a discussion of the TCA method and process outcomes of this research, followed by a reflection upon the research activity and experiences of the author over the duration of the research and what in hindsight could be done differently. This was followed by a précis of how the research outcomes might benefit from system suppliers adopting the TCA method in terms of process improvement, product design and whole-life costs, and also how TCA might benefit other personnel working with the suppliers products. The chapter ended with some considerations for the potential adopter.

19 Conclusions

This chapter contains a summary of what was done, the achievement against research objectives, the research outcome deliverables, what lessons learnt could be useful to others and provides some candidates for further research and development work.

19.1 Research Summary

This research has provided a more complete insight: the TCA process guides thought to identify concealed ME(I) sources, sinks, bearers and transfers that may not otherwise be included in SoS /System definition. The initial motivation for the research was to capitalise on these to provide personnel working with a delivered system to bring into play facilities to address unforeseen operational challenges, and subsequently identify where these unintended transfers might lead to unexpected undesirable emergent phenomena only revealed 'late in the day' where the detrimental impact on profit and reputation is high.

Even though this research has reduced emphasis on information transfer, it does not diminish its importance. An Information Exchange Model of Information Exchange Requirements is a fundamental artefact crucial to the requirement and subsequent design definition of complex SoS constituents, for example significant military platforms such as capital ships and fighting aircraft, hence the determination and definition of information requirements and modelling is necessarily well-defined within engineering standards and system architecture tools and frameworks. It was decided to focus the research reported in this thesis on the less well addressed aspects of Material and Energy transfer, and the Source, Sink and Bearer components of transfer. However because information management has such a significant role in the successful operation of systems / SoS, and furthermore in the successful exploitation of the outcomes of this work, (although not a focus of this work), consideration of 'I' is retained in brackets in the acronym ME(I) to indicate the importance of information and to keep mindful of it.

Pieces and variations of the TCA method are probably used by specialist engineering disciplines currently, but are likely dispersed, sporadic and not consistently documented. The TCA process formalises them together as a reference artefact available to all, and encourages systems thinking in engineering staff perhaps with little previous cause or exposure using concepts and terminology with which they are familiar: Improving the 'Creating System'.

The TCA process reveals latent capability for ME(I) transfer that may form susceptibilities for undesirable transfers or unintended networks that could be brought under control to reduce the risk of undesirable emergent properties or exploited to extend and/or enhance system and supra-system capabilities: Improving the 'Created System'.

Deliverables provided are:

- TCA Meta-Model Concept
- TCA method and process with illustrations of use, practical application and PLM integration
- PC based Concept Demonstrator
- PC based functional demonstrator and User Guide (BEng. Project)

Enhancements could be activated to fulfil ME(I) transfer shortfalls enabling a composing System-of-System to be maintained fit-for-purpose to address unforeseen tasks and/or changes, both internal and external, throughout the lifecycle at an affordable scale.

The TCA method is not a panacea for all ills, and certainly not a substitute for wisdom & expertise, but it is a vehicle that can bring mutual benefits to both system suppliers and their customers by capitalising upon the human talents within both their enterprises.

19.2 Aim and Objective Achievement

This research aimed to enable suppliers of system-of-system constituents to provide at an affordable scale something in their scope of supply for their operational customers to use with their knowledge, wisdom and abilities to help prevent unforeseen situations resulting in undesirable outcomes. To achieve this aim the research has provided a method with a process to guide system suppliers to incorporate components of solutions that can be configured together in a timely manner by the personnel engaged with the SoI, who are the first to experience the unforeseeable change when it reveals itself. Although the case studies provided acceptable information for this research, it was desired to have further examples of system adaption to unforeseen events from a Thales case study but this was unavailable as previously mentioned.

In order to fulfil the aim, a number of objectives were formulated:

- Review the current literature to verify the need and formulate the research questions
  A selection of the literature reviewed appears as chapter 3, and continues. At the time of writing the currency of the need and aim of this research is supported by William Roper, director of the US Strategic Capabilities Office, in a Breaking Defense article (13/04/16) that reported "*today the SCO's own director warned the Senate against placing too much trust in technology. In wartime, under assault from a savvy enemy, systems start breaking down, William Roper said, and the winner will be the side whose human beings adapt best to the chaos.*"(Freedberg 2016).
- Analyse and from this assert generically why SoS become unable to do what is required of them and the root causes for this state.

The author did not want to be drawn into an attempt to come up with 'A Theory of Everything' and was also apprehensive that an attempt to provide a generic deliverable that was applicable to every case would not provide sufficient return-on-investment of resources, resulting in something that was genericised out of all practical employment by industrial systems suppliers. This research provides an assertion in language that is not only meaningful to those systems-oriented personnel with the accountability to meet user needs, but also to those engaged in the traditional engineering disciplines with the responsibility of 'making it happen' to foster effective cooperation.

- Create a novel viewpoint of the problem and a method/process to address the problem
  The literature review provided a few instances mentioning material, energy and information, but none were found that discussed the active management and transfer of these quantities to bring about a desired situation. In common with many other systems engineers the author previously had a traditional engineering role, and systems engineering provided a new view of familiar systems based on functionality rather than in terms of hardware/software. Thinking in terms of functionality is often not immediately intuitive to those comfortable with visualisation in terms such as watts and revolutions per minute. From the assertion above this research provides a novel viewpoint with a method and process to manage ME(I) transfer by design that can be used to address problems from the sub-system to system-of systems level as a vehicle for agile thinking over vertically integrated levels.

- Develop and validate the concept/method/process with examples and case studies
  Chapters 9, 10 and 12 contain case studies and illustrative examples together with the contribution they made to the development of the TCA method and process.

- Capture the research in a thesis able to assist others to implement and benefit from it.
  This thesis contains a concept, method and process for maintaining the fitness-for-purpose of a system-of-interest by analysis of its material, energy and (to a lesser extent) information transfers. In addition to this, it contains an exploration of the thought process to determine this new insight, how it could be integrated into a system suppliers PLM processes, the issues that an adopting supplier should consider, and demonstration with commonplace PC-based applications how this new view of the system could appear within a IT-based design information repository. The potential benefit to the adopters creating and created systems are identified and areas for further work suggested.

19.3 Research Tenet Influence

At the outset of this research the author set himself some guiding principles in the form of five research tenets designed to influence the research outcomes towards forms whereby systems suppliers could appreciate how their adoption could potentially benefit their business, how they might be adopted into their engineering processes and how they could enhance their products. These tenets are reproduced below with descriptions of how the research outcomes were influenced by them.

- TCA research outcomes should be exploitable: not ‘Shelf-ware’

  The author has been mindful that this work should answer the ‘So What’ question, and has included examples of how an exploiting system supplier might benefit, suggested aspects of adoption that they consider and likely difficulties they might have. A concept demonstrator, intended to be a point-of-departure for a functional implementation using the adopting systems suppliers preferred IT applications has been validated as such by the B.Eng. undergraduate final-year project that developed a functional demonstrator from it.

- Outcomes should be incremental: ‘Quick Wins’ en-route

  Numerous formal presentations and research outputs were provided to Thales on a regular basis, as well as several other informal presentations to project staff throughout the duration of the research. The early concept of unintended connections revealed by a ‘broad-band’ examination of the intended connections within a system or a SoS stimulated the thought of preliminary and critical design review exploration of their presence and likely effects on system behaviour, in a similar manner to that used to generate a FMECA.

- Exploitation of the method/process should not be a burden on users: A ‘minimal extra effort’ on staff

  Artefacts present within a products design definition that contain information to populate an ME(I) meta-model are suggested. There will be some extra effort initially (as there is with the adoption of systems engineering) but how much will depend on several factors, such as the machine readability of design artefacts and the information density of them and probably be unique to each potential exploiter. Areas of engineering that may exist within a system supplier that use thought processes similar to those used for meta-model generation are suggested.

- The TCA research should use an iterative, developmental approach

  At the outset this research set out to create something to enable systems suppliers to facilitate the humans that interact with their systems in the field to maintain their systems fit-for-purpose in the event of unforeseen situations. In the course of research an assertion of why thing were not fit-for-purpose gave rise to the concept of intentional and unintentional connections was an early output, which was followed by the consideration of connections as transfers of material, energy and information. This was followed by the demarcation of connections into intended, inherent and independent ME(I) transfers, then their decomposition into ME(I) SSBs and after this the notion of unconnected ME(I) SSBs.

- The end result should be able to be integrated and harmonised with a systems suppliers Product Lifecycle Management (PLM) system

  The main research outcome, the ME(I) meta-model, is conceptual; hence its representation is not tied to any specific form, and lends itself to a representation preferred by the adopting system supplier. Two examples of how the meta-model can be visualised, as a transform chain and a function-flow diagram, have been shown in this thesis. The adoption of a ME(I) meta-model is not a prerequisite to exploitation benefit; the stimulation of thought processes to consider unintended connections, perhaps supported by one or two questions in design review checklists could easily provide timely rectification of causes of undesirable emergent behaviour early in the lifecycle.

19.4 Hypothesis and Research Questions

Hypothesis:

'It is the inability to make the necessary correct, complete and timely transfers of Material, Energy and Information that prevent socio-technical systems achieving what is desired.'

The author considers this assertion has been validated in the context of the project, which is focussed upon the first research question below 'What can be done [by systems suppliers] to address the 'unknown-unknowns'?" Outside of this context it could be argued that a socio-technical system could have the ability to make the necessary correct, complete and timely transfers of material, energy and information to achieve what is desired but the human elements of the system lack the will to make them happen, perhaps due to a sense of personal endangerment, fears of the consequence of their actions or from a sense of morality or ethics. The address of these factors usually lies within the doctrine and training components of capability; the personnel working either with or as part of the socio-technical system and outside the scope of this research, but nevertheless the assertion remains valid.

Research Questions:

- 'What can be done to address the unknown-unknowns?"

  All situations will have constraints. Subsequently there is only so much that can be done within these constraints, which applies to preparations to address difficulties that may arise in future endeavours. We might consider it prudent to utilise the space in our shirt pocket to carry a Swiss army knife, but may be faced with the unexpected loose bolt.

  This research answers this question by providing a method with processes to guide system suppliers to incorporate components of solutions that can be configured together in a timely manner by the personnel engaged with the SoI to accurately address the unforeseen change when it reveals itself.

- 'Why is the current situation problematic?'
  The environment in which complex socio-technical systems are created and operated is becoming ever more dynamic and interconnected which is highly conducive to the propagation of unforeseen problems. If left unaddressed this can have serious consequences.
- 'When will FFP maintenance be done?'
  Incorporation of provision for ME(I) transfer enhancement is done at 'Design Opportunities': that is whenever it is convenient and economical throughout the system lifecycle to do so. Utilising ME(I) transfer enhancement provisions will be done when necessary to address an unforeseen problem once identified and a preferred solution chosen.
- 'How will FFP maintenance be achieved?'
  Provisions for ME(I) transfer enhancement to maintain fitness-for-purpose will range from design only, functional models, virtual prototypes, board layouts, installed components to live spares. The level of provision made will be tailored as desired by the systems supplier and customer as appropriate. ME(I) transfer provisions will be brought 'on-line' to transfer ME(I) with activities commensurate with the maturity of the provision; for example the functional model will require engineering design, build, test and installation to realise the new ME(I) transfer affordance, whereas more mature provisions will need a simple hardware reconfiguration or enabling of software routines.
- 'Where will FFP maintenance be done?'
  As with the 'How' question above, this will be dependent on the maturity of provision made for ME(I) transfer enhancement; it will range from the premises of original equipment manufacturers to the operational front-line.
- 'Who will do FFP maintenance?'
  As with the 'How' question above, this will be dependent on the maturity of provision; it will range from the original equipment manufacturers engineering staff to the operational front-line personnel.

19.5 Contribution to knowledge

This research changes the way people look at systems and systems-of-systems.

- The research has created a novel viewpoint of a system-of-interest from the perspective of a system's Material, Energy and Information (ME(I)) transfers; not only the ME(I) transfers necessary for the system to fulfil its operational requirements which the systems' designers have intentionally implemented by means of hardware, software and human operators, but also the ME(I) Sources, Sinks and Bearers (SSB) inherent with the physical means by which the 'intended' transfers are implemented and additionally the other ME(I) SSBs that are independent of the system-of-interest but nevertheless have an effect on it.

- This research has added to the body of knowledge by demonstrating how covert ME(I) SSBs can be revealed using the TCA method and showing how to discover a systems potential and capacity for unintended ME(I) transfer using the TCA process. Unintended transfer does not appear in the design description of a system, and hence is uncontrolled and perhaps even utilised unbeknown to the design authority.
- This research has shown how to find unintended ME(I) SSBs and transfers likely to be troublesome or provide an opportunity to effectively and efficiently enhance the systems' ability to transfer ME(I) to operational advantage at the time of discovery or at some time in the future.
- This research provides an improvement to the "integrate with specialist engineering" activity of the systems engineering process by better integrating together systems designers and specialist engineers around the common viewpoint of an ME(I) meta-model to capitalise on the skills of both to assess unintended ME(I) SSBs and transfers and take appropriate action.
- This research has shown system suppliers by example how they can implement the TCA viewpoint and method into their PLM system used to create the systems they deliver to their customers by providing examples using readily available software applications for calculation (EXCEL) and visual analytics (Cytoscape).

19.6 Further Work

Further work should start with the formulation of new research questions taking this research as a point-of-departure driven by the needs of the industrial partner. This subsection contains the author's suggestions for further work based on his experience working with the research industrial partner.

Pilot integration with CHORUS 2.

The foundation work for an integration of the TCA method with the PLM processes within the Thales CHORUS2 global management system has been done and appears in part B. Prior to a pilot trial of TCA on a project, it may be advantageous to carry out an independent case-study to examine where in the existing PLM system the TCA method activities would best fit; for example how they might be correlated, what impact they would have on projects, and where analysis outcomes and subsequent actions would be recorded etc. This could perhaps be done as a MEng or MSc individual project by a Thales sponsored student.

Independent pilot trial on a project.
During the course of this research considerable effort was spent attempting to establish a case-study using a Thales project in order to provide best benefit from the research to the industrial partner, however despite engaging with projects this was not available within the timescales of the research which meant that non-Thales studies had to be used.

It would be mutually beneficial to the TCA research maturity and Thales to run a pilot trial of TCA on a project using the modified CHORUS2 PLM processes that embody the TCA method coming from the integration study described above. This could be done as a study on a historical project, or on a live project, or perhaps both. Thales would need to decide what would provide them with best benefit taking account of the constraints and resources available at the time. As with the CHORUS2 PLM process integration pilot above, this could be a candidate for a postgraduate individual project.

Systems Engineering TCA Module / Short Course.
The author and his academic supervisor have discussed the form and content a TCA taught module for systems engineering MSc / MEng and postgraduate distance learning might take. Subsequent to this, the author, in response to an enquiry by senior Thales engineering staff, said that an introduction to TCA as a short course was feasible. Joint academic / industrial development of a taught module driven by the needs and desired learning outcomes of the industrial partner would add to the skills of engineering staff who, in synergy with the PLM processes incorporating TCA should improve both engineering processes and delivered products.

Research ‘FFP Prognostics and Diagnostics’.
The implementation of FFP prognostics, coupled with Health and Usage Monitoring and operational analysis would be valuable as a decision support facility, to answer questions that often arise in stressful, time-constrained situations such as ‘Is my system able to provide surge capability for 48 hours?’ ‘Can I adapt from role ‘X’ to role ‘Y’ with adequate time and capability margin?’ ‘What can I do now to increase my likelihood of mission success in the future?’ This is a highly complex area where answers are dependent on many interacting variables; the author considers that a first stage would be at the level of a feasibility study, perhaps introducing the concept of FFP Prognostics and Diagnostics into existing operational analysis work to obtain an indication of likely benefit to planners and commanders in the field.

Research ‘Composite ME(I) Transfer Analysis’.

The motivation of this research was to help personnel operating with complex socio-technical systems address unforeseen problems. Tackling such a problem would almost certainly require new 'get X from A to B' tasks. It was recognised early in this research that rarely will an ME(I) transfer consist of one ME or I element alone: it will be a composite of all three. The research has been conducted with the appreciation of this, but it was not incorporated into the modelling and visualisation of ME(I) transfers to ensure the research remained tractable and could be accommodated within constraints. A ME(I) composite might be considered as a vector quantity with a dimensionless magnitude in a three-dimensional reference frame, whose axes are Material, Energy and Information. Headroom for transfer may exist in different proportions for each: For example an 'intended' material transfer may have significant headroom to transfer information and/or energy; information could be written on transferred materials, or its mechanical characteristics could be exploited to provide structural support or apply force under gravity. Expressing ME(I) transfers as vector quantities could facilitate the machine determination of ME(I) pathfinding for desired complex and composite transfers.

Research 'ME(I) Pathfinding'.

ME(I) Meta-models may expedite finding a viable pathway for a desired transfer of a ME(I) composite, but the characteristics of SSBs in candidate pathways may prevent the desired transfer. This might be visualised as a variation of by Reason's "Swiss Cheese" model of layered security (Reason 1990). In Reasons model 'holes' of various sizes in slices of cheese represent susceptibilities at different levels in a system. In some circumstances these holes can undesirably align to allow an attack that will fit through the smallest hole in the aligned series of holes to pass through the defensive layers and damage the system. In the TCA variation of Reason's model the 'slices' would represent SSBs and the 'holes' (in three dimensions they would be 'pockets') the ability to output, transport and accept an ME(I) composite. Whereas the alignment of 'holes' in Reasons model is undesirable and to be avoided, in the TCA variant the alignment of 'pockets', is desired, where the smallest pocket in the aligned series has to be able to transfer the composite ME(I) quantity. Such candidate paths would need subsequent assessment of the effect they would have on the transferred ME(I) composite, for example in terms of the degradation of correctness, transport losses, transfer latency, sequence of transfer effects, ME(I) pocket interdependencies and how these factors affect the efficacy of the task output.

Research 'Transformation-Enabled ME(I) Transfers'

The ME(I) composite to be transferred may be amenable to transformation to allow transfer by a constrained candidate pathway. For example for transfer purposes a simple Material transformation is from a liquid or a gas to a solid by containerisation. Energy transducers are abundant throughout engineered systems and may be able to be exploited. The encryption of information is a transformation allowing transfer of sensitive information by unsecure bearers. An automated search of a systems ME(I) Meta-Model utilising 'intended' transducers could increase the number of viable pathway candidates for exploitation to restore or enhance fitness-for-purpose.

If this further work described above shows promise, its outcomes should inform further development. One next step candidate could be to add a fourth dimension to the model as the ME(I) transfer pockets would likely be dynamic: that is they will open, change shape and close over time, such that opportunities to transfer a ME(I) composite would be time-limited, rather than permanent windows of opportunity.

19.7 Chapter Summary

This chapter has described candidates for further TCA development and research to provide some food for thought for the reader who may be thinking of exploiting the TCA work herein or who would like to explore further research challenges associated with it. The author has not assigned priority or importance to these candidates as it is felt that this is best left to the reader to decide which, if any, they consider best suits their individual needs.

19.8 Concluding Statement

This work has produced a technique that provides a novel insight into SoS' and their constituent systems which it captures in a new systems engineering artefact – the ME(I) Meta-Model. This technique is supported by an analysis method to facilitate incorporation into a preferred PLM/design suite at a scale that provides the best cost/benefit.

This new method fits with the systems engineering process and provides improved management of the lifecycle by revealing covert mechanisms for ME(I) transfer early in the lifecycle that if left unexamined may cause unexpected emergent properties which only reveal themselves later when difficult and costly to bring under control.

Systems do have to be adapted to maintain fitness-for-purpose, and the outcomes of this work have a role in providing at an affordable scale ME(I) transfer affordance enhancements that give the human elements in a socio-technical system 'something to work with' when they need to adapt what they have to hand to address an unforeseen situation.

It is hoped that the technique and method provoke thought in the academic community and provide a stimulus for further research and application in other disciplines, and that an appreciation of covert ME(I) SSBs in a SoI becomes an accepted, tailor-able activity in the systems engineering process to produce a ME(I) Meta-Model that benefits both systems suppliers and the human elements of the socio-technical systems they provide.

References

Alberts, D, J Gartska, and F Stein. 2012. “Composable Capabilities On Demand.” Washington DC. http://www.mitre.org/work/systems_engineering/guide/enterprise_engineering.

Alberts, David. 2011. *The Agility Advantage*. 1sted. DoD CCRP. http://dodccrp.org/files/agility_advantage/Agility_Advantage_Book.pdf.

Boardman, John, and Brian Sauser. 2006. “System of Systems – the Meaning Of ‘of.’” In *2006 IEEE/SMC International Conference on System of Systems Engineering Los Angeles, CA, USA - April 2006*, 118–23. Los Angeles.

Burge, S. 2007. “A Functional Approach to Quality Function Deployment (Putting the Function Back into Quality Function Deployment).” http://www.burgehugheswalsh.co.uk/Uploaded/1/Documents/A-Functional-Approach-to-Quality-Function-Deployement-v3.pdf.

———. 2011. “The Systems Engineering Toolbox: Functional Modelling.” http://www.burgehugheswalsh.co.uk/uploaded/1/documents/fm-tool-box-v1.0.pdf.

Burrowes, Darren, and Matthew Squair. 1999. “Managing-the-Emergent-Properties-of-Design.” In *INCOSE IS*, edited by ADI Limited, 5. Carrington, Austrailia: INCOSE. http://criticaluncertainties.com/2011/07/11/managing-the-emergent-properties-of-design/.

Checkland, P, and J Scholes. 2000. *Soft Systems Methodology in Action*. New York USA: Wiley.

Conklin, Jeffrey. 2006. *Dialogue Mapping : Building Shared Understanding of Wicked Problems*. 1sted. Chichester, England: Wiley Publishing.

Coppola, Anthony (ROME AIR DEVELOPMENT CENTER GRIFFISS AFB NY). 1979. “A Design Guide for Built-in-Test (BIT).” *United States Defense Technical Information Center*.

Creswell, J. W. 2009. *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches. (2009). Thousand Oaks, CA: Sage*. Thousand Oaks.

Cytoscape.org. 2016. “Cytoscape.” http://www.cytoscape.org/.

Dahmann, Judith, and Kristen Baldwin. 2008. “An Implementers â€™ View of Systems Engineering for Systems of Systems.” In , 11–16. Montreal: IEEE. http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=4518994.

Dahmann, Judith S, and Kristen J Baldwin. 2008. “Understanding the Current State of US Defense Systems of Systems and the Implications for Systems Engineering.” *2008 2nd Annual IEEE Systems Conference*, April. Ieee, 1–7. doi:10.1109/SYSTEMS.2008.4518994.

De Weck, Oliver. 2011. “Engineering Systems.” In *Engineering Systems*, 65–96. MIT. http://strategic.mit.edu/docs/es_book_004_proof.pdf.

Delaurentis, Daniel. 2005. “Understanding Transportation as a System-of-Systems Design

Problem.” Charlottesville USA: IEEE SMC. http://arc.aiaa.org/doi/abs/10.2514/6.2005-123.

Demarco, Tom. 2009. “Viewpoints.” *IEEE Software*, no. Jul/Aug 2009: 95–96. http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5076468.

Denscombe, M. 2008. “Communities of Practice: A Research Paradigm for the Mixed Methods Approach.” *Journal of Mixed Methods Research* 2 (3): 270–83.

DoD. 2004. “Chapter 4 -- Systems Engineering.” In *DoD Defense Aquisition Guidebook*, 1248. Defense Acquisition University. https://acc.dau.mil/docs/dag_pdf/dag_complete.pdf.

Easterby-Smith, M., R. Thorpe, and A. Lowe. 1991. *Management Research: An Introduction*. London.: Sage.

Eisner, H, J Marciniak, and R McMillan. 1991. “Computer-Aided Systems of Systems Engineering.” In *Proceedings IEEE COnference on Systems, Man and Cybernetics*, 531–37.

EU_Commission. 2012. “Directions in Systems of Systems Engineering.” Brussels, Belgium. http://cordis.europa.eu/fp7/ict/embedded-systems-engineering/documents/report_system_of_system.pdf.

Forrester, J. 1961. “Origin of System Dynamics.” *System Dynamics Society*. http://www.systemdynamics.org/DL-IntroSysDyn/start.htm.

Freedberg, Sidney. 2016. “Counting on Chaos in the Offset Strategy: SCO.” *Breaking Defense*. http://breakingdefense.com/2016/04/counting-on-chaos-in-the-offset-strategy-sco/?utm_campaign=Breaking+Defense+Daily+Digest&utm_source=hs_email&utm_medium=email&utm_content=28377870&_hsenc=p2ANqtz-9waSWm0JbRDOV2ENbhZAY4LmpAEthT2Lyt7aBqpj6QMQOhhnzqf7jI3Gwy.

Garland, Theodore (University of California). 2015. “The Scientific Method as an on-Going Process.” http://idea.ucr.edu/documents/flash/scientific_method/story.htm.

Henshaw, Michael J De C. 2011. “Assessment of Open Architectures within Defence Procurement Issue 1: Systems of Systems Approach Community Forum Working Group 1 - Open Systems and Architectures.” London, UK. https://dspace.lboro.ac.uk/dspace-jspui/bitstream/2134/8828/1/SoSACF-WG1-Final_Report(Iss1)Aug11%255B1%255D.pdf.

Hitchins, Derek. 2003a. *Advanced Systems: Thinking, Engineering and Management*. 1sted. Norwood, USA: Artech House Inc.

———. 2003b. “Stakeholder Analysis.” In *Advanced Systems: Thinking,Engineering & Management*, 1sted., 203–5. Artech House Inc.

———. 2005. “Guide to the Practice of Systems Engineering.” http://systems.hitchins.net/systems/guide-to-the-practice-of.html.

Honour, E. 2004. “Understanding Value of Systems Engineering (6.2.3).” In *INCOSE International Symposium, June 20-24, 2004*, edited by 14 6.2.3 Understanding the Value of Systems Engineering. INCOSE International Symposium, 1207–22. Tolouse, France: INCOSE. doi:10.1002/j.2334-5837.2004.tb00567.x.

Howick, S. 2012. "Mixing OR and Management Science in Practice." Loughborough. http://www.strath.ac.uk/mansci/staff/howicksusanprof/.

Hubka, Vladimir, and Ernst Eder. 1988. *Theory of Technical Systems*. 3rded. Berlin: Springer.

INCOSE. 2009. "Z1 Guide (Revision 3)." INCOSE (Re. http://incoseonline.org.uk/Program_Files/Publications/zGuides_1.aspx?CatID=Publications.

———. 2015. *Systems Engineering Handbook*. 4thed. Wiley Publishing. http://www.incose.org/ProductsPublications/sehandbook.

INCOSE_UK. 2010. "Systems Engineering Competencies Framework." INCOSE. http://incoseonline.org.uk/Documents/Groups/UKChapter/FRAMEWORK_WEB_Jan2010_Issue3.pdf.

INCOSE BKCASE. 2016. *Systems Engineering Book of Knowledge*. Edited by Richard Adcock. 1.6. Hoboken, New jersey USA. www.sebokwiki.org.

INCOSE MBSE WG. 2012. "INCOSE IW12." In *MBSE Workshop*, 2012. INCOSE.

INCOSE SoS Working Group. 2012. "INCOSE SoS Working Group SoS Pain Point Survey Results." In *NDIA SE Conference October 25, 2012*. San Diego, CA, USA: INCOSE. http://www.dtic.mil/ndia/2012system/ttrack214770.pdf.

Jamshidi, M. 2009. "Introduction to Systems of Systems." In *Systems of Systems Engineering: Principles and Applications*, 1sted., 4. CRC Press.

Jenney, Joe. 2011. "The Managers Guide: Kano Diagrams." http://themanagersguide.blogspot.co.uk/2011/02/6323-kano-diagrams.html.

Johnson, R B, A J Onwuegbuzie, and L A T Turner. 2007. "Towards a Definition of Mixed Methods Research." *Journal of Mixed Methods Research* 1(2): 112–33.

Keswani, Manoj (INCOSE). 2016. "Specialty Engineering." *INCOSE-PI-2015-005-1.0, Version 1.0*. Accessed May 13. http://www.incose.org/docs/default-source/Working-Groups/infrastructure-wg-documents/005-specialty-engineering-pamphlet.pdf?sfvrsn=6.

Kinder, Andrew. 2012. "System of Systems : ' Defining the System of Interest .'" In *2012 7th International Conference on System of Systems Engineering, Genoa, Italy - 16-19 July 2012*, 463–68. Genoa.

Kinder, Andrew, Michael Henshaw, and Carys Siemieniuch. 2014. "International Journal of System of Systems Engineering." *System of Systems Modelling and Simulation – an Outlook and Open Issues* 5 (2). Inderscience Enterprises Ltd.: 150–92. http://dx.doi.org/10.1504/IJSSE.2014.064835.

———. 2015. "Proceedings of 2015 10th IEEE System of Systems Engineering Conference (SoSE)." In *A Model-Based Approach to System of Systems Risk Management*, 122–27. San Antonio, United States: IEEE. doi:10.1109/SYSOSE.2015.7151940.

Lawson, Harold W. 2010. *A Journey through the Systems Landscape*. 1sted. London : College Publications,.

Levine, William S. 2000. *Control System Fundamentals*. 1sted. Boca Raton, FL, USA: CRC Press.

“Literature Reviews.” 2014. *The Writing Center, University of North Carolina at Chapel Hill*. http://writingcenter.unc.edu/handouts/literature-reviews.

Lueth, Knud. 2014. “IoT Market – Forecasts at a Glance.” *IoT Analyitics*. https://iot-analytics.com/iot-market-forecasts-overview/.

MacIntosh, Robert. 2009. “Being Clear About Methodology, Ontology and Epistemology.” http://doctoralstudy.blogspot.co.uk/2009/05/being-clear-about-methodology-ontology.html.

Macmillan. n.d. “Macmillian Dictionary Entry: FFP.” http://www.macmillandictionary.com/dictionary/british/fit-for-purpose.

Maier, Jonathan R., and Georges M. Fadel. 2008. “Affordance Based Design: A Relational Theory for Design.” *Research in Engineering Design* 20 (1): 13–27. doi:10.1007/s00163-008-0060-3.

Maier, Mark. 1998. “Architecting Principles for Systems-of-Systems.” *Systems Engineering* 1 (4): 267–84. doi:10.1002/(SICI)1520-6858(1998)1:4<267::AID-SYS3>3.0.CO;2-D.

———. 2012. “Architecting Principles for Systems-of-Systems.” http://www.infoed.com/Open/PAPERS/systems.htm.

Mcmanus, Hugh, and Daniel Hastings. 2006. “A Framework for Understanding Uncertainty and Its Mitigation and Exploitation in Complex Systems.” *IEEE Engineering Management Review* 34 (3): 20.

Moore, William, and Robert Damper. 1986. “Applications of Built-in-Test Equipment within Large Systems.” *IEE Proceedings G (Electronic Circuits and Systems)* Vol.133 (4): 221. http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=4646844.

Nilsen, Erik, and P Jansma. 1989. “Galileo ’ S Rocky Road to Jupiter.” *Ask*, no. 42: 5–10. http://www.nasa.gov/offices/oce/appel/ask/issues/42/42s_galileo_rocky_road_jupiter.html.

Pahl, Gerhard, and Wolfgang Beitz. 1986. *Engineering Design : A Systematic Approach (Konstruktionalehre Translation)*. Edited by Ken Wallace. London (Orig. Berlin): Design Council, (orig. Springer).

Reason, James. 1990. “The Contribution of Latent Human Failures to the Breakdown of Complex Systems.” In *Philosophical Transactions of the Royal Society Series B*, Series B, 475–84. London: Royal Society of London. doi:10.1098/rtsb.1990.0090.

Rechtin, Eberhardt. 2000. *THE ART OF SYSTEMS ARCHITECTING*. Edited by Mark W. (Aerospace Corporation) Maier. 2nded. Boca Raton London New York Washington, D.C.: CRC Press. https://lib.lhu.edu.vn/ViewFile/11173.

Ring, Jack, and Azad Madni. 2005. “Key Challenges and Opportunities in ‘System of Systems’

Engineering." *2005 IEEE International Conference on Systems, Man and Cybernetics* 1. Ieee: 973–78. doi:10.1109/ICSMC.2005.1571272.

Ring, Jack, Antonio Pizzarello, Oris Friesen, and Byron Davies. 2011. "System of Systems Readiness Assessment." In *2011 21st International Conference on Systems Engineering*, 2:357–61. Ieee. doi:10.1109/ICSEng.2011.71.

Rittel, Horst, and Melvin Webber. 1973. "Dilemmas in a General Theory of Planning." *Policy Sciences* 4: 155–169. http://www.uctc.net/mwebber/Rittel+Webber+Dilemmas+General_Theory_of_Planning.pdf.

Roske, Vincent. 1998. "Military Simulation: Where We Are and Where We Ought to Be Going." In *1998 Winter Simulation Conference*, 771–72.

RU Secure. 2013. "Fit for Purpose." http://www.yourwindow.to/information-security/gl_fitforpurpose.htm.

Rumsfeld, Donald. 2002. "NATO Speech: Press Conference by US SoD." In , 8. Brussels: NATO. http://www.nato.int/docu/speech/2002/s020606g.htm.

Sillitto, Hillary. 2010. "Lean SE: Who Can Afford to Ignore It?" In *INCOSE*, 10. INCOSE Lean SE Working Group.

———. 2011. "Integrating System Thinking System Science & Systems Engineering - Understanding the Difference and Exploiting the Synergies." In *INCOSE ASEC*, 20. INCOSE.

———. 2012. "'Composable Capability' - Principles, Strategies and Methods for Capability Systems Engineering." In , 8. Thales UK.

———. 2014. *(Architecting Systems: Concepts, Principles and Practice*. 1sted. College Publications. http://sillittoenterprises.com/book/.

Smith, Rupert. 2005. *The Utility of Force*. 1sted. London: Pengiun.

Sykttner, Lars. 2006. *General Systems Theory*. 2nd ed. Worls Scientific Publishing Co. pte. http://books.google.co.uk/books?id=tG6QKNgYs9sC&pg=PA56&lpg=PA56&dq=skyttner+%22system+is+something+to+be+recognised%22&source=bl&ots=WhSR4aBTIp&sig=ov1H7MsDE_ql3HNn05bHEBVxHZc&hl=en&sa=X&ei=RrUEUsmKJpTw0gWYr4CYCw&ved=0CGMQ6AEwBw#v=onepage&q=skyttner %22system.

Thales. 2009. "INNOVATION, RESEARCH AND DEVELOPMENT Mastering Complexity." doi:ABN 66 008 642 751.

TRAK. n.d. "TRAK Community Wiki: Defence Line of Development." http://trak-community.org/index.php/wiki/Defence_Line_of_Development.

UK MoD. 2008. "UK MoD AOF." *Aquisition Operating Framework*. https://www.gov.uk/acquisition-operating-framework.

Watson, Richard, and Jane Webster. 2002. "Analyzing the Past to Prepare for the Future: Writing a

Literature Review.” *MIS Quarterly; Jun 2002*, 11. http://classes.uleth.ca/200501/mgt2700b/Articles/Webster & Watson.pdf.

Whewell, William. 1837. *History of the Inductive Sciences*. 3rd. London and Cambridge, UK: John W. Parker. doi:http://dx.doi.org/10.1017/CBO9780511734342.

———. 1847. *Philosophy of the Inductive Sciences*. 2nd ed. London, UK: John W Parker. https://archive.org/details/philosophyinduc00goog.

Wilson, Brian. 2001. *Soft Systems Methodology Conceptual Model Building and Its Contribution*. 1sted. Wiley.

Workinger, Scott. 2007. “Complexity in Systems of Systems.” *Honorcode Inc.* http://oldsite.incose.org/sfbac/2007events/070911ComplexitySoS-v121.pdf.

Zachman, John. 2008. “Zachman Framework.” https://www.zachman.com/about-the-zachman-framework.

This page is intentionally blank

Appendices

Note: these appendices refer to the “FFP” technique/method/process as this original name for the “TCA” technique/method/process was changed in response to a required correction.

A1: PhD Research Proposal

Maintaining System of Systems Fitness-For-Purpose in dynamic situations

Research Outline

“System of Systems” (SoS) describes the circumstance in which a number of individual systems (e.g. products, facilities, services etc.) are brought together to achieve particular desired effects within a particular context or environment. Mayer distinguishes SoS by the independence of their components, their evolutionary nature and emergent behaviour [1] The criteria of “Fit-For-Purpose” (FFP) for a SoS will differ between stakeholders, and will also change with time [2] between points over its lifecycle, such as performance, integration and payment milestones. A SoS compliant to specification may not be universally considered FFP; indeed the SoS specifications will rarely contain all that is required to achieve FFP. Initially the focus of this research is the FFP of a Delivered SoS, (DSoS), but it will necessarily take account of interacting SoSs, utilizing the work of Boardman and Sauser [3] defining five elements that differentiate a system from a SoS, for example those that implement, deploy, supply and maintain the delivered SoS.

The characteristics of a DSoSs are dynamic, and often contain human elements. Its characteristics can be altered by both external influences and internal effectors such as climate, duty, aging and component replacement. Rarely are these independent variables: changes in one of them may affect the others. Not all may be known, and those that are may not be known with the same level of fidelity. [4] Furthermore, their interactions may be non-linear, have latency or not be predictable with a high degree of certainty.

This means that providers (e.g. systems engineering organisations) have great difficulty in engineering DSoSs that are enduringly FFP. [5] [6] [7] All major project teams are tasked with transitioning from one project situation to another desired project situation. However knowledge of the current and future situations and their effectors and influences may be unevenly spread throughout the team or insufficiently known by any member of the team. Often the engineering of new and existing stimuli to orchestrate a change towards the desired situation is complex, subjective and heavily time constrained, which can lead to increased numbers of errors and omissions. Without an up-to-date, readily appreciable, common understanding of a delivered systems’ FFP profile, effort expanded to achieve, say, a current performance FFP may lead to significant re-work to achieve a subsequent integration FFP. It is intended to investigate [8], [9] and [10] in this aspect.

Martin [11] describes seven dynamic systems that must be acknowledged and understood: a context system within which resides a problem system, which is addressed by the intervention system. The realisation system develops the intervention system into the deployed system, which interacts with collaborating and competing systems, altering the context system. Additionally this may also alter the problem, or create other problems. A sustainment system provides necessities and support to the deployed system.

Hitchins [12] suggests a new systems engineering paradigm founded on the principles of open systems using a holistic, elaborative approach that uses a strategy for the management of complex interrelated systems via the management of interactions which drive overall system characteristics and behaviours. For example, the introduction of complementary systems to neutralise perturbations and increase feedback to improve overall stability, and the management of cohesive and dispersive influences.

The identification of parameters affecting DSoS FFP at the boundary of interest at a point in time, and the detection and measurement of change in these parameters are considered fundamental aspects of FFP transition management. This research is building on the references above, other analogous works and also draws upon ideas from other disciplines such as Earned Value Management with the aim to create and develop a technique to predict the likelihood of FFP achievement,. The key academic outcome will be a fundamentally new understanding for systems staff to engage in effective holistic engineering and assist them with the time-constrained problem of transitioning situations in complex, dynamic endeavours.

The historical and current project data, access to project engineering staff and periodic placements for the student from Under a suitable NDA, Thales should provide practical guidance on project transitioning activities and the specification of appropriate tools to enable evaluation, validation, and verification of the research upon real problems so a tangible industrially exploitable output that will engender a Fitness-For-Purpose (FFP) mind- set is created.

Envisaged Outputs

March 2013 Deliverables

- Initial Literature Review Report containing an initial critical review of relevant papers.
- Work plan to October 2013
- Research novelty identified if possible.

September 2013 Deliverables

- First Year 10K Word Report containing problem identification, further critical review of relevant papers as appropriate, research novelty, any initial modeling, design, investigative work and initial analysis and results.
- Description of work for second and third years, with work plan identifying individual tasks.
- Project presentation of progress to date.

September 2014 Deliverables

- A four page report stating the work completed and identifying significant achievements to date, confirming research novelty and refining the work plan until end of the third year. The report should identify two publications that will be submitted for refereeing during the third year or have already been submitted in the second year.
- Outline thesis plan with Gantt chart.
- Finalised thesis plan.

June 2015 Deliverables

- Draft thesis delivered.

September 2015 Deliverables

- Final Thesis delivered.

References
[1] Mayer, M: "Architecting Principles for Systems-of-Systems www.infoed.com/Open/PAPERS/systems.htm"
[2] Ring, J. et al: "Systems of Systems Readiness Assessment" 21st International Conference on Systems Engineering, 2011
[3] Boardman, J.; Sauser, B: "Systems of Systems; The Meaning of "of"" IEEE/SMC International Conference on Systems Engineering 2006
[4] Ring, J.; Madni, A.: "Key Challenges and Opportunities in Systems of Systems Engineering", IEEE International Conference on Systems, Man and Cybernetics 2005
[5] US DoD: Systems Engineering Guide for Systems of Systems, Version 1.0, August 2008
[6] Kaplan, Jeremy M: "A New Conceptual Framework for Net-Centric, Enterprise-Wide, System-of-Systems Engineering" Centre for Defense and National Security Policy, National Defense University, 2006 http://www.ndu.edu/CTNSP/docUploaded/DTP%2030%20A%20New%20Conceptual%20Framework.pdf
[7] Pyster, R and Gardner, P: "Critical Success Factors in Systems of Systems Engineering" Convocation of the USC Center for Systems and Software Engineering (CSSE), at USC October 2006, sunset.usc.edu/events/2006/CSSE_Convocation
[8] Isycri study "Interoperability of Systems in Crisis Situations" http://www.irit.fr/isycri/eng/presentation.html
[9] Dependable SoS: http://research.cs.ncl.ac.uk/cabernet/www.laas.research.ec.org/dsos/
[10] Dependable SoS http://www.dependablesos.org/
[11] Martin, James N: "The Seven Samurai of Systems Engineering: Dealing with the complexity of 7 interrelated systems" INCOSE 2004 Symposium.
[12] Hitchens, Derek K: Advanced Systems; Thinking, Engineering and Management. ISBN 1-58053-619-0.

A2: Cardinal Point Specification for Industrial Case Studies

FFP Case Study CPS v0.1.doc

FFP Industrial Case Study: Cardinal Point Requirements

Introduction

The FFP research has created a method that relates system-of-system capabilities to constituent system / sub-system functions in terms of the interchanges of matter, energy and information interchanges involved. Alongside the method, an engineering process that implements it has been developed and applied to a representative major SoS constituent (a Naval ship).

Aim

The industrial case study should enable a top-down approach from the SoS capability level to complement the development done at the SoS constituent level described above. This document provides a number of cardinal point requirements to assist the selection of an industrial case study to inform further development of both method and process.

Cardinal Point Requirements

The case study should be of a SoS, whose constituents have

- Operational Independence
- Managerial Independence
- Evolutionary Development
- Emergent Behaviour
- Geographical Distribution
- Heterogeneity
- Networks

The case study should provide the capability requirement, acceptance criteria and test method documents, with the User Requirements (URD), System Requirements (SRD) and System Definition (SDD) documents of the SoS's main constituents. (Note: it's acknowledged that the information required may not be in the form of a textual "document" and that titles may differ from those used here).

The case study should provide contextual documents such as CONOPS and associated CONEMP, CONUSE documents.

24/02/2014

A3: RLC Workshop Plan

1. **Brief introduction: Who What When Where Why How Who.**
   Who am ?
   Steve Hinsley, ex- BAE Systems Engineer (to Dec. 2011)
   .
   What am I doing?
   Gathering experiences of end-users of Products & Services, both good and bad.
   .
   Why am I doing it?
   The choice of research topic was driven by the author's observations over several years of working in industry on non-trivial platform systems with several companies based both in the UK and abroad. There appeared to be a trend of delivered goods and services that, although meeting their requirements, needed modification to maintain a desired capability from the composing SoS, and hence be made FFP.
   .
   When am I doing it?
   Over the next year or so.
   .
   How am I doing it?
   As a full-time student; it's the topic of a Systems Engineering PhD.
   .
   Where am I doing it?
   Loughborough University, School of Electronic, Electrical and Systems Engineering, (EE&SE) as part of the Engineering Systems of Systems (ESoS) group.

2. **Presentation**
   Present the PowerPoint.

3. **Questions and Feedback**
   Time-Limited session to answer questions that assist comprehension of the presentation and provide an opportunity for attendees to provide feedback.

4. **Example of Help**
   So that I address real pain points, I would like examples of What and Why activities have gone well or not, and how you think this work may have enabled avoidance and recovery in terms of Material, Energy and Information… that was Complete, Correct and Timely.

5. **Flipchart Writing**
   Groups of no more than 5 capture experiences on flipcharts

6. **Flipchart Top 3 Experiences**
   One person from each group presents their top 3 to the others

7. **Thanks and Closure**
   SWH thanks attendees for their time and leaves cards for anyone wishing to discuss further.

OUTCOME:
(i) End-user awareness of the FFP research (ii) A collection of flipcharts with experiences (iii) SWH's contact details left with interested attendees for follow-up.

A4: RLC Case Study: Workshop Output

This appendix contains a précis spreadsheet that collates information generated by the RLC workshop. Five groups of five people captured operational experiences on flipcharts, which were analysed to determine if the perceived good and bad experiences were due to ME(I) transfer characteristics and what ME(I) SSBs were involved.

	A	B	C	D	E	F
1	UID	Flipchart	Expansion	SSB origin	MEIX Problem	SSBs
2	1	Uniform designed to be worn outside (waist) sleeves down. Tucked-in sleeves up?				
3	2	Aircon on snatch vehicles (IRAQ): Drivers not turning off on long stops (Batteries)	The vehicle batteries are quickly flattened by the aircon remaining on when the engine has stopped.	Intended	Untimely energy sink	Source: vehicle batteries. Bearer: vehicle cable harness, Sink: HVAC Unit.
4	3	Cupola Hatch (Spray Deck)	Water Ingress	Unintended	Incorrect material bearer and sink	Source: environmental water. Bearer: wind and gravity, Sink: vehicle hatch.
5	4	JCB Mods; Rifle holder in the cab door doesn't work, no side bins for kit, webbing, etc.	Rifle not secure, space	Intended	Incorrect material sinks	Source: Crew member. Bearer: Crew member. Sink: Rifle holder.
6	5	JCB Mods; Rifle holder in the cab door doesn't work, no side bins for kit, webbing, etc.	Insufficient storage space	Unintended	Incomplete material sinks	Source: Crew member. Bearer: Crew member. Sink: None.
7	6	Flat Racks: Two types; "A" and "GP". GP is the only one for containers. Why not build just a GP flatrack?	Brief examination of both type of racks suggested a universal type was feasible. One respondent said 70% of racks were "A" type, and spent months finding GP's on operations because most supplies were containerised.	Intended	Incorrect material sink	Source: Material dispatch. Bearer: flat rack. Sink: Stores requisitioner.
8	7	Flat Racks: Corner casts fill with earth when deploying on soft ground, then has to be removes before loading onto a kingss-SWB trailer.	The earth becomes so compact and hard it needs something like a crowbar or hammer and chisel to remove it.	Unintended	Unintended material sink	Source: Soft ground. Bearer; ? Sink: Flatrack pocket
9	8	Bedford MJ: New wheels, PWRS, 5th Gear.	Suggested improvements to the previous vehicle rather than procure the current MAN vehicle.	Intended	Incomplete information source	Source: User community. Bearer: IPT members. Sink: Requirement specification.
10	9	SV tailgate pins: locking pins stick out at around 45 degrees down at head height when the tailgate is down unless pushed back in again.	Hazardous, especially in the dark.	Unintended	Unintended energy bearer and sink	Source: vehicle. Bearer: Locking pin. Sink: Passing personnel.
11	10	Jerrycan holder on SV: Water Jerrycans don't fit in. Only suitable for fuel cans.	Plastic water jerrycans cans bulge and can't be inserted into the racks.	Intended	Incorrect material bearer	Source: vehicle crewmember. Bearer: vehicle crewmwmber. Sink: Jerrycan holder.
12	11	Titan / Trojan: Plant crane arm very slow; one hydraulic pump	Retards operations often necessary in hazardous situations	Intended	untimely energy source and bearer	Source: Hydraulic pump. Bearer: hydraulic lines. Sink: Plant crane rams.
13						

Group "A" / Group "B" / Group "C" / Group "D" / Group "E" / Discussions

RLC Workshop Group "A"

	A	B	C	D	E	F
1	UID	Flipchart	Expansion	SSB origin	In terms of MEIX	SSBs
2	1	Side visibility: (Top of window too low)	Obstacles are hidden from the driver's view. A Fresnel lens has been added to the passenger window to alleviate another blind-spot	Intended	incomplete energy and information bearer	Source: Objects. Bearer: Sightline. Sink: Crew.
3	2	IST Turning circle (better with rear wheel turn)	The greater (than previous vehicle) turning circle means that entering many premises is difficult	Intended	incorrect material bearer	Source: Vehicle current position. Bearer: vehicle. Sink: vehicle's next position.
4	3	Engine oil dipstick (extension on old versions required)	Difficult to access	Intended	incorrect material bearer	Source: Engine Sump. Bearer: Dipstick. Sink: Crew.
5	4	Side bins fill with water and do not drain out completely	There is a lid seal, but any water ingress and any from stowing wet equipment for example cannot drain away.	Intended	incorrect material bearer	Source: External environment. Bearer: Stores . Sink: Bins.
6	5	No Cab Radio	The radio fitted as standard to the commercial variant has been removed.	Intended	incomplete energy and information bearer	Source: External RF Transmissions . Bearer: RF Link . Sink: Crew.
7	6	BV in wrong place	The Boiling Vessel is sited in the centre of the cab, but the switch is on the passenger side. Thus a lone driver unable to stop cannot switch it on whilst driving, and hence has to wait for a hot meal at his destination.	Intended	incorrect energy sink and bearer	Source: Crew. Bearer: Crew . Sink: BV switch.
8						

RLC Workshop Group "B"

	A	B	C	D	E	F
1	UID	Flipchart	Expansion	SSB origin	In terms of MEIX	SSBs
2	1	Tailgate too high, too heavy, canvas too high (on SV)	Current vehicle more difficult than previous Bedford vehicle, but MAN vehicle has far superior cross-country performance.	Intended	Incorrect energy sink and bearer	Source: Crew. Bearer: Crew. Sink: Tailgate / Canvas.
3	2	Not enough roof storage space for cam net & load sheet	Can result in blocked HVAC intakes and heat exchanger	Intended	Incomplete Material Sink	Source: Net & Sheet. Bearer: Crew. Sink: Storage position.
4	3	Cam nets do not fit vehicles SV and SVR	Retained from previous vehicles	Intended	Incorrect energy sink and bearer	Source: Net. Bearer: Crew. Sink: Vehicle.
5	4	Unable to cam up effectively without walking on canvas roof, potentially damaging structure (on SV)	Canvas supports were metal, but were changed to fibreglass.	Unintended	Unintended exchange utilised by user	Source: Net. Bearer: Crew. Sink: Vehicle.
6	5	Lack of storage for personal kit on SVR	any "spare" space considered suitable is used		Inadequate Material Sink	Source: Crew. Bearer: Crew. Sink: Storage position.
7	6	Spare wheel on wrong side of vehicles for UK SV and SVR	On offside (unchanged from continental variant)		Incorrect Material Sink	Source: Spare wheel. Bearer: Crew. Sink: Spare wheel storage.
8	7	Canvas not easily removed and stored for flat rack use (SV)		Intended	Incorrect energy sink and bearer	Source: Canvas Fixings. Bearer: Crew. Sink: Storage position.
9						

RLC Workshop Group "C"

UID	Flipchart	Expansion	SSB origin	In terms of MEIX	SSBs
1	Mirrors electric (adjustment)	Mirrors cannot be finely adjusted	Intended	Incorrect energy bearer	Source: Crew. Bearer: Crew. Sink: Mirror.
2	Passenger mirror	Mirror cannot be pan and tilted by the driver to facilitate vehicle manoeuvring	Intended	Incorrect energy bearer	Source: Crew. Bearer: Crew. Sink: Mirror.
3	Spare wheel wrong side	On offside on UK variant (unchanged from continental variant).		Incorrect Material Sink	Source: Spare wheel. Bearer: Crew. Sink: Spare wheel storage.
4	Steering circle	The greater (than previous vehicle) turning circle means that entering many premises is difficult	Intended	incorrect material bearer	Source: Vehicle current position. Bearer: vehicle. Sink: vehicle's next position.
5	Cab tilt support bar		Intended		Source: . Bearer: . Sink: .
6	Gear change too slow (from "D" to "R")	Operations compromised: e.g. Vehicle cannot be "rocked" out of low traction hollows.	Unintended	Untimely energy bearer	Source: Current vehicle position. Bearer: vehicle. Sink: desired vehicle position.

RLC Workshop Group "D"

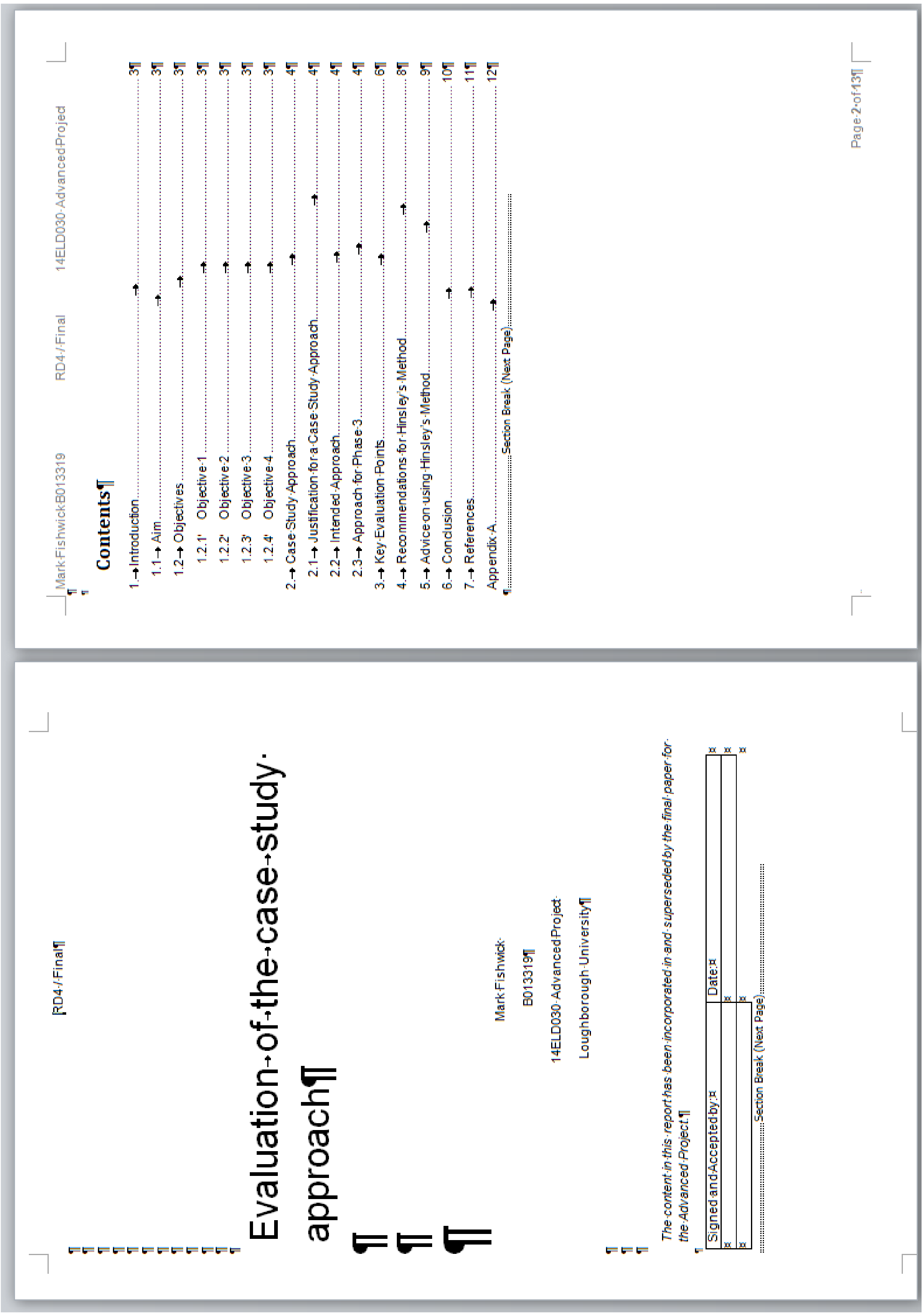
UID	Flipchart	Expansion	SSB origin	In terms of MEIX	SSBs
1	Load deck higher difficulty to access (9"-12" higher than previous vehicle	Difficult to load vehicle	Intended	Incorrect material bearer	Source: Crew. Bearer: Crew. Sink: Load Deck.
2	Lashing holes in floor: road spray enters load bay and wets stores being carried	This means that water and debris invulnerable stores as loaded first to protect vulnerable stores, rather tan "last-on, first-off" which reduces efficiency of supply	Unintended	Incorrect material bearer	Source: ground surface. Bearer: ?. Sink: Cargo.
3	Canvas supports: were metal, now fibreglass, no longer supports a person's weight.	Canvas supports were metal, but were changed to fibreglass. Crew climb on canvas roof to cam-up efficiently.	Unintended	Unintended exchange utilised by user	Source: Cam Net. Bearer: Crew. Sink: vehicle.

RLC Workshop Group "E"

UID	Flipchart	Expansion	SSB origin	MEIX Problem	SSBs
1	n/a	Rotzler Self-Recovery Winch: Some SVs are fitted with a hydraulically-powered self-recovery winch. SV's have an electronic handbrake. If the winch is attempted to be used to pull something towards the vehicle, the handbrake will automatically release as the engine is rewed and pull the vehicle towards it!	Intended	Incorrect energy transfer	Source: Pump. Bearer: Cable. Sink: Load.

RLC Workshop Group Discussions

A5: MEng project Evaluation Report: Mark Fishwick



RD4 / Final

Evaluation of the case study approach

Mark Fishwick
B013319
14ELD030 Advanced Project
Loughborough University

The content in this report has been incorporated in and superseded by the final paper for the Advanced Project.

Signed and Accepted by:	Date:

Section Break (Next Page)

Mark Fishwick B013319 RD4 / Final 14ELD030 Advanced Project

Contents

Section Break (Next Page)

Page 2 of 13

1. Introduction

This report is an evaluation of the process used to apply Hinsley's methodology. It will evaluate how the case study was evaluated and provide recommendations on the process to Hinsley. It is being written in support of research objective RO5 for the Advanced Project:

- RO5: Evaluate the application of Hinsley's methodology and produce recommendations for Hinsley's methodology.

In order to achieve this objective, this report will consist of four sections. The first section will cover the approach taken for the case study. The second section will be an evaluation of this approach. The third section will consist of recommendations for Hinsley based on the evaluation of the case study approach.

The final section will incorporate content which was originally intended for inclusion in RD5 (User guide for Hinsley's methodology. [RO6]). The original research deliverable and research objective was chosen to allow for variation depending on the outcomes from the case study evaluation. It is the author's view that a user guide for Hinsley's method would add little value and instead the author intends to include a section in this report. This additional section will consist of advice on using Hinsley's method based on the author's experience of applying it in a case study context.

This report is being produced as research deliverable RD4 for the Advanced Project.

1.1 Aim

The aim of this report is to evaluate the application of Hinsley's method and produce recommendations for the development of Hinsley's method.

1.2 Objectives

In order to meet this aim a number of objectives have been identified:

1.2.1 Objective 1

Introduce the approach taken for applying Hinsley's method to the case study.

1.2.2 Objective 2

Evaluate the approach taken for applying Hinsley's method to the case study

1.2.3 Objective 3

Produce recommendations for Hinsley based on the evaluation of the approach taken.

1.2.4 Objective 4

Produce advice on using Hinsley's method based on the experience of applying it in a case study context.

2. Case Study Approach

This section introduces the approach taken for the case study, which includes the application of Hinsley's method. It is split into three sub-sections. The first sub-section contains a justification for why a case study approach was used. The second sub-section introduces the intended approach, which was detailed in RD2. This covers the three phases to the case study at a high level, which was sufficient for phases 1 and 2. The third sub-section details the actual approach taken for Phase 3 as this is considered in order to provide the context for the evaluation of Hinsley's method.

2.1 Justification for a Case Study Approach

To include:

- Justification on why a case study evaluation was appropriate

See notes from GW2 (p66/67 of log book and formal feedback)

2.2 Intended Approach

The intended approach for the case study was detailed in RD2. It consisted of three phases which are as follows:

- Phase 1: Case Study Identification – identify a case study which meets the defined selection criteria and for which sufficient suitable information is available for use.
- Phase 2: Case Study Scope – define the scope of the problem for the case study and map out the causes of the problem and the systems within which it resides.
- Phase 3: Applying Hinsley's Method – Apply the chronological FFP process developed by Hinsley to the case study.

Originally the intention was to conduct the case study using a pilot run through followed by a full run through. However a formal pilot run through was only conducted for Phase 1, the results of which are captured in RD2. The full run through of all three phases is captured in RD3, with Phase 1 and Phase 2 captured as part of the Problem Explanation and Phase 3 captured in three parts: MEI Exchange models, Evaluation of the MEI Exchange models and Recommendations for the Case Study Owner.

More detail on how the direction of the case study was changed can be found in Appendix A.

2.3 Approach for Phase 3

Phase 3 was recorded in the section on MEI Exchange models in RD3. The approach set out in RD2 was that Phase 3 would simply consist of applying Hinsley's Chronological FFP Process (see [1]) to the case study data in order to produce MEI Exchanges models for evaluation. The case study used what at the time was version 2 of the Chronological FFP Process (see [1]) developed by Hinsley. This has since been up-issued to version 3 (see [2]), although the differences between the two versions were the result of a discussion between the author and Hinsley whilst the author was conducting the case study using version 2.

The following paragraphs detail the approach taken for Phase 3, which has been derived from the actual conduct of the case study, which was recorded in RD3.

Most of the information for the case study was derived from the feasibility study into the proposed modification (see [3]) which was used to develop a model of the intended MEI exchanges. The sources, sinks and bearers were derived from the underlying data and are dependent on the author's qualitative opinions as opposed to being derived from quantitative data. Following the process defined by Hinsley's method, the author identified areas of interest based on the qualitative opinions on what should be considered for inclusion.

The inherent MEI exchanges were again identified based on the author's understanding of those exchanges which would actually be relevant. The model showing the combined intended and inherent MEI exchanges was developed based on these qualitative opinions.

The independent MEI exchanges were identified based on those systems which did not directly interact with the system of interest. This primarily included looking at equipment within the engine bay which bleed air passed through and the potential impact of the proposed modification or future changes to this equipment. The only independent MEI exchange not covered by this was the potential of the change of fuel type. However the author would expect that such a change would involve reviewing the impact of the change.

3. Key Evaluation Points

The following is a list of key evaluation points based on the approach taken for the case study. They are intended to capture the key issues which became apparent during the conduct of the case study and lead directly to recommendations to be provided to Steve Hinsley on his method.

- Results would be difficult to reproduce as different users of Hinsley's method would focus on different things dependent on their knowledge of the system (or system of systems)
- The process is highly reliant on qualitative opinions and did not appear to contain a catch all (e.g. some way of ensuring that "everything" was considered). This may indicate that the process needs to be tailored for each application prior to actual use.
- There was no clear cut way of identifying independent MEI exchanges which were relevant to the system. Whilst the definition and importance of MEI exchanges is clear, the author found it extremely difficult to independent MEI exchanges beyond those already highlighted as having potential by the case study owner.
  - The effect of intended and inherent MEI exchanges should be generally well understood by any system's designers. It is the summation of these which may yield interesting results in addition to the independent MEI exchanges.
  - The author's experience of working with aircraft system of systems is that individual engineering departments are responsible for their own systems and any other systems or bays with which their own systems interact. It is in Design Reviews and higher level reviews where some of the findings from the case study would be expected to be picked up. However the author would question whether relevant independent MEI exchanges would be picked up based on the limited guidance in Hinsley's method.
  - It seems that the intended and inherent MEI exchanges would be best captured by those already familiar with the system. However it is likely that independent MEI exchanges would be best captured by those slightly removed from the system of interest (i.e. in the same way that Design Reviews are conducted by those in other parts of the same company).
- The proposed modification and other future modifications could reduce the agility of the system of systems. This can be defined as "...the ability of a system...to adapt to rapid, unexpected or unknown change from its environment." [4] This can be considered to be the case for any change to be made to the aircraft, in that any modifications made have the potential to alter (either positively or negatively) the ability of the system to incorporate future changes.
  - Hinsley's method appears to be aimed at looking at an entire system or system of systems. However the time taken to analyse a relatively small modification indicates that the time taken to apply Hinsley's method to an entire system or system of systems would be excessive.
  - Based on the analysis conducted, it appears that Hinsley's method does provide a more complete understanding of the system of interest. However if

Hinsley's method was used for a larger system of interest, it appears that it would significantly increase the effort required to fulfil produce a similar output. This is because the system addressed in the case study was relatively simple and a larger system would almost inevitably be more complex, necessitating additional time and resources. Section Break (Next Page)

4. Recommendations for Hinsley's Method

The following is a list of recommendations for Hinsley's method. These have been derived from the key evaluation points in Section 3 and are intended to capture the key issues which arose whilst applying Hinsley's method to a case study. It is important to note that the use of Hinsley's method was based on the Chronological FFP Process (v3.0), using other materials from Hinsley to aid understanding.

- A more detailed process, including definitions and examples of the terminology is required to ensure a consistent application of the process by different users. This would help to ensure that results could be reproduced (allowing conclusions to be verified) by ensuring that the meaning of different steps are less open to individual interpretation.
- Guidance on how to tailor the process, in particular for complex systems or system of systems, is required in order to ensure that the process can actually be applied using a reasonable amount of time and resources. Based on the small system of interest considered for the case study, it is not expected that the process could reasonably be applied to an entire system or system of systems. As such it would be helpful to include guidance on how to select areas where the complete process could be applied based on a more top level application of the process.
- From the results of the case study and the difficulties experienced of identifying independent MEI exchanges, it is recommended that some consideration is given to the type of people who should use the process. It is anticipated that the intended and inherent MEI exchanges could be best identified by those closely involved with the system. However it is anticipated that the independent MEI exchanges could be best identified by those working not closely involved with the system as they would be more likely to think of issues which could be considered as being outside of the system of interest.
- It appears that Hinsley's method could be used in part to analyse the agility of a system or a system of systems. One interpretation of Hinsley's method is that it can be used to maintain a system of system's fitness for purpose by analysing its agility, that is: "…the ability of a system…to adapt to rapid, unexpected or unknown change from its environment." [4]
- It may be useful to look at how an iterative approach can be taken using Hinsley's method. It may be worth developing a similar but separate process which can be used to assist with the iteration of the process. Section Break (Next Page)

5. Advice on using Hinsley's Method

This section is intended to provide advice to future users of Hinsley's method based on the author's experience of applying Hinsley's method to a case study based on a minor proposed modification to a complex system of systems, the Panavia Tornado. It should be noted that this advice is based on a single case study evaluation covering a relatively small system of interest and may not be fully applicable to other case study contexts.

- In theory, Hinsley's method could be applied to a large and complex system of systems. However based on the case study conducted by the author, this would require a large amount of time and resources, even if the required information was readily available and in a suitable format. As such, the author recommends that an engineering judgement be made on how the system of interest is determined. This should focus on areas where there is clear potential for issues to arise (or where issues could lead to serious problems) as opposed to analysing the entire system or system of systems.
- Hinsley's method should be used by at least two users: one with intimate knowledge of the system of interest and one with little previous experience of the system of interest (e.g. from another domain or different project). The first user is likely to be best placed to identify the intended and inherent MEI exchanges, whereas the second user would be well placed to identify additional inherent MEI exchanges as well as the independent MEI exchanges.
- Users of Hinsley's method should take note of Hinsley's statement that the process is "Not a substitute for wisdom & expertise" [5]. Based on the author's experience of conducting a case study using Hinsley's method, it seems that relevant engineering experience and knowledge of the system of interest is likely to be required in order to realise any benefits from using the process.

As part of seeking the case study owner's approval for the publication of RD3 and the final paper, it would be beneficial to obtain answers to a number of questions concerning the potential usefulness of Hinsley's method. A proposed set of questions is as follows:

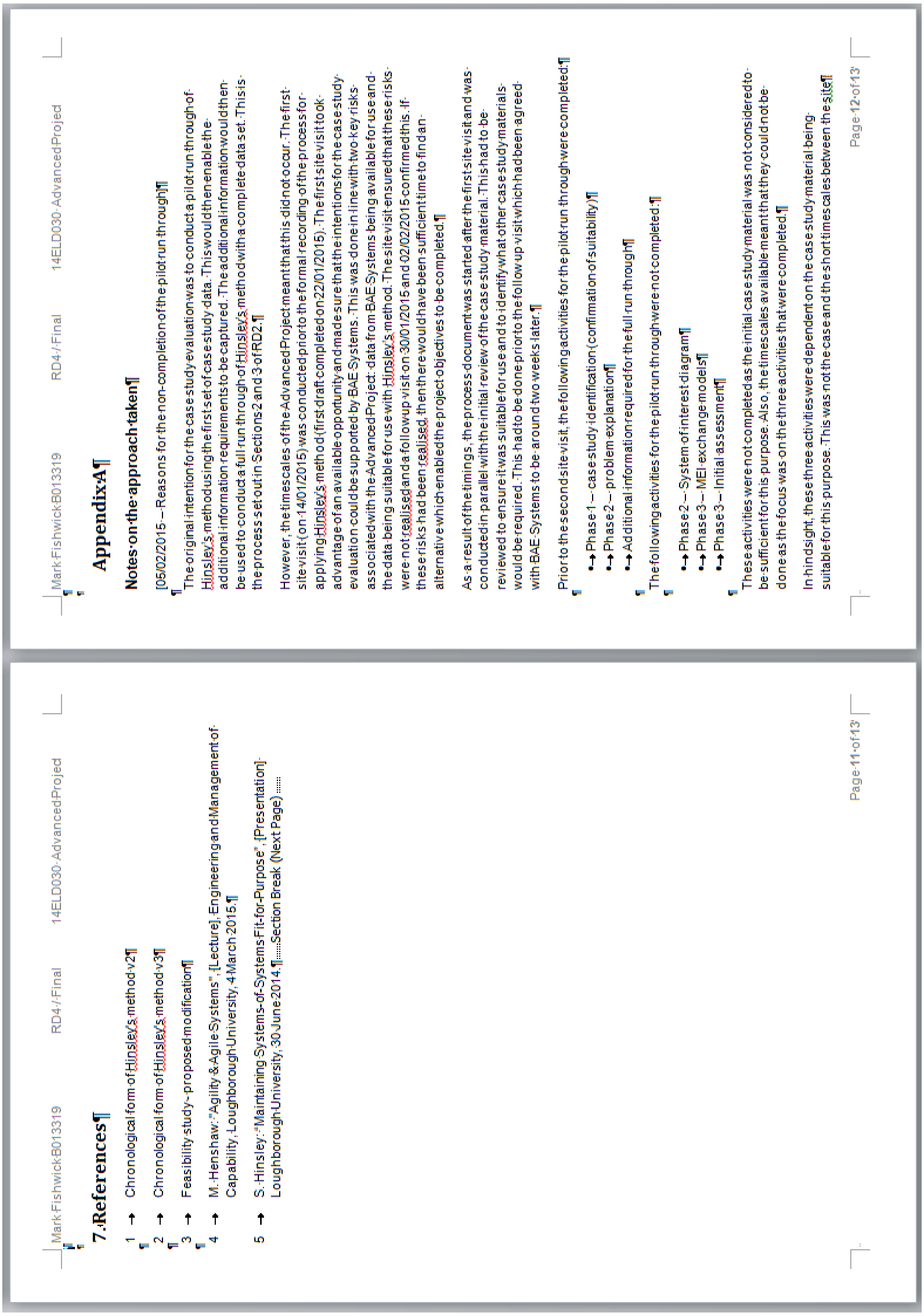
- Would using this kind of approach in the future be useful?
- Did the case study evaluation flag up any problems / exploitation routes?
- How might the case study owner envisage using such a tool?

6. Conclusion

The aim of this report was to evaluate the application of Hinsley's method and produce recommendations for the development of Hinsley's method. The author has highlighted 4 key evaluation points based on the case study evaluation. These have yielded 5 recommendations for Hinsley's method as well as 3 pieces of advice, intended for users of Hinsley's method in its current format. This information will be fed back to Steve Hinsley and is intended to assist with the development of Hinsley's method.

The key evaluation points, recommendations and advice will be formally presented in the final paper and discussed in the conclusion to the final paper.

Section 2 introduced the approach taken for applying Hinsley's method to the case study, thus fulfilling objective 1. This approach was subsequently evaluated in Section 3, thus fulfilling objective 2. A set of recommendations for Hinsley were presented in Section 4, thus fulfilling objective 3. Advice on using Hinsley's method was presented in Section 5, thus fulfilling objective 4. Section Break (Next Page)


Mark Fishwick B013319 RD4 / Final 14ELD030 Advanced Projed

7. References

1 Chronological form of Hinsley's method v2

2 Chronological form of Hinsley's method v3

3 Feasibility study - proposed modification

4 M. Henshaw: "Agility & Agile Systems", [Lecture], Engineering and Management of Capability, Loughborough University, 4 March 2015.

5 S. Hinsley: "Maintaining Systems-of-Systems Fit-for-Purpose", [Presentation] Loughborough University, 30 June 2014. Section Break (Next Page)

Page 11 of 13

Mark Fishwick B013319 RD4 / Final 14ELD030 Advanced Projed

Appendix A

Notes on the approach taken

[05/02/2015 – Reasons for the non-completion of the pilot run through]

The original intention for the case study evaluation was to conduct a pilot run through of Hinsley's method using the first set of case study data. This would then enable the additional information requirements to be captured. The additional information would then be used to conduct a full run through of Hinsley's method with a complete data set. This is the process set out in Sections 2 and 3 of RD2.

However, the timescales of the Advanced Project meant that this did not occur. The first site visit (on 14/01/2015) was conducted prior to the formal recording of the process for applying Hinsley's method (first draft completed on 22/01/2015). The first site visit took advantage of an available opportunity and made sure that the intentions for the case study evaluation could be supported by BAE Systems. This was done in line with two key risks associated with the Advanced Project: data from BAE Systems being available for use and the data being suitable for use with Hinsley's method. The site visit ensured that these risks were not realised and a follow up visit on 30/01/2015 and 02/02/2015 confirmed this. If these risks had been realised, then there would have been sufficient time to find an alternative which enabled the project objectives to be completed.

As a result of the timings, the process document was started after the first site visit and was conducted in parallel with the initial review of the case study material. This had to be reviewed to ensure it was suitable for use and to identify what other case study materials would be required. This had to be done prior to the follow up visit which had been agreed with BAE Systems to be around two weeks later.

Prior to the second site visit, the following activities for the pilot run through were completed:

- Phase 1 – case study identification (confirmation of suitability)
- Phase 2 – problem explanation
- Additional information required for the full run through

The following activities for the pilot run through were not completed:

- Phase 2 – System of interest diagram
- Phase 3 – MEI exchange models
- Phase 3 – Initial assessment

These activities were not completed as the initial case study material was not considered to be sufficient for this purpose. Also, the timescales available meant that they could not be done as the focus was on the three activities that were completed.

In hindsight, these three activities were dependent on the case study material being suitable for this purpose. This was not the case and the short timescales between the site

Page 12 of 13

visits meant that the pilot run through could not be completed. If the case study material had been sufficient then it is likely that the second site visit would have been delayed in order to provide sufficient time to review the case study material. However doing this could have potentially delayed the project, leading to additional risks.

The breakdown involving a pilot run through and a full through was intended to guide the process of the case study evaluation as part of the Advanced Project. If Hinsley's method was being used to look at a case study from within the business then this breakdown would not necessarily be appropriate. However, the author would expect that the initial problem would not have sufficient information to conduct the desired assessment. If the initial problem is of a larger scope than the case study considered in the Advanced Project then it is expected that there would be sufficient information available to conduct the pilot run through. This is desirable as it would likely yield initial conclusions within a shorter timescale than a full run through, potentially allowing the key aspects to be looked at in greater detail.

A6: Précis of Thales Engagement

This précis only contains salient engagements with Thales that relate to the research described in this thesis, and does not include telephone and e-mail communications.

Oct 2012: Discussion of initial interest in research proposal from Thales UK systems engineering functional lead (Loughborough).

Nov 2012: Research proposal modified in response to Thales comments.

Jan 2013:PhD. briefing to Thales UK and Thales France systems engineering functional leads (Loughborough).

Feb 2013: Research progress meeting with Thales UK and Thales France systems engineering functional leads (Loughborough).

May 2013: Six-Month Report to Thales for comments.

July 2013 PhD briefing to Thales UK and Thales France systems engineering functional leads (Loughborough).

July 2013: Studentship agreement signed-off by Thales VP for Legal and Contracts, Loughborough University Senior Grants and Contracts officer and Student.

Aug 2013: Research discussion with Thales UK Head of Systems Engineering (Thales Glasgow).

Oct 2013: 12 month report review with Thales industrial Supervisor.

Nov 2013: IS 2014 Conference Paper Review with Thales Industrial supervisor.

Jan 2014: Systems research way forward meeting with Thales industrial supervisor at Loughborough.

Feb 2014: Presentation to Thales UK heads of engineering at Thales Systems Engineering Research & Technology Review, (Thales Reading).

Feb 2014: FFP Research Focus telecons with Thales industrial supervisor.

Mar 2014: INCOSE ASEC Presentation telecons with Thales industrial supervisor

Mar 2014: Presentation to FFP research meeting and discussions with Thales UK and Thales France systems engineering functional leads (Thales Crawley)

Apr 2014: Research and Case Study Presentation to candidate case study project Team, (Thales Cheadle Heath)

Aug 2014: Research Overview & Way Forward meeting with Thales industrial supervisor (Loughborough)

Sep 2014: FFP research review, (Thales Crawley)

Nov 2014: Research and Case Study Presentation and discussion with Principal Systems Engineer andT3S engineering manager of candidate case study project (Thales Bristol)

Dec 2014: Contribution to Thales Systems Engineering Research end of year report.

Dec 2014: FFP Research Update to Thales (LU)

Feb 2015: Research presentation, discussion and demonstration of candidate case-study project with Principal Systems Engineer andT3S engineering manager (Thales Reading).

Apr 2015: Presentation and discussions with Thales UK heads of engineering at Thales Systems Engineering Research & Technology Review, (Thales Weybridge)

Aug 2015: IEEE Journal paper review with Thales industrial supervisor

Sept 2015: FFP Senior staff presentation (Thales Weybridge)

Sept 2015: Teleconference research presentation and discussion with Thales System Architect. (Thales Templecombe)

Sept 2015: Teleconference research presentation and discussion with Thales VP of Engineering (Thales Weybridge)

Oct 2015: Teleconference research presentation and discussion with Thales System Architect (Thales Templecombe)

Nov 2015 IS 2016 Conference paper approval meeting with Thales industrial supervisor (Loughborough)

Nov 2015: Research Presentation to Senior staff presentation to Thales VP of Engineering and Director Quality & Customer Satisfaction (Thales Weybridge)

Jan 2016: Contribution to Thales Systems Engineering Research end of year report.

Apr 2016: FFP research completion meeting with Thales UK and Thales France systems engineering functional leads and Thales VP of Systems Engineering (Loughborough).

A7: An "eTUP" for the FFP Technique

Predict Through-Life Fitness-For-Purpose

OVERVIEW & EXPECTED BENEFITS

The collection of societal needs that have to be satisfied by the systems intended to meet them is an increasingly difficult target for system suppliers. Needs are ever more unpredictable: appearing, disappearing, changing and interacting faster than solutions able to address them can be instantiated. Solutions themselves similarly continually change as a result of both external and internal influences – upgrades, reconfigurations, etc.

This practice addresses the problem of maintaining Systems-of-Systems (SoS) Fit-For-Purpose (FFP) after unforeseeable changes in operation, composition or external factors, and addresses this problem by delivering an engineering method and process to assist the suppliers of SoS constituents (i.e. Systems) to equip their human elements to address their current problems and/or desires. Research shows that a SoS that does not achieve or maintain FFP is because it cannot implement the correct, timely and complete transfer of Material, Energy and Information (MEI) between its constituents and with its external environment that is necessary to achieve a particular result.

This practice provides a novel viewpoint and hence a more complete understanding of the System-of-Interest (SoI). This greater understanding can be applied in numerous ways as can any knowledge of the SoI, but here the focus is on three general objectives:

- Uncovering concealed root causes of embryonic potential problems in the SoI
- Guiding engineers to enhance the affordance***** of SoS constituents for the transfer of material, energy and information
- Indicating prospective avenues for innovation.

***** *(defined at the INCOSE ASEC 2011 conference as "Features that provide the potential for interaction by "Affording the ability to do something, as perceived by the user, to achieve some goal"" (Sillitto 2011))*

PRACTICE DESCRIPTION

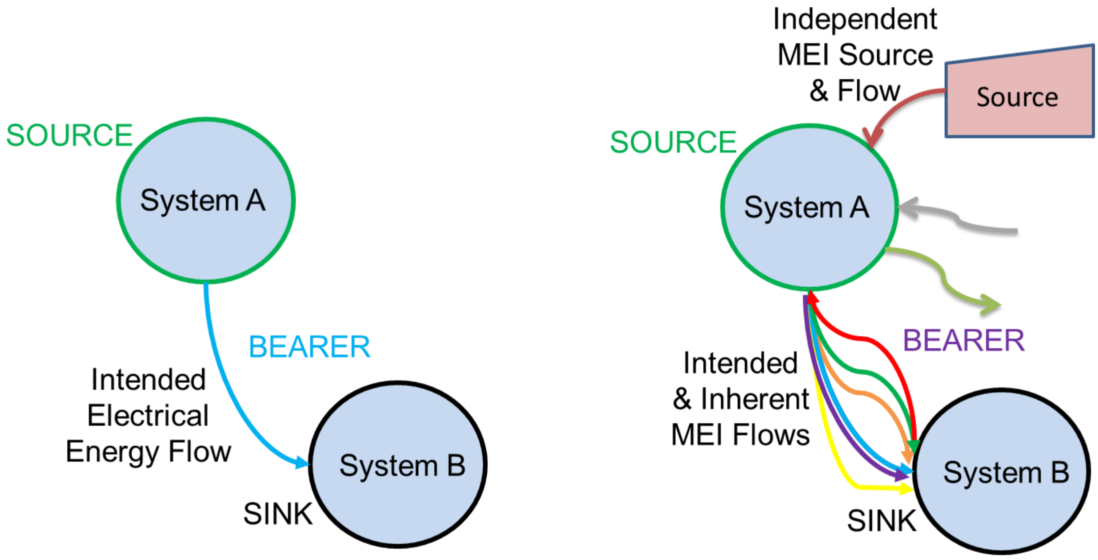
Essentially this practice consists of six steps:

(i) Begin a MEI meta-model representation of the system-of-interest as a diagram of interconnected MEI SSBs that bring about the '***intended'*** MEI transfers designed to bring about the desired system operation.

(ii) Characterise these ‘intended’ MEI SSBs in terms of their *ability* (spectra), *opportunity* (duty) and *influence* (magnitude) to determine ***transfer headroom.***

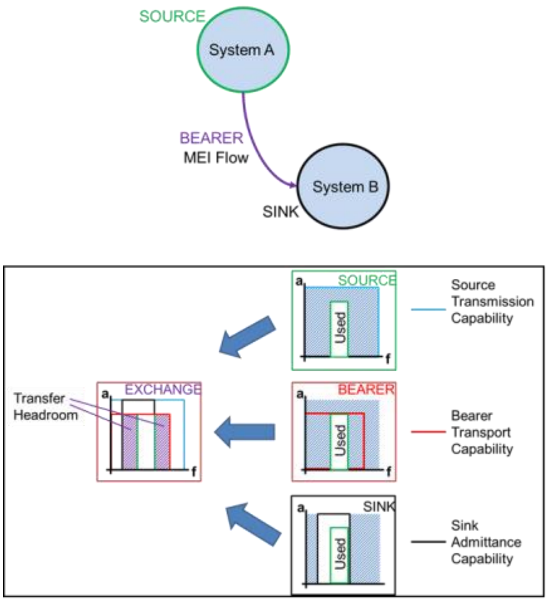
(iii) Visualise the MEI SSBs that are ‘***inherent***’ with the ‘intended’ MEI SSBs and characterise them as above, and add to the meta-model. For example a Steel Wire Armoured (SWA) DC power cable Intentionally connecting two components will also Inherently conduct AC, connect them thermally, magnetically and also mechanically, any of which might be problematic or exploitable.

(iv) Visualise the MEI SSBs that are ‘***independent’*** of the ‘intended’ MEI SSBs, characterise them as above, and add to the meta-model. For example vibrations from remote machinery via a common structure.

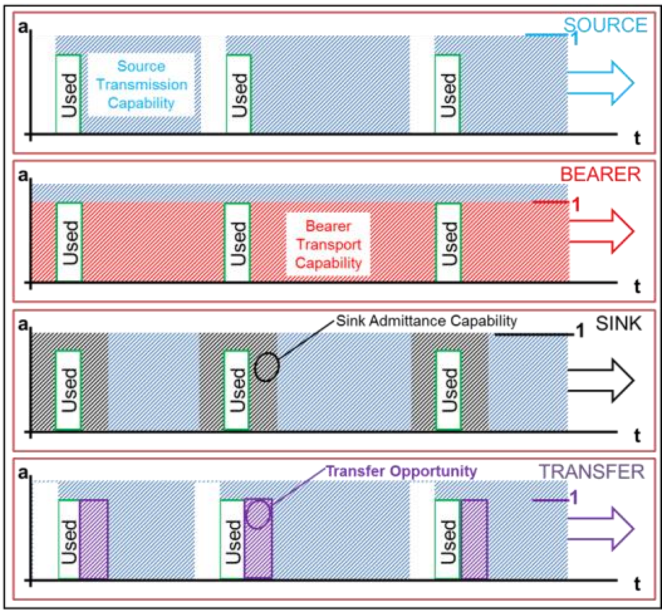


“Designed-For” *“Actual”*

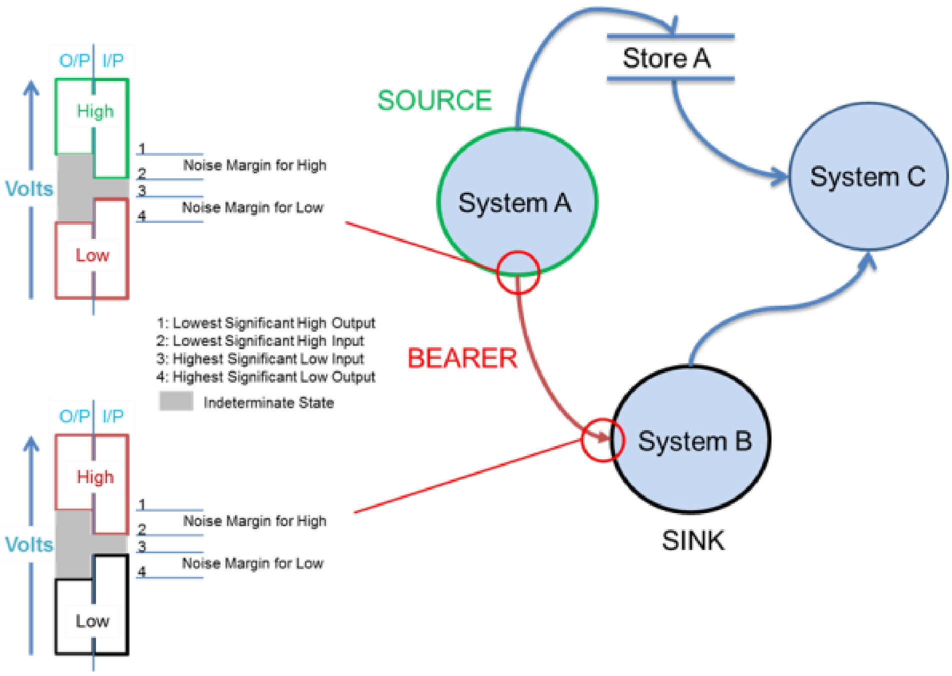
(v) Determine the unintended transfer mechanisms formed by connected SSBs that have the ability (i.e. SSBs with a common spectra) and the opportunity (i.e. SSBs with common active periods) and with the influence (i.e. SSBs with able to transfer sufficient amounts of MEI) to change the designed-for operation of the system of interest.



The ability for MEI Transfer



The opportunity for MEI Transfer



The influence of an MEI Transfer

(vi) Decide what action (if any) needs to be taken about these influential unintended MEI transfers to either reduce any risk they pose to an acceptable level or to exploit them to the desired level of system MEI transfer affordance enhancement, recording each decision and its rationale.

IMPLEMENTATION CHECKPOINT

A MEI meta-model exists with characterised MEI SSBs and MEI transfers endorsed as insignificant, mitigated or exploited with their sanctioning rationale.

COMMON PITFALLS

The knowledge of ‘inherent’ and ‘independent’ MEI transfers in the system-of-interest may not be readily apparent within any one engineering discipline, but dispersed across several specialists’ disciplines. The electrical characteristics of mechanical structures might be considered by mechanical engineers, for example in terms of galvanic corrosion, and by electrical engineers for example in terms of earth bonding. The mechanical characteristics of electrical cabling may be considered by various engineering disciplines for example in terms of strain relief, sway space, thermal expansion and cable routing. An early collation of disparate specialist viewpoints into one artefact would have avoided or mitigated many problems caused by inherent and ‘independent’ MEI transfers that remained covert throughout design and development only to reveal themselves ‘late in the day’ when they were difficult to rectify and costly in terms of both margin and reputation.

A8: BEng Project Proposal

Electronic, Electrical and Systems Engineering

Loughborough University

Individual project - Initial project specification

Note: This initial specification is to be given to the student prior to Gateway 1 to enable the student to start work on the project. The specification is extended and formally recorded as part of Gateway 1 and is finalised as part of Gateway 2.

Supervisor: M. Henshaw

Student: Nathan Robert White

Programme: ☐ ECS BEng ☐ ECS MEng ☐ EEE BEng ☐ EEE MEng ☒ SE BEng ☐ SE MEng

Project title: Autonomous Indication and Visualisation of Risk and Opportunity in unintentional interfaces

Project description:

During the design phase, engineers often consider only the direct implications of their design choices and interfaces, however they neglect to consider the inherent risks and opportunities that are presented as a result of these interfaces. These inherent risks and opportunities can affect how the wider system of systems maintains its' Fitness For Purpose. The inherent risks and opportunities can be classified into one of three categories; material, energy or information. An inherent risk that may not be considered during the design phase could be the transfer of thermal energy along a steel armoured cable. An inherent opportunity that may not be considered could be the opportunity to pass additional information along a cable outside of the used bandwidth. By taking the basic example of an aircraft carrier as a conceptual demonstrator, and categorising the systems constituent componenets into sources of information, bearers of information and sources of information, we can begin to identy the inherent risks and opportunities presented in the system. The sources, sinks and bearers all have an optimum frequency range in which they operate, however there is also an inherent opportunity to pass information along a common bandwidth between these three constituent components of the system, providing the time domain is also common. The aim of this project is to autonomise the identification of these inherent opportunities and visually indicate their presence to the intended user of the conceptual demonstrator.

Estimated project breakdown:

- 20 % **Background research and analysis**. Find out what's relevant to the project, what's been done before and what hasn't, etc. Does this information give any clues as to how the project should be approached, what direction it should take, are there any pitfalls to be avoided, etc?
- 0 % **Experiment.** Conduct initial experimental work to collect data to support or test initial research and/or test stages of or complete circuitry, hardware, equipment, software, systems, etc.
- 20 % **Design**. Based on initial research and/or experiment, design the required elements of circuitry, hardware, software, systems, etc.
- 0 % **Construction**. Make required circuitry, PCB's, hardware, etc.
- 40 % **Software/programming**. Write any software that is required. This could be in any low or high level language and in any environment.
- 10 % **Theoretical development/analysis**. Develop an existing or new theory. This can include the design and/or modelling of circuitry, equipment, systems, etc that is tested in simulation only or the collection and/or analysis of previously available data.
- 10 % **Report/paper writing**. Write any interim or final reports or papers.

Page 1 of 1

Loughborough University

A9: BEng Project Requirements

Cardinal Point Requirements Specification

Automated MEI Transfer

Maintaining Systems of Systems Fit for Purpose

1. Introduction

When a complex system or system-of-systems is assembled, it sometimes doesn't function or behave as is necessary to fulfil a desired need. The Maintaining Systems of Systems (SoS) Fit for Purpose research asserts that a cause of this is unintended transfers of material, energy and information (MEI) between the constituents of the system or SoS. The process of detection of unintended transfers and determination if they pose either a risk or an opportunity has to be an automated process due to the large amount of MEI Sources, Sinks and Bearers SSBs) in all but the most trivial of systems.

A concept demonstrator of an automated process using a simplified example of a major SoS constituent exists to show how a functional demonstrator could appear. The project task is to use the existing concept demonstrator to create a functional demonstrator.

This document outlines the cardinal requirements for the functional demonstrator.

2. Cardinal Point Requirements

2.1 The functional demonstrator functionality shall be demonstrated using the same simplified example of a major SoS constituent as used by the concept demonstrator.

2.2 The functional demonstrator shall use EXCEL and Cytoscape PC applications for the capture, analysis and visualisation of MEI transfers and SSBs as used by the concept demonstrator.

2.3 The functional demonstrator shall use frequency and time domain analysis as used by the concept demonstrator to tag groups of MEI SSBs as either Prospective or Potential MEI transfers respectively.

2.4 The functional demonstrator shall use sensitivity analysis to flag if potential MEI transfers may be either a risk or an opportunity.

2.5 The functional demonstrator user will be able to interrogate the MEI SSBs captured in EXCEL and filter them by any captured characteristic to display MEI SSBs with a characteristic commonality.

3. Deliverables

3.1 FFP Functional demonstrator

3.2 Simplified SoS constituent data set in EXCEL format

3.3 Simplified SoS visualisation files in Cytoscape format.

3.4 Functional demonstrator User Guide.

SW Hinsley 28/10/15

A10: BEng Project Final Report Extracts: Nathan White

2015 - 2016

Part C Individual Project
Final Report

Name: Nathan Robert White

ID Number: B224460

Programme: Systems Engineering

Module Code: 15ELC025

Supervisor: Henshaw, Michael J D Prof

Project Title: Automatic Indication and Visualisation of Risk and Opportunity in Unintentional Interfaces

Abstract:

In a SoS the likelihood of all stakeholders being satisfied with the output is extremely low, that is they do not find the output Fit-For-Purpose (FFP). The FFP research asserts the lack of stakeholder satisfaction is due to unintended transfers of Material Energy or Information (MEI). The SoS constituents can be classified into Sources, Sinks and Bearers, and through the complex mathematical analysis of their frequency and time domain characteristics, these unintended transfers of MEI can be investigated to evaluate whether they pose a risk or an opportunity to the FFP of the SoS.

With no currently available software to aid with the complex mathematical analysis of a SoS constituents' frequency and time domain characteristics, a prototype 'FFP Functional Demonstrator' has been developed. It consists of a FFP analysis tool used to evaluate the frequency and time domain characteristics of a SoS constituents in Microsoft Excel and also a visualisation aid to assist with the visualisation of the FFP research through the use of the Cytoscape web application.

Multiple systems engineering tools were employed during the project including a functional flow diagram and systemic textual analysis and the holistic requirements model was followed to ensure successful customer validation and verification.

2015 - 2016

Contents

1

1 Definitions

Mid band - The frequencies between the high and low break frequencies
Source - A source of MEI, such as a reservoir (M)
Sink - A sink of MEI, such as a database (I)
Bearer - A bearer of MEI, such as an electrical cable (E)
Break Frequency High - The frequency at which the transferred quantity is half what it is at mid-band and reduces with increasing frequency
Break Frequency Low - The frequency at which the transferred quantity is half what it is at mid-band and increases with increasing frequency
Prospective MEI Transfer - A SSB connection that has overlapping frequency characteristics
Potential MEI Transfer - A SSB connection that has overlapping frequency characteristics and overlapping active time periods
MEI Connection - A SSB connection that has not had its frequency or time domain characteristics investigated
MEI Transfer - A transfer of MEI from a source to a sink via a bearer.
Max Excursion - The maximum quantity of MEI that a source can output, or that a bearer can carry or that a sink can accommodate.
Used Excursion - The excursion of an MEI quantity that a source can output, a bearer can carry or a sink can accommodate that is used by design to make an intended transfer of MEI.
Synchronous - The Source, Sink and Bearer are functional at the same time
Asynchronous - The Source, Sink and Bearer are not functional at the same time

2 Abbreviations and Acronyms

SoS – System of Systems
FFP – Fit-For Purpose
M – Material
E – Energy
I – Information
MEI – Material, Energy or Information
MEIX – Material, Energy or Information Transfer
SSB – Source, Sink and Bearer
Fb Hi – Break Frequency High
Fb Lo – Break Frequency Low
NWS – Naval Weapon System
FFD – Functional Flow Diagram
UID – Unique Identity Number
FDom – Frequency Domain
TDom – Time Domain
CAT – Customer Acceptance Test

3 Introduction

3.1 Project Description

Within a System of Systems (SoS) there are many interfaces through which material, energy or information (MEI) may be transferred. The vast majority of system interfaces are due to explicit design; however there will also be unintentional interfaces that have not been considered. Complex SoS often do not function in such a way as to fulfil a desired need, and the Maintaining SoS Fit for Purpose (FFP) research asserts that a cause of this is unintended transfers of MEI between the constituents of the system or SoS. However, not all unintentional interfaces pose a risk to the successful running of the system and evidence would suggest that some such interfaces expose potential opportunities for new system capabilities and can thus be used to enhance the performance of the system or SoS.

The FFP approach classifies constituent system components into Sources, Sinks and Bearers (SSBs) of MEI and these SSBs create a pathway for MEI transfer. The transfer of MEI is not possible across all SSBs that are connected; complex mathematical analysis must be performed to ascertain if the transfer of MEI is possible. Where MEI transfer (MEIX) is possible, there are limiting factors due to the frequency and amplitude characteristics of the SSBs, and further mathematical analysis must be undertaken to enable an FFP expert to determine if an MEI transfer poses a risk or an opportunity. There is a lack of available software available to aid with the identification and analysis of the MEI transfers, thus at the present time the complex mathematical analysis must be performed manually.

The presentation of the FFP findings can be difficult because in every system the network of MEI transfers can become extremely complex and only with intimate knowledge of the system can understand how all MEI transfers interact. Therefore it is necessary to visualise the MEI transfer network to help present the findings of the analysis of the system SSBs and resulting MEI transfers to any interested parties.

The customer for this project is Mr. Steve Hinsley, a PhD student in the Loughborough University System of Systems Group, with Thales being his PhD sponsor and the company that hold the intellectual property rights on much of the information used during this project.

3.2 Project Aims

In all but the most trivial of systems there is a large number of SSBs, so the creation of a tool to automatically aid with the identification and complex mathematical analysis of the MEI transfers is of great benefit to an FFP expert. This project aims to create a FFP analysis tool that can be used to identify and analyse the MEI transfers for any system or SoS, additionally this project aims to create a visualisation aid to assist with the presentation of the findings from the FFP analysis tool. The two components will form what the project customer has described as a "FFP Functional Demonstrator" which will be used by experts in a wide range of engineering fields to evaluate a systems' Fitness-For Purpose.

To aid with the development of the tool a simplified Naval Weapon System (NWS), shown in appendix 1, will be used to form the SSB data, however the tool will be transferrable and will have the capability to be used for the analysis of any system or SoS irrespective of its size and complexity.

The FFP analysis tool will be created using Microsoft Excel and will perform the following actions:

(1) Frequency analysis on the SSBs to tag 'Prospective Transfers'
(2) Time domain analysis on the Prospective transfers to tag 'Potential Transfers'
(3) Sensitivity analysis on the Potential transfers to enable the user to select MEI transfers that pose a risk or an opportunity

The visualisation aid will utilise the Cytoscape web application, Cytoscape is an open source software platform for visualising interaction networks [1]. The visualisation aid will enable the user to view the MEI transfer network in an engaging layout, utilising the visualisation algorithms built into the Cytoscape application.

3.3 Project Deliverables

Project deliverables are the tangible products created through the development of a system [2]. For this project the deliverables to the project customer are the FFP analysis tool, the Cytoscape visualisation aid and a user guide encompassing both the analysis tool and the visualisation aid. To meet the requirements for a BEng Systems Engineering project an interim report, a final report and a poster must be produced for assessment, and a student logbook must also be kept. Table 1 below lists the deliverables for this project.

Project Area	Deliverable
FFP Functional Demonstrator	FFP Analysis Tool to identify MEI transfers posing a risk or opportunity, using frequency, time domain and sensitivity analysis.
	Cytoscape Visualisation Aid to be used to further the understanding of the complex MEI transfer networks
	User Guide detailing exactly how to use the Functional Demonstrator
Project Deliverables	Interim Report outlining project progress
	Final Report on project development, validation and verification, and success
	Poster for presentation of the final project progress
	Logbook a record of the work undertaken

Table 1 – Project Deliverables

4 Problem Overview

4.1 Project Background

Upon the delivery of a validated and verified project, it can be said that the project in question has satisfied its' requirements, however this does not necessarily mean that every stakeholder who interact with the system is happy with the result, i.e. that all stakeholders consider it Fit-For Purpose (FFP): good enough to do the job it was designed to do [3]. The research undertaken by Mr. Hinsley suggests that a system or SoS are considered not FFP because the transfer of MEI between system constituents and the system environment is not happening in a correct, timely and complete manor.

During the design phase, an engineer will be acutely aware of the MEI transfers that are being used by the system; these are what are considered intended transfers. However what they will not be aware of are the independent and inherent transfers of MEI that are a result of the intended MEI transfer. The independent transfers are often secondary transfers, required to facilitate the intended transfer, and inherent transfers are transfers that occur because of the intended transfer. Figure 1 illustrate the difference between design intentions and actual design, figure 1(a) shows how a system's MEI transfers were designed, and figure 1(b) shows the true MEI transfers in the system. An example of this is in a Steel Wire Armoured DC Power cable; the intended transfer is the power (electrical energy), and an inherent transfer could be the transfer of heat (kinetic energy) to the surroundings.

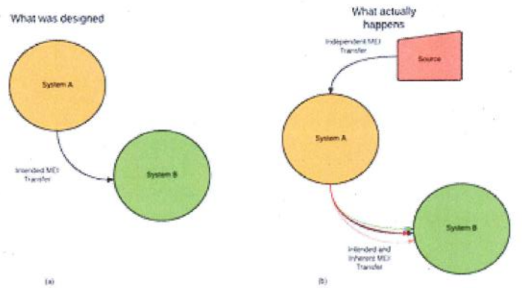


Figure 1 – Comparison of how a SoS MEI transfers is designed compared with the true MEI transfers of the SoS [4]

In a more complex system the number of independent and inherent transfers is of greater significance, as with the increasing number of these transfers, the risk of one of these posing a risk to the SoS being FFP increases. Figure 2 illustrates how a SoS with four systems is infinitely more complex than a SoS with two systems, and it should be

noted how many inherent and independent transfers there are in figure 2 (b), even in this simple example.

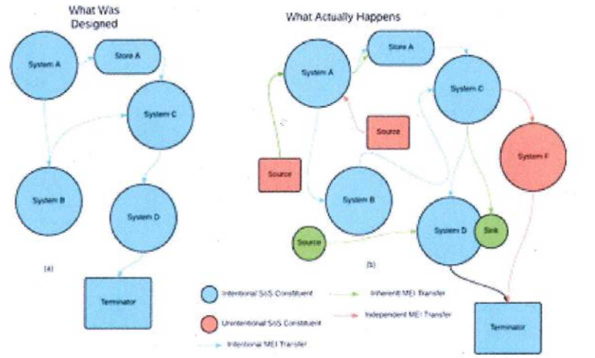


Figure 2 – Comparison of how a more complex SoS MEI transfers is designed compared with the true MEI Transfers of the SoS [4]

By implementing the FFP research into the design of a SoS, it is possible to enhance the likelihood that as many stakeholders as possible will consider the SoS FFP. The SoS will have the capability to be unaffected by unforeseen changes in its mode of operation, internal and external factors. As Figure 2 shows the total number of MEI transfers in a small SoS can be high, therefore for the FFP research to be correctly implemented it is necessary for some kind of software or tool to be available to aid the engineer. A second point to be noted, as is evident in this report, is that it is much easier to explain the FFP research and findings through the use of visualisation aids.

4.2 Currently Available Software

As discussed in section three there is currently no software available that supports the exploration of MEI transfers in a SoS and the accompanying mathematical analysis. Mr. Hinsley has created a 'conceptual demonstrator', to enable him to create a working list of all MEI transfers in the NWS, however this only exists in the form of a spreadsheet. The 'conceptual demonstrator' does not have the functionality to perform any mathematical analysis and it is an extremely complex spreadsheet. Only a user with an advanced understanding of the FFP research concept, such as in the NWS example, and the functionality of Microsoft Excel could use the 'conceptual demonstrator' to perform FFP analysis on a SoS. The 'conceptual demonstrator' is also incompatible with the Cytoscape application chosen as the software for the visualisation aid, and the user must be both competent and confident with both applications to create a visualisation of the MEI transfers from the 'conceptual demonstrator'.

4.3 Project Scope

The Project Management Body of Knowledge defines project scope as "the work that needs to be accomplished to deliver a product, service, or result with the specified features and functions." [5]. In order to accurately define the project scope it was necessary to use a system of interest diagram, shown in figure 3. The diagram was used to evaluate the project scope and to demonstrate how the wider system environment affects the Functional Demonstrator. The system of interest diagram shows that the requirements of a BEng Systems Engineering project must be satisfied as well as the requirements of the project customer. This was an extremely useful tool as throughout the project lifecycle it was easy to become focused on creating the functional demonstrator, ignoring the requirements of a final year project.

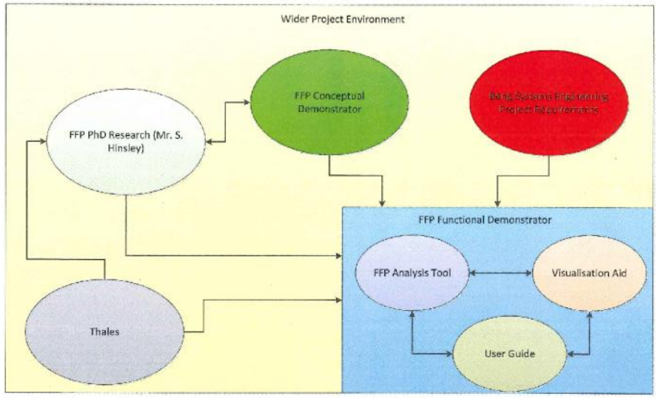


Figure 3 – System of Interest diagram

To ensure the project scope definition was whole and complete, a work activity breakdown (WAB) was completed, see appendix 2. One of the major risks identified in the early stages of this project was "scope creep," which is defined as "when a change – an update or addition – to the whole or even part of the project has been requested when the project is already underway" [6]. The risk of "scope creep" in this project was significant, as the FFP Analysis Tool was developed and improved, the customer put forward several proposals as to how, in their view, the tool could have been improved and modified. The implementation of these modifications would have been time consuming and would not have contributed towards the overall success of the project. Referring to the WAB throughout the project ensured

that only work relevant to successful project completion was undertaken, and helped to eliminate any "scope creep", whilst also aiding in the tasks of estimating dates for significant project milestones and determining the time allocation which was appropriate for each individual phase of the project.

5 Literature Review

In order to ensure that the Functional Demonstrator was delivered to an acceptable standard a full literature review was conducted. A substantial amount of literature was considered during this phase of the project, and subsequently not every source text has been included in this literature review; however the findings from key resources have been included.

The first area of research focused on user interface design, as the FFP analysis tool is a complex piece of software, and poor interface design could have rendered the FFP analysis tool unfit for purpose. The second research area was focused on user documentation, as the user guide is a key component of the Functional Demonstrator as it provides the user with a step by step guide on how to use the FFP analysis tool, and also how to use Cytoscape as a visualisation aid. The final area of research was centred on visual analytics and visual data mining, to ensure that the design of the Cytoscape visualisation aid would be effective.

5.1 User Interface Design

The research on user interface design began with ISO:9241, the industry standard covering the ergonomics of human-computer interaction. ISO 9241 defines a user interface as "All components of an interactive system that provide information and controls for the user to accomplish specific tasks with the interactive system."[7], and a user as "a person who interacts with a product"[7]. These definitions have been included as they are used extensively throughout the literature review, and clarity is essential to the successful understanding of the key concepts taken from the literature review.

ISO 9241 states that there are six principles of human-centred design [7]:
(1) The design is based upon an explicit understanding of users, tasks and environments
(2) Users are involved throughout design and development
(3)The design is driven and refined by user-centred evaluation
(4) The process is iterative
(5) The design addresses the whole user experience
(6) The design team includes multidisciplinary skills and perspectives

ISO:9241 also makes reference to the fact that human-centred design activities are interdependent. Figure 4 [7], is adapted from the industry standard, and it is evident that each stage of the design process is dependent on the stages prior to it being successfully completed. It also shows that the design process should be iterative where appropriate, both in terms of specifying user requirements and producing design solutions.

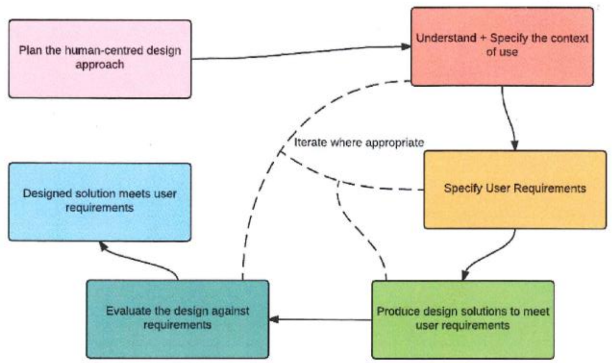


Figure 4 – Interdependence of human-centred design activities [7]

The final conclusion taken from this stage of the user interface design research is regarding conformance to ISO:9241. ISO:9241 states that conformance to the standard is achieved by performing the following:

(1) satisfying all the requirements
(2) identifying applicable recommendations
(3) explaining why particular recommendations are not applicable
(4) stating whether or not the applicable recommendations have been followed.

Further reading around user interface design was necessary as ISO:9241 only comments on the principles of design and conformance, it does not have any practical examples based on previous work on user interface design. Spolsky [8] states that "a user interface is well designed when the programme behaves exactly how the user thought it would". Spolsky [8] also goes on to discuss how design is the art of making choices, as each time you provide an option to the user, then you are asking them to make a decision and he also makes reference to the fact that problems arise with user interfaces when "the user has to make a decision they don't care about" [8]. Further conclusions that can be drawn from Sposlky's work are that effective user interface designers use consistency intelligently and although it may not show off their creative spark, in the long run it makes the user happier [8].

A key measure of successful user interface design is usability testing, ISO:9241 defines usability as "the extent to which a system, product or service can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use" [7]. Shneiderman and Plaisant [9] give five measures of

usability; time to learn, speed of performance, rate of errors by users, retention over time and subjective satisfaction, whilst Spolsky [8] states that usability testing actually tests "how learnable a programme is".

5.2 User Documentation

Due to the importance of the user guide as expressed in the introduction to this section, in depth research into writing user documentation was conducted. Low et al. [10] state that before writing any user documentation the audience must first be considered, as a common issue with poor user documentation is that reader resistance is high. Another point that Low et al. [10] make is the format of the user documentation is important; online and paper manuals have differing sets of requirements, and therefore should differ in style and layout. A further point taken from the literature is that the user and their characteristics must be considered prior to constructing any user documentation, Alamargot et al. [11] give four primary user characteristics; age, working memory capacity, prior knowledge and reading skills.

The construction of a successful and useable user guide depends a great deal on the writing style; Low et al. [10] give a series of recommendations as to the style of any user documentation:

(1) Choose words carefully: ensure that "the text remains bright, light and interesting".
(2) Keep the text short and readable
(3) Use symbols and illustrations to reduce the amount of text required
(4) Maintain a consistent style
(5) Minimise the words to provide a quick and easy guide
(6) Avoid appendices, they are rarely read.

Alamargot et al. [11] outline a series of common problems with user documentation; instructions are often disregarded, actions are not performed or are performed improperly and there is often a discrepancy between instructions and equipment. Alamargot et al. [11] suggest the use of pictograms as a substitute for written indications and instructions. They define a pictogram as "a stylized figurative drawing that is used to convey information of an analogical/figurative nature directly to indicate an object or to express an idea" [11]. However some limitations on the use of pictograms are also expressed; they are never universally understood, it takes time for their use to become effective, and there is the potential for significant confusion [11].

5.3 Visual Analytics

Visual analytics can be described as "the science of analytical reasoning facilitated by interactive visual interfaces" [12]. The visualisation aid is a secondary element to the Functional Demonstrator; however it is a key tool for the user when expressing the findings from using the Functional Demonstrator to stakeholders in the project, as humans often form mental models to process data [13]. The visualisation aid will enable those not familiar with the FFP research to form an appropriate mental model to enable faster and greater understanding of the FFP research and the findings from it. A common term for the act of visualising data is 'visual data mining', Simoff et al. [14]

define visual data mining as "The process of interaction and analytical reasoning with one or more visual representations of an abstract data that leads to the visual discovery of robust patterns in these data that form the information and knowledge utilised in informed decision making". Summarising a further point by Simoff et al.[14], during visual data mining large and normally incomprehensible amounts of data are visually represented through the use of effective visualisation techniques [14]. A key element of the work by Simoff et al. [14] is the argument that there are three important aspects of visual data mining:
(1) The tasks
(2) Visual representation
(3) The process

Beilken and Spenke [15] suggest that the end goal of visual data mining is "to help a user get a feeling for the data, to detect interesting knowledge and to gain a deep visual understanding of the data set", and Niggeman [13] argues that "Data Visualisation can reveal hidden information enclosed in the model". However several pieces of literature have expressed concerns about the loss of detail in visual data mining, and that visual data mining should be approached with caution when the level of detail is great.

5.4 Conclusions from the Literature Review

The user interface design research highlighted a series of important considerations that were relevant to this project. Firstly, the need for a complete and validated set of user requirements to enable conformance with ISO:9241, the Functional Demonstrator is intended for use by people in real engineering industries, therefore conformance with ISO:9241 is necessary for the demonstrator to be accepted as an effective tool. Secondly, the importance of user focused design and iterating the design process; this enables greater understanding of the requirements of the user interface, and should lead to successful user interface design. Finally, reducing user decision making increases the quality of user interface design. Users are averse to making unnecessary decisions, and when faced with them, they often make a choice without considering the wider implications, which could have a negative impact on the user interface.

Following an analysis on the research conducted into user documentation construction, three key points should be noted; firstly the style and format of the user guide should depend on the intended user. The requirements of a user document where the intended user is older, less computer literate and has poor reading skills differ significantly if the user is younger, highly computer literate and has good reading skills. The next conclusion drawn from the user documentation research is that text should be kept to a minimum. Readers of the user guide do not want to read any more than is necessary, will frequently interpret what they have read incorrectly, and will make assumptions when it is unsafe to do, therefore it is important to keep text to a minimum, however quality must not be sacrificed for conciseness, a balance between the two must be found. The research also highlighted how the use of pictures and particularly pictograms, if presented correctly, can vastly improve the effectiveness of the user documentation. The attention of the reader is drawn to pictures, and will frequently

avoid reading text when a picture is available for them to study, however if a picture is misleading or incorrect, this can reduce the effectiveness of the user guide.

The research into visual analytics highlighted some significant areas for consideration, firstly, the idea that humans form a mental model from a piece of data. Each human will form a unique mental model from the same visualisation of a dataset, and a more effective visualisation aid will enable humans to make similar mental models, thereby improving the understanding of the problem. The second important conclusion from the research were the three key aspects of visual data mining, as this can be used as a framework for the process of designing the visualisation aid to ensure completeness and accuracy. Finally, the research also highlighted the potential for loss of detail, which must be given thought when designing the visualisation aid. The function of the visualisation aid is to further understanding of the FFP research but a loss of detail could result in a user not fully understanding the data, and therefore the visualisation aid would become unfit-for purpose.

6 Requirements Capture

In order to fully understand the desired output from the project, it was necessary to capture and analyse a detailed and complete set of project requirements. This aided with the direction of the design and build phase of the project, and also ensured that the needs and desires of all stakeholders were satisfied, in an attempt to make the output from the project fit-for purpose.

6.1 Cardinal Requirements

Mr. Hinsley provided the following list of cardinal requirements:

(1) The functional demonstrator functionality shall be demonstrated using the same simplified example of a major SoS constituent as used by the concept demonstrator.

(2) The functional demonstrator shall use EXCEL and Cytoscape PC applications for the capture, analysis and visualisation of MEI transfers and SSBs as used by the concept demonstrator.

(3) The functional demonstrator shall use frequency and time domain analysis as used by the concept demonstrator to tag groups of MEI SSBs as either Prospective or Potential MEI transfers respectively.

(4) The functional demonstrator shall use sensitivity analysis to flag if potential MEI transfers may be either a risk or an opportunity.

(5) The functional demonstrator user will be able to interrogate the MEI SSBs captured in EXCEL and filter them by any captured characteristic to display MEI SSBs with a characteristic commonality.

These are the fundamental project requirements, and project validation can only be achieved if these requirements have been satisfied.

8 Design and Build

With a complete set of validated requirements in a formal format, the project could enter the design and build phase. A systems approach was adopted throughout; the requirements were edited and improved as the project was developed, the design process was iterative and all elements of the functional demonstrator were developed in conjunction with each another to ensure successful integration and cohesion. The Systems Engineering Management Plan (SEMP) that was constructed stated that in the event of a document or piece of software being modified; a new file would be saved to enable the modifications to be tracked. During the design and build phase this practice was performed with all documents and software, for example the FFP analysis tool was delivered at version fifteen.

8.1 FFP Analysis Tool

The FFP analysis tool was developed from the 'Conceptual Demonstrator' provided by Mr. Hinsley. The conceptual demonstrator took the form of an Excel spreadsheet with nine worksheets; however there was no evidence of the links between the various worksheets and it was difficult to follow the conceptual demonstrator from start to finish, even with the assistance of a demonstration. Therefore a major design consideration when constructing the FFP analysis tool was that it should be possible for a novice user of the FFP analysis tool to follow the sequence of the tool without having to understand the FFP research.

A functional flow diagram (FFD), shown in figure 9, was constructed as a visual aid to facilitate improved explanation of the tool and the way in which it is structured and how the various sections of mathematical analysis are integrated. The final order of actions in the tool differs slightly from the order shown in the FFD, however this is due to the limitations of Excel and is explained in section 8.1.2.

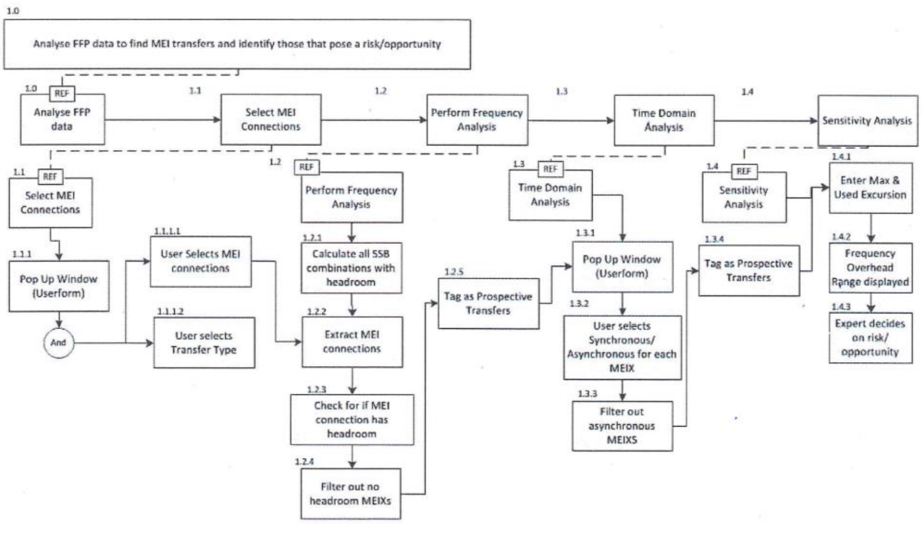


Figure 9 – FFP analysis tool functional flow diagram

8.1.1 Inputting Sources, Bearers and Sinks

The FFP analysis tool is designed for use with any SoS Source, Bearer and Sink constituents, therefore the final version will appear like figure 10. This blank sheet allows the user to input their own Source, Sinks and Bearers, and the associated frequency characteristics directly into the cells. The presence of a key and a note on the relevant pages in the user guide are to satisfy user requirements eight and nine. The suggested unique identity number (UID) format is given in the user guide; however the user is free to use their own. The user guide, shown in appendix 5, contains a list of abbreviations and definitions, common to the FFP PhD research, to enable the user to understand what data they are inputting. The frequency characteristic cells have been formatted to automatically convert the input number to standard form.

Several more intuitive methods of entering the SSB data were investigated; however entering the data directly into the cells was selected as it allows the user to input the data at their own pace. Using a popup input box was investigated however the user would have had to enter the Source/Sink/Bearer and the associated frequency characteristics at the same time. This may not be possible due to the availability of the information, and therefore affect the user's satisfaction with the FFP analysis tool.

Figure 10 – Sources, Sinks & Bearers sheet from the FFP analysis tool.

8.1.2 Frequency Analysis of all SSBs

The FFD shown in figure 9 suggests that the first action performed by the tool is enabling the user to select MEI connections, however following the sequence of the user guide; the next step in the tool is to perform the mathematical frequency analysis. This is due to the limitations of Excel, as mentioned in section 6.1. There is a requirement for the frequency characteristics of all potential MEI connections to be analysed, i.e. every possible combination of SSBs, to find all possible MEI connections that have headroom in the frequency domain, and keep a permanent record of the results. To enable Excel to perform the analysis on all potential MEI connections the action, in this case the '(5) Perform Mathematical Frequency Analysis' button, must be situated on the worksheet where the data lies. The (5) included in the button caption is to relate the button action to the related step in the user guide. To enable a novice user to be able to follow the tool

from start to finish, it was decided that the frequency analysis will be performed prior to the user selecting MEI connections.

The frequency characteristics that the user enters into the tool are the high and low break frequency of the Sources, Sinks and Bearers. Mr. Hinsley has provided the following definitions to ensure consistency with his PhD research:
Break Frequency High (Fb Hi) - The frequency at which the transferred quantity is half what it is at mid-band and reduces with increasing frequency.
Break Frequency Low (Fb Lo) - The frequency at which the transferred quantity is half what it is at mid-band and increases with increasing frequency.

Figures 11(a) and (b) are simple examples of how a plot of frequency against amplitude could appear for a Source, Sink or Bearer. Figure 12 shows how the frequency against amplitude plot could appear if an MEI connection was plotted on the same axes. The shaded region is the 'headroom' that poses a risk or opportunity to the designer; however it should be known that figure 12 is simply a visualisation aid; the reality is that the plot of the MEI connection's frequency characteristics could appear in many ways. For there to be headroom in the frequency domain the smallest Fb Hi must exceed the greatest Fb Lo, and this is the mathematical analysis that must be performed on every possible MEI connection.

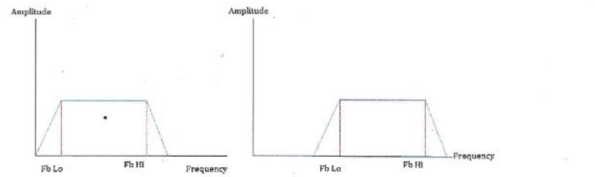


Figure 11 – Example plot of frequency against amplitude for any Source, Sink or Bearer

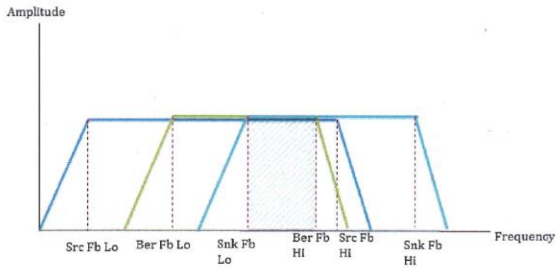


Figure 12 – Example plot of frequency against amplitude for a connected Source, Bearer and Sink including the headroom region (shaded area)

The FFP analysis tool has a non-functional performance requirement that the mathematical analysis be an automatic process, meaning the user does not have to perform any analysis and handles all possible SSB combinations in one loop. Using the VBA editor in Excel, a piece of code was written to perform the mathematical analysis automatically. The code automatically extracts the number of Sources, Bearers and Sinks independently, and then performs the mathematical analysis on every possible SSB combination. The algorithm used was Min Fb Hi ≥ Max Fb Lo, and every SSB combination that met this condition was displayed on a separate worksheet, titled 'Frequency Domain Headroom' to meet another non-functional performance requirement that a list of all the unconnected SSBs with headroom in the frequency domain must be kept for later use, refer to appendix 6 for the VBA code for this section of the FFP analysis tool. The tool will only display the UIDs of the SSBs with headroom, in the format 'SRxxBExxSNxx', all in one cell, as this piece of information is required for use in code written for a later part of the tool. As previously mentioned, a major design consideration in the tool was that a novice user must be able to follow the steps, so a final piece of functionality built into the frequency analysis code was that the worksheet where the next step, according to the user guide, is located is automatically displayed on the user's screen. To run the code a button was added to the spreadsheet, care was taken to ensure its position would not hide certain parts of the spreadsheet to the user.

8.1.3 Select MEI Connections

The next step in the FFP analysis tool is for the user to select the known MEI connections. An MEI connection is a SSB combination that has not yet had its frequency or time domain characteristics investigated to identify whether there is headroom or not. A UserForm was constructed to enable the user to select their own MEI connections, a UserForm is "custom-built dialog box that you build using the Visual Basic Editor" [17], and is shown figure 13. The UserForm will automatically detect the number of Sources, Sinks and Bearers independently and display the name and UID in the appropriate column. A drop down menu was also included to allow the user to select the type of MEI connection. The title of the worksheet where the UserForm is located is 'MEI Connections'.

2015 - 2016

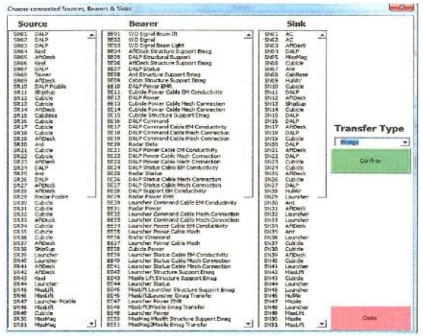
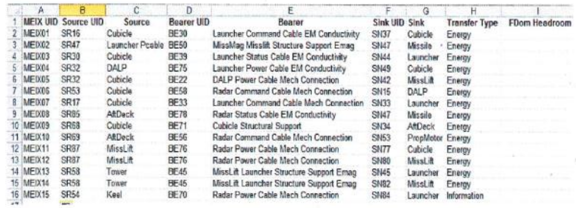


Figure 13 – UserForm allowing user to select MEI connections

The user clicks on the row containing the desired Source to select it and then repeats for the Bearer and Sink, each column is independent to the others; any combination of rows could be selected. Once the user has selected the desired SSBs in the MEI connection and the transfer type, the green 'Confirm' button is pressed, and the highlighted Source, Bearer and Sink from the UserForm are displayed in the first available row on MEI Connections worksheet, and this process can be repeated many times without having to close the UserForm, figure 14 shows how the MEI connections worksheet appears after the user has selected their MEI Connections. Pressing the red 'Close' button will close the UserForm and the worksheet will be displayed again containing any MEI connections that have been added by the user. The buttons are positioned a considerable distance apart to ensure that the User cannot accidentally close the UserForm when attempting to select an MEI connection.



	A	B	C	D	E	F	G	H	I
1	MEIX UID	Source UID	Source	Bearer UID	Bearer	Sink UID	Sink	Transfer Type	FDom Headroom
2	MEIX01	SR16	Cubicle	BE30	Launcher Command Cable EM Conductivity	SN37	Cubicle	Energy	
3	MEIX02	SR47	Launcher Pcable	BE50	MissMag Misslift Structure Support Emag	SN47	Missile	Energy	
4	MEIX03	SR30	Cubicle	BE39	Launcher Status Cable EM Conductivity	SN44	Launcher	Energy	
5	MEIX04	SR32	DALP	BE75	Launcher Power Cable EM Conductivity	SN49	Cubicle	Energy	
6	MEIX05	SR32	Cubicle	BE22	DALP Power Cable Mech Connection	SN42	MissLift	Energy	
7	MEIX06	SR53	Cubicle	BE58	Radar Command Cable Mech Connection	SN15	DALP	Energy	
8	MEIX07	SR17	Cubicle	BE33	Launcher Command Cable Mech Connection	SN33	Launcher	Energy	
9	MEIX08	SR85	AftDeck	BE78	Radar Status Cable EM Conductivity	SN47	Missile	Energy	
10	MEIX09	SR68	Cubicle	BE71	Cubicle Structural Support	SN34	AftDeck	Energy	
11	MEIX10	SR69	AftDeck	BE56	Radar Command Cable Mech Connection	SN53	PropMotor	Energy	
12	MEIX11	SR87	MissLift	BE76	Radar Power Cable Mech Connection	SN77	Cubicle	Energy	
13	MEIX12	SR87	MissLift	BE76	Radar Power Cable Mech Connection	SN80	MissLift	Energy	
14	MEIX13	SR58	Tower	BE45	MissLift Launcher Structure Support Emag	SN45	Launcher	Energy	
15	MEIX14	SR58	Tower	BE45	MissLift Launcher Structure Support Emag	SN82	MissLift	Energy	
16	MEIX15	SR54	Keel	BE70	Radar Power Cable Mech Connection	SN84	Launcher	Information	

Figure 14 – MEI Connections worksheet after the user has selected their MEI connections

8.1.4 Finding the MEI Connections with Frequency Domain Headroom

Having selected the MEI connections, the user must next initiate code in the tool to check if each connection has headroom in the frequency domain. This is a two stage process, primarily due to the limitations of Excel, and is spread across two worksheets, again due to the limitations of Excel.

The first action of the tool is to copy the SSB UIDs, in the form 'SRxxBExxSNxx', from the MEI connections selected by the user onto the Frequency Domain Headroom worksheet. For the user to initiate this action a button is located on the same worksheet as the UserForm used to select the MEI connections. After pressing this button and copying the UIDs the tool then takes the user to the worksheet where the next step is located.

The second stage is where the tool cycles through the list of UIDs from the MEI connections selected by the user to see if the combined UID appears in the list created by performing the mathematical frequency analysis on all possible SSB combinations. Excel does not have the functionality to perform a comparison between the two alphanumeric UIDs, so it was necessary to write an additional function, which is shown in appendix 7, to remove the letters from the combined UID. The tool removes the letters from both sets of combined UIDs and then compares to see if the number from the MEI connection appears in the list from the SSB connections. If it does at any point then 'Yes' is printed in the 'FDom Headroom' column on the MEI connections worksheet, in the row that the UID appears on, if it does not then 'No' is printed in the same column and row. After the tool has performed all these actions, the MEI Connections sheet is activated on the user's screen, as that is where the next step of the tool is located.

An MEI Connection with headroom in the frequency domain is called a 'Prospective Transfer', and the next action performed by the tool is the Prospective Transfers are copied onto a new worksheet so that time domain analysis can be performed. There is a non-functional performance requirement that a record of the MEI connections without frequency domain headroom be stored permanently, hence this step being necessary. On the MEI Connections worksheet there is a button with the text 'Filter out no FDom Headroom MEIXs', and when the user presses this button, the tool re-orders the worksheet, placing the MEIXs with a yes in the 'FDom Headroom' column at the top followed by those without. The tool orders each set of MEIXs by their MEIX UID. The final action of this step is to load up the 'Prospective Transfers' worksheet where the time domain analysis functionality is located.

8.1.5 Time Domain Analysis

With an accurate list of Prospective Transfers available to the user, the next step is to perform time domain analysis. This is an action the user must perform, as there are no calculations that can be performed to assist the user and there is little that can be done to make the process automatic. It is up to the user to select which Prospective Transfers are synchronous in the time domain. A synchronous transfer is defined as when the SSB constituents are active at the same time, the user must ask themselves are the SSB constituents likely to be in use at the same time?

A UserForm was constructed to enable the process of selecting synchronous and asynchronous MEIXs to be as intuitive as possible, and is shown in figure 15. There

is a button on the Prospective Transfers sheet with the caption 'Select synchronous/ asynchronous MEIXs', which when pressed by the user initialises the UserForm. The UserForm automatically detects the number of MEIXs on the Prospective Transfers worksheet and loads them into the UserForm. The user then selects the first row and presses either the green 'TDom Synchronous' to write 'Yes' into the column with the title 'TDom Synchronous' or orange 'TDom Asynchronous' button to write 'No' into the same column. Each time the user presses the synchronous or asynchronous button the highlighted row on the UserForm will move down by one to enable the user to move quickly down the rows. A skip button has been included to prevent the user from having to move their cursor to skip a row and will also prevent users from thinking that they must select the synchronous or asynchronous button for every MEIX on the UserForm, as during usability testing with the customer this was a comment that was made. Figure 16 shows how the Prospective Transfers worksheet appears after the user has selected the synchronous and asynchronous MEIXs.

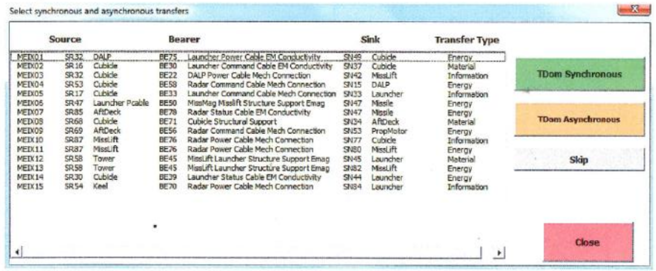


Figure 15 – Time Domain Analysis UserForm

	A	B	C	D	E	F	G	H	I
1	MEIX UID	Source UID	Source	Bearer UID	Bearer	Sink UID	Sink	Transfer Type	TDom Synchronous
2	MEIX01	SR32	DALP	BE75	Launcher Power Cable EM Conductivity	SN49	Cubicle	Energy	Yes
3	MEIX02	SR16	Cubicle	BE30	Launcher Command Cable EM Conductivity	SN37	Cubicle	Energy	Yes
4	MEIX03	SR32	Cubicle	BE22	DALP Power Cable Mech Connection	SN42	MissLift	Energy	No
5	MEIX04	SR53	Cubicle	BE58	Radar Command Cable Mech Connection	SN15	DALP	Energy	No
6	MEIX05	SR17	Cubicle	BE33	Launcher Command Cable Mech Connection	SN33	Launcher	Energy	No
7	MEIX06	SR47	Launcher Pcable	BE50	MissMag Misslift Structure Support Emag	SN47	Missile	Energy	Yes
8	MEIX07	SR85	AftDeck	BE78	Radar Status Cable EM Conductivity	SN47	Missile	Energy	No
9	MEIX08	SR68	Cubicle	BE71	Cubicle Structural Support	SN34	AftDeck	Energy	Yes
10	MEIX09	SR69	AftDeck	BE56	Radar Command Cable Mech Connection	SN53	PropMotor	Energy	No
11	MEIX10	SR87	MissLift	BE76	Radar Power Cable Mech Connection	SN77	Cubicle	Energy	No
12	MEIX11	SR87	MissLift	BE76	Radar Power Cable Mech Connection	SN80	MissLift	Energy	Yes
13	MEIX12	SR58	Tower	BE45	MissLift Launcher Structure Support Emag	SN45	Launcher	Energy	Yes
14	MEIX13	SR58	Tower	BE45	MissLift Launcher Structure Support Emag	SN82	MissLift	Energy	Yes
15	MEIX14	SR30	Cubicle	BE39	Launcher Status Cable EM Conductivity	SN44	Launcher	Energy	No
16	MEIX15	SR54	Keel	BE70	Radar Power Cable Mech Connection	SN84	Launcher	Information	No

Figure 16 – Prospective Transfers worksheet

When the user has tagged a Prospective Transfer as synchronous it becomes a 'Potential Transfer', and the next action for the tool is for the Potential Transfers to be copied onto a new worksheet so that the sensitivity analysis can be performed. As with the prospective transfers, there is a non-functional performance requirement that a permanent record of the prospective transfers be kept, hence this step being necessary.

There is a button on the Prospective Transfers sheet with the text 'Filter out asynchronous MEIXs', and when the user presses this button, the tool re-orders the worksheet by placing the MEIXs with a 'Yes' in the 'TDom Headroom' column at the top followed by this with a 'No' in the same column. The tool orders each set of MEIXs by their MEIX UID. The final action of this button is to load up the 'Potential Transfers' worksheet where the sensitivity analysis functionality is located. The VBA code used to perform this action is shown in appendix 7.

8.1.6 Sensitivity Analysis

The third and final stage of the FFP analysis tool is for the user to perform the sensitivity analysis; where the frequency and excursion characteristics are evaluated to decide whether each individual MEIX poses a risk or an opportunity to the FFP of the SoS. Excursion is the name given, by Mr. Hinsley in his PhD research, to the quantity of MEI that each Source, Sink or Bearer can carry. SSBs frequently have the capability to carry additional MEI, providing the frequency characteristics of the MEIX allow the additional excursion to be used. The FFP analysis tool prompts the user to enter the excursion information, both the maximum capability and the actual used excursion, and then displays the frequency overhead for the user to evaluate whether each MEIX poses a risk or an opportunity.

During discussions with the customer prior to the design and build of the sensitivity analysis user interface it was noted that the maximum and used excursion data may not always be available to the user; therefore the decision was taken not to construct a UserForm to allow the user to input the excursion data. Figure 17 shows how the Potential Transfers worksheet appears immediately after the Potential Transfers have been copied form the Prospective Transfers worksheet. There are columns for user to input the maximum and used excursion for Sources, Bearers and Sinks at a suitable time. There is no additional functionality built into the tool to analyse the maximum and used excursion data, it the user's responsibility to input the data and calculate themselves whether the difference between the maximum and used excursion poses a risk or an opportunity to the FFP of the SoS.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	MEIX UID	Source UID	Source	SR Max Excursion	SR Used Excursion	Bearer UID	Bearer	BE Max Excursion	BE Used Excursion	Sink UID	Sink	SN Max Excursion	SN Used Excursion	Transfer Type	Frequency Domain Overhead
2	MEIX01	SR32	DALP			BE75	Launcher Power Cable EM Conductivity			SN49	Cubicle			Energy	
3	MEIX02	SR16	Cubicle			BE30	Launcher Command Cable EM Conductivity			SN37	Cubicle			Energy	
4	MEIX03	SR32	Cubicle			BE22	DALP Power Cable Mech Connection			SN42	MissLift			Energy	
5	MEIX04	SR53	Cubicle			BE58	Radar Command Cable Mech Connection			SN15	DALP			Energy	
6	MEIX05	SR17	Cubicle			BE33	Launcher Command Cable Mech Connection			SN03	Launcher			Energy	
7	MEIX06	SR47	Launcher Pcable			BE50	MissMag MissLift Structure Support Emag			SN47	Missile			Energy	
8	MEIX07	SR85	AftDeck			BE78	Radar Status Cable EM Conductivity			SN47	Missile			Energy	
9	MEIX08	SR68	Cubicle			BE71	Cubicle Structural Support			SN34	AftDeck			Energy	
10	MEIX09	SR60	AftDeck			BE56	Radar Command Cable Mech Connection			SN53	PropMotor			Energy	
11	MEIX10	SR87	MissLift			BE76	Radar Power Cable Mech Connection			SN77	Cubicle			Energy	
12	MEIX11	SR87	MissLift			BE76	Radar Power Cable Mech Connection			SN80	MissLift			Energy	
13	MEIX12	SR58	Tower			BE45	MissLift Launcher Structure Support Emag			SN45	Launcher			Energy	
14	MEIX13	SR58	Tower			BE45	MissLift Launcher Structure Support Emag			SN82	MissLift			Energy	
15	MEIX14	SR30	Cubicle			BE39	Launcher Status Cable EM Conductivity			SN44	Launcher			Energy	
16	MEIX15	SR54	Keel			BE70	Radar Power Cable Mech Connection			SN84	Launcher			Information	

Figure 17 – Potential Transfers worksheet

An additional piece of functionality that has been added to assist the user with the sensitivity analysis is to show to the user the frequency domain overhead range. The

overhead range is the difference between the maximum low break frequency and the minimum high break frequency. There is a button located on the Potential Transfers worksheet with the caption 'Show Frequency Overhead', which when pressed will calculate and display the frequency overhead range, with the code being shown in appendix 9. The user than then use this information, alongside the maximum and used excursion to decide whether each MEIX poses a risk or an opportunity to the FFP of the SoS.

8.1.7 Additional Features of the FFP Analysis Tool

During usability testing with the customer it was noted that there are many abbreviations and acronyms used in the tool, and it was decided that a key would be necessary to inform users as to the abbreviations and acronyms used. A key was added to each worksheet, and an example key is shown in figure 18. The key contains only abbreviations relevant to the worksheet on which it is placed, and is located in the rows and columns directly adjacent to the FFP data. The key has been positioned in a place where the user will not have to move it to see any of the data contained on the worksheet. It should also be noted that at the bottom of the key is a reference to the relevant pages of the user guide, this additional feature was also added as a result of comments made during usability testing.

KEY

UID - Unique Identity Number
SRC Fb Lo - Source Break Frequency Low
SRC Fb Hi - Source Break Frequency High
SNK Fb Lo - Sink Break Frequency Low
SNK Fb Hi - Sink Break Frequency High
BER Fb Lo - Bearer Break Frequency Low
Ber Fb Hi - Bearer Break Frequency Hi
1.00E+02 - Standard Form Number 100

Refer to Pages 2 & 3 of the user guide

Figure 18 – Example of a key from the FFP analysis tool

8.1.8 Convert to Cytoscape Compatible Format

The file format required to save the additional functionality added using the VBA editor in Excel is not compatible with Cytoscape; therefore it was necessary to add further functionality to convert the Excel worksheets into a format compatible with Cytoscape, an example of the VBA code required to perform this conversion is shown in appendix 10. Figure 19 shows an example of the button that is located on three of the worksheets to enable the user to copy a desired worksheet and convert it to a file format compatible with Cytoscape. Pressing the button opens a dialog box allowing the user to choose a file location and name; however the file format is locked, to ensure conformity with the file format required for use with Cytoscape. However the button is not located on every worksheet, the Sources, Sinks and Bearers and Frequency Domain Headroom worksheets do not contain data that the user would wish to visualise, and even if they had a desire to, it is not in a format that Cytoscape could use to produce an effective visualisation aid . As a result, the button shown in figure 19 is only shown on the three worksheets that the user would wish to visualise and Cytoscape can use to produce a visualisation. The user can press this button at any time and the tool will convert only the requested worksheet into the desired format.

Convert To Cytoscape Compatible Format

Figure 19 – Example of the Convert to Cytoscape Compatible Format button

8.2 User Guide

The cardinal requirements outlined in section 6.1 state that a key deliverable for this project is a user guide, instructing the user how to use all elements of the Functional Demonstrator. The user guide was constructed in conjunction with each stage of the FFP analysis tool to ensure that it was an effective user guide and is shown in appendix 5. The research into writing user documentation highlighted that it was important to keep text to a minimum, but also to ensure that enough information was contained in the document to avoid users having to make unnecessary decisions. The use of pictures and pictograms was suggested, although the research also highlighted how care is required when using pictures and pictograms, and the importance of choosing a style and using it throughout the documentation was also noted.

The selected style for the user guide was a step by step time line of how to perform each stage of the FFP analysis tool with an accompanying explanation. A second user guide was constructed that listed the instructions according to the area of the process they related to, but it was rejected during usability testing as the instructions did not flow and it was difficult to follow the user guide from beginning to end. Usability testing of the user guide also highlighted the need for a list of definitions and acronyms as there are several terms used to categorise SSBs and MEIXs at different phases throughout the FFP analysis tool. These terms are often used to name worksheets, as column headings and in the function button captions, therefore it was decided that a list of acronyms and abbreviations would enable the user to look up any and define any terminology they felt necessary. Pictures have been used extensively throughout the user guide, some have been used as a substitution for text descriptions of how to perform an action, and others have been used as a reference for the user to compare what is displayed on the screen against what is included in the user guide to ensure the tool is functioning correctly.

8.3 Visualisation Aid

The scope for this project was to design a Functional Demonstrator for use with any SoS constituents. The visualisation aid is intended to be used as an additional tool to aid the user with presenting the findings from using the FFP analysis tool. Every user

will have a unique set of SoS constituents and as a result Cytoscape will produce a unique visualisation. The customer prioritised a fully functioning FFP analysis tool, and therefore due to time constraints only the functions built into Cytoscape were explored. However this exercise still produced some interesting findings and exposed how Cytoscape can be utilised to produce many different visualisations of the same SoS constituent data.

Cytoscape utilises a multitude of layout algorithms to enable the user to customise their visualisation, each layout has a different effect on the output from the same set of input data. Similarly, each set of input data will react differently to the same layout algorithm. Figure 20 shows how the visualisation the default layout algorithm produced on a random set of MEIXs from the NWS example. Figure 21 shows the result when applying a different layout algorithm (yFiles--> Circular) to the same data. Comparing the two figures we can see that the same data can produce two very different visualisations when using the Cytoscape built in layout algorithms.

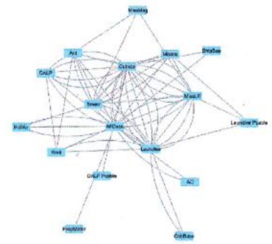


Figure 20 – Cytoscape visualisation of a selection of MEIXs from the NWS example

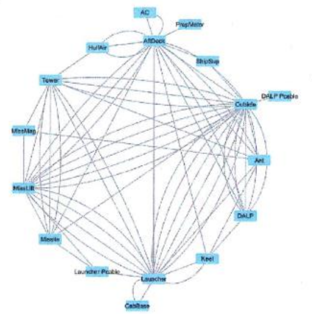


Figure 21 – Cytoscape visualisation of the same data used in figure 21, with a different Cytoscape layout algorithm applied

The visualisation produced also depends on the input parameters set by the user; for example in the NWS example many SSBs have common names, looking at figure 22(a) we can observe that this is the reason for multiple connections between each named SSB. However Cytoscape allows the user to change the visualisation to handle each SSB individually, using the UID instead. Figure 22(b) shows a visualisation of the same data used in figure 22(a), using the UIDs as a pose to the SSB name as the input parameter. Some users will find a visualisation similar to figure 22(a) useful, whereas others may find the visualisation in figure 22(b) useful; it is the responsibility of each user to decide which they feel is the most appropriate visualisation.

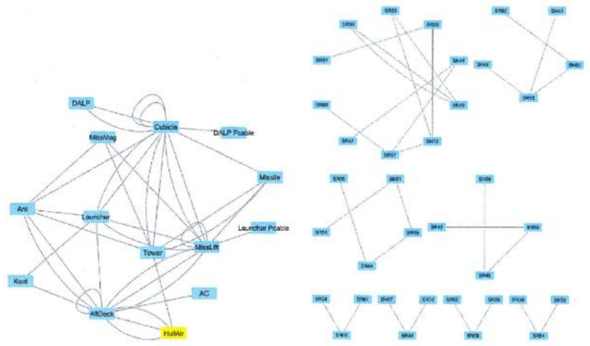


Figure 22 – Visualisation of a selection of MEIXs from the NWS example using two different input parameters

Cytoscape also has several different layout styles that alter the appearance of the visualisation produced. Figure 23(a) shows a selection of MEIXs using the default layout, figures 23(b) and 24 show the same visualisation using different layout styles. These are just a selection of the layout styles offered by Cytoscape, and Cytoscape also contains built in functionality to enable the user to customise the layout style in any way they desire to tailor the visualisation to their needs.

12 References

[1] http://www.cytoscape.org/what_is_cytoscape.html, accessed 9th April 2016.

[2] M. Morley: "Example Project Deliverables", http://smallbusiness.chron.com/examples-project-deliverables-31486.html, accessed 9th April 2016.

[3] http://www.macmillandictionary.com/dictionary/british/fit-for-purpose, accessed 9th April 2016.

[4] S. Hinsley: "Maintaining Systems-of-Systems Fitness-For-Purpose Presentation" PowerPoint Presentation (reference: Thales_090415_v0.4_part_for_nw.pptx), 2015.

[5] A Guide to the Project Management Body of Knowledge (PMBOK Guide) - Fourth Edition. Project Management Institute, 2008

[6] http://teamgantt.com/blog/scope-creep-the-two-dirtiest-words-in-project-management/, accessed 10th April 2016.

[7] ISO 9241-210:2010, "The ergonomics of human-computer interaction".

[8] J. Spolsky: "User Interface Design for Programmers", Apress, 2001.

[9] B. Shneiderman and C. Plaisant: "Designing the User Interface: Strategies for effective human-computer interaction", Pearson Higher Education, 2001.

[10] R. Low with H. Ford, J. Pallott and J. Hall: "Writing User documentation: A practical guide for those who want to be read", Prentice Hall, 1994.

[11] D. Alamargot, P. Terrier and J-M. Cellier: "Written Documents in the Workplace", Oxford Press, 2007.

[12] J. Thomas and K. Cook: "Illuminating the Path: Research and Development Agenda for Visual Analytics", IEEE Press, 2005.

[13] O Niggemann: "Visual Data Mining of Graph-Based Data", Department of Mathematics & Computer Science, University of Paderborn, Germany, 2001

[14] S. J. Simoff, M. H. Böhlen and A. Mazeika: "Visual Data Mining: Theory, Techniques & Tools for Visual Analytics", Springer Publications, 2008.

[15] C. Beilken and M. Spenke: "Visual interactive data mining with InfoZoom – the Medical Data Set", Proceedings 3rd European Conference on Principles & Practice of Knowledge Discovery in Databases, Prague, 1999.

[16] Adapted from S. Burge: "Holistic Requirements Model", http://www.burgehugheswalsh.co.uk/uploaded/documents/HRM-Tool-Box-V1.0.pdf, accessed April 12th 2016.

[17] http://www.fontstuff.com/ebooks/free/fsuserforms.pdf, Accessed 16th April 2016

Appendix 5 – FFP Functional Demonstrator User-Guide

1 Abbreviations

This section outlines any abbreviations used throughout the user guide.
M – Material
E – Energy
I – Information
MEI – Material, Energy or Information
MEIX – Material, Energy or Information Transfer
SSB – Source, Sink and Bearer
TDom – Time Domain
FDom – Frequency Domain

2 Definitions

This section outlines the definitions of terms used throughout the user guide.

Break Frequency High
The frequency at which the transferred quantity is half what it is at mid-band and reduces with increasing frequency

Break Frequency Low
The frequency at which the transferred quantity is half what it is at mid-band and increases with increasing frequency

Mid band
The frequencies between the high and low break frequencies

Source
A source of MEI, such as a reservoir (M)

Sink
A sink of MEI, such as a database (I)

Bearer
A bearer of MEI, such as an electrical cable (E)

Prospective MEI Transfer
A SSB connection that has overlapping frequency characteristics

Potential MEI Transfer
A SSB connection that has overlapping frequency characteristics and overlapping active time periods

MEI Connection
A SSB connection that has not had its frequency or time characteristics investigated

MEI Transfer
A transfer of MEI from a source to a sink via a bearer.

Max Excursion
The maximum quantity of MEI that a source can output, or that a bearer can carry or that a sink can accommodate.

Used Excursion
The excursion of an MEI quantity that a source can output, a bearer can carry or a sink can accommodate that is used by design to make an intended transfer of MEI.

Synchronous

2015 - 2016

The Source, Sink and Bearer are functional at the same time

Asynchronous
The Source, Sink and Bearer are not functional at the same time

3 Step by Step Instructions

This section contains a step by step guide as to how to use the functional demonstrator to provide detailed FFP analysis.

1. Open up the spreadsheet titled *'FFP Analysis Tool,* enabling all macros and clicking yes to making this file a trusted document. These warnings are due to the additional functionality added, no errors have actually occurred.
2. *Erase all SSB Data.* On the *Sources, Sinks & Bearers* sheet enter all system Sources in column B, with their unique id number (UID) in column A. The low and high break frequencies must be entered in columns C and D. It is not necessary to convert the number to standard form, the spreadsheet has been formatted to do this for you. To input a standard form number, type the number in a similar fashion to the example: 2.34E+14 or 2.34E-14. Do not leave blank rows as this will prevent future tasks from being successfully completed.

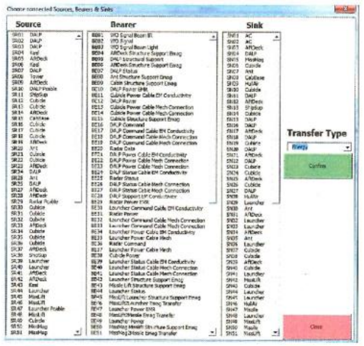
   Note: When entering UID numbers ensure that single figure numbers are entered 01, 02 and so on.
3. On the *Sources, Sinks & Bearers* sheet enter all system Sinks in column G, with the UID in column F. The low and high break frequencies must be entered in columns H and I, and again it is not necessary to convert to standard form. See step 2 to see how to enter numbers in standard form. Do not leave blank rows as this will prevent future tasks from being successfully completed.
4. On the *Sources, Sinks & Bearers* sheet enter all system bearers in column L, with the corresponding unique ID in column K, with low and high break frequencies in columns M and N. Again, it is not necessary to convert numbers to standard form, see step 2 for how to enter a standard form number. Do not leave blank rows as this will prevent future tasks from being successfully completed.

   The completed sheet should appear like Figure 3.1 below

Figure 3.1 shows an example *Sources, Sinks & Bearers* sheet containing Sources, Sinks and Bearers.

Note: The colours on the spreadsheet do not affect the function, they represent

5. On the *Sources, Sinks & Bearers* sheet, press the '(5) Perform Mathematical Frequency Analysis' button.
   This will create a list of the UIDs of all Sources and Sinks with headroom in the frequency domain on the worksheet titled *Frequency Domain Headroom*. When this action is successfully completed the tool will automatically direct you to the *MEI Connections* sheet where step 6 is located.
6. The tool should have directed you to the *MEI Connections* sheet. Press the '(6) Select MEI Connections' button to bring up a dialog box that will enable you to select the MEI connections and the type of transfer that will occur. Select the Source, Bearer and Sink in the connection, and use the drop down menu to select the transfer type and press the '*confirm*' button.
   Each time the confirm button is pressed, the selected Source, Bearer and Sink will be added to the next available row in *MEI Connections*. To remove an incorrect row, close the box using the close button, delete the row, press the '(6) Select MEI Connections' button and continue.



The completed list will look appear similar to Figure 3.3 below.

	A	B	C	D	E	F	G	H	I
1	MEIX UID	Source UID	Source	Bearer UID	Bearer	Sink UID	Sink	Transfer Type	FDom Headroom
2	MEIX01	SR16	Cubicle	BE30	Launcher Command Cable EM Conductivity	SN37	Cubicle	Energy	
3	MEIX02	SR47	Launcher Pcable	BE50	MissMag Misslift Structure Support Emag	SN47	Missile	Energy	
4	MEIX03	SR30	Cubicle	BE39	Launcher Status Cable EM Conductivity	SN44	Launcher	Energy	
5	MEIX04	SR32	DALP	BE75	Launcher Power Cable EM Conductivity	SN49	Cubicle	Energy	
6	MEIX05	SR32	Cubicle	BE22	DALP Power Cable Mech Connection	SN42	MissLift	Energy	
7	MEIX06	SR53	Cubicle	BE58	Radar Command Cable Mech Connection	SN15	DALP	Energy	
8	MEIX07	SR17	Cubicle	BE33	Launcher Command Cable Mech Connection	SN33	Launcher	Energy	
9	MEIX08	SR85	AftDeck	BE78	Radar Status Cable EM Conductivity	SN47	Missile	Energy	
10	MEIX09	SR68	Cubicle	BE71	Cubicle Structural Support	SN34	AftDeck	Energy	
11	MEIX10	SR69	AftDeck	BE56	Radar Command Cable Mech Connection	SN53	PropMotor	Energy	
12	MEIX11	SR87	MissLift	BE76	Radar Power Cable Mech Connection	SN77	Cubicle	Energy	
13	MEIX12	SR87	MissLift	BE76	Radar Power Cable Mech Connection	SN80	MissLift	Energy	
14	MEIX13	SR58	Tower	BE45	MissLift Launcher Structure Support Emag	SN45	Launcher	Energy	
15	MEIX14	SR58	Tower	BE45	MissLift Launcher Structure Support Emag	SN82	MissLift	Energy	
16	MEIX15	SR54	Keel	BE70	Radar Power Cable Mech Connection	SN84	Launcher	Information	

Figure 3.3 – MEI Connections after step 6 has been completed

7. The first ten UIDs have been included to prevent a UID incompatible with the tool being selected. To add additional UIDs, highlight column A and hover over the black square in the bottom right hand corner of the last cell and drag down to the last required row, this will automatically fill column A with sequential UIDs.
8. Move back to *MEI Connections* and press the button with the caption '(8) Extract UIDs for Comparison'. This will automatically extract the source and sink UIDs into the same format as those imported on the *Frequency Domain Headroom* sheet, and display them in column B. Figure 3.4 below shows how the Frequency Domain headroom sheet will appear after step 8 has been actioned.

	A	B
1	SR-SN with Headroom	MEI Transfers
2	SR01SN05	SR13SN24
3	SR01SN07	SR36SN37
4	SR01SN08	SR19SN15
5	SR01SN09	SR29SN37
6	SR01SN10	SR21SN43
7	SR01SN12	SR12SN17
8	SR01SN13	SR28SN36
9	SR01SN14	SR39SN44
10	SR01SN16	SR46SN50
11	SR01SN17	SR46SN50
12	SR01SN18	SR61SN61
13	SR01SN20	SR41SN41
14	SR01SN21	SR75SN65
15	SR01SN22	SR52SN71
16	SR01SN23	SR73SN76
17	SR01SN25	SR16SN50
18	SR01SN26	SR85SN76
19	SR01SN27	SR69SN59
20	SR01SN28	SR11SN29
21	SR01SN29	SR35SN70
22	SR01SN32	SR41SN74
23	SR01SN33	
24	SR01SN34	
25	SR01SN36	

9. Press the '(9) Perform Frequency Analysis' button. This will check each MEI exchange created in step 6 against the list of sources and sinks with headroom in the frequency domain created in step 5. The results will appear on the MEI connections sheet in the 'FDom headroom' column. Figure 3.5 shows how this will appear. If there is headroom, column H will read 'Yes', and if there is not, column H will read 'No'. The tool will automatically redirect you to the *MEI Connections* sheet where the next step is located.

	A	B	C	D	E	F	G	H	I
1	MEIX UID	Source UID	Source	Bearer UID	Bearer	Sink UID	Sink	Transfer Type	FDom Headroom
2	MEIX01	SR24	DALP	BE34	Launcher Power Cable EM Conductivity	SN38	Cubicle	Energy	Yes
3	MEIX02	SR34	Cubicle	BE40	Launcher Status Cable Mech Connection	SN45	Launcher	Information	Yes
4	MEIX03	SR20	Ant	BE21	DALP Power Cable EM Conductivity	SN23	Cubicle	Material	Yes
5	MEIX04	SR33	AftDeck	BE39	Launcher Status Cable EM Conductivity	SN42	MissLift	Energy	No
6	MEIX05	SR10	DALP Pcable	BE11	Cubicle Power Cable EM Conductivity	SN10	Cubicle	Information	Yes
7	MEIX06	SR46	MissLift	BE50	MissMag Misslift Structure Support Emag	SN51	MissLift	Information	Yes
8	MEIX07	SR62	Tower	BE62	Radar Data FOptic Mech Connection	SN90	Missile	Material	No
9	MEIX08	SR46	MissLift	BE47	Launcher Power EMR	SN44	Launcher	Material	Yes
10	MEIX09	SR66	Ant	BE78	Radar Status Cable EM Conductivity	SN66	Tower	Material	No
11	MEIX10	SR58	Tower	BE71	Cubicle Structural Support	SN63	Cubicle	Information	No
12	MEIX11	SR65	Tower	BE72	Radar Power Cable Mech Connection	SN78	MissMag	Energy	No
13	MEIX12	SR47	Launcher Pcable	BE51	MissMag2Missile Emag Transfer	SN49	MissLift	Energy	No
14	MEIX13	SR60	Ant	BE71	Cubicle Structural Support	SN78	MissMag	Material	No
15	MEIX14	SR35	Cubicle	BE42	Launcher Structure Support Emag	SN40	Cubicle	Information	No
16	MEIX15	SR58	Tower	BE80	Radar Status Cable Mech Connection	SN60	Missile	Material	No
17	MEIX16	SR44	Launcher	BE44	Launcher Status	SN37	Cubicle	Material	No
18	MEIX17	SR61	MissLift	BE57	MissMag2Missile Push	SN45	Launcher	Energy	No
19	MEIX18	SR53	Cubicle	BE41	Launcher Status Cable Mech Connection	SN18	DALP	Information	No
20	MEIX19	SR67	AftDeck	BE63	Missile	SN49	MissLift	Energy	No
21	MEIX20	SR43	Keel	BE34	Launcher Power Cable EM Conductivity	SN15	DALP	Energy	No
22	MEIX21	SR71	CabBase	BE65	Ant Structural Support	SN48	Launcher	Information	No

10. Press the '(10) Filter out no FDom Headroom MEIXs' button. This will reorder the list, placing those with headroom first, in order of MEIX UID, those without headroom second, in order of MEIX UID. The tool will copy those with headroom

onto the *Prospective Transfers* sheet and redirect you to that sheet where the next step is located. Figure 3.6 shows how the *MEI Connections* will appear after step 9 has been performed.

UID	UID	Source	UID	Bearer	UID	Sink	Headroom
MEIX01	SR07	DALP	BE11	Cubicle Power Cable EM Conductivity	SN13	ShipSup	Yes
MEIX02	SR30	Cubicle	BE27	DALP Status Cable Mech Connection	SN28	HullAir	Yes
MEIX04	SR74	PropMotAcou	BE38	Cubicle Power	SN23	Cubicle	Yes
MEIX06	SR20	Ant	BE33	Launcher Command Cable Mech Connect	SN14	Cubicle	Yes
MEIX07	SR47	Launcher Pcable	BE74	PropMotor Acoustics	SN47	Missile	Yes
MEIX09	SR30	Cubicle	BE12	DALP Power	SN33	Launcher	Yes
MEIX11	SR43	Keel	BE42	Launcher Structure Support Emag	SN28	HullAir	Yes
MEIX14	SR60	Ant	BE46	MissLift2Launcher Emag Transfer	SN17	AftDeck	Yes
MEIX17	SR78	Ant	BE89	ShipSup Drive	SN16	DALP	Yes
MEIX19	SR27	AftDeck	BE71	Cubicle Structural Support	SN50	Missile	Yes
MEIX21	SR64	AftDeck	BE73	AftDeck Structural Support	SN47	Missile	Yes
MEIX23	SR76	Tower	BE36	Radar Command	SN60	Missile	Yes
MEIX03	SR42	AftDeck	BE43	Missile Lift Structure Support Emag	SN40	Cubicle	No
MEIX05	SR67	AftDeck	BE52	MissMag2MissLift Emag Transfer	SN27	DALP	No
MEIX08	SR86	PropMotor	BE87	MissLift Launcher Structural Support	SN67	Ant	No
MEIX10	SR12	Cubicle	BE06	AftDeck Structure Support Emag	SN28	HullAir	No
MEIX12	SR27	AftDeck	BE32	Launcher Command Cable Mech Connect	SN33	Launcher	No
MEIX13	SR48	MissLift	BE49	Launcher Power	SN49	MissLift	No
MEIX15	SR76	Tower	BE59	Missile	SN36	Launcher	No
MEIX16	SR68	Cubicle	BE79	MissMag Structural Support	SN45	Launcher	No
MEIX18	SR36	Cubicle	BE42	Launcher Structure Support Emag	SN03	AftDeck	No
MEIX20	SR75	PropMotVibe	BE83	MissMag Misslift Structural Support	SN68	CabBase	No
MEIX22	SR45	MissLift	BE46	MissLift2Launcher Emag Transfer	SN35	Ant	No
MEIX24	SR32	Cubicle	BE37	Launcher Power Cable Mech	SN38	Cubicle	No

11. Step 10 should have redirected you to the *Prospective Transfers* sheet. Press the '(11) Select synchronous/ asynchronous MEIXs' button, this will show a dialog box allowing you to confirm whether each MEI transfer is synchronous or asynchronous in the time domain. Figure 3.7 shows an example of this box. The skip button will allow you to move onto the next row without having to confirm if the transfer is synchronous or asynchronous.

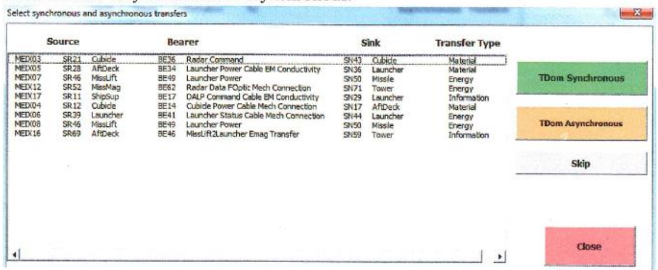


Figure 3.7 – Dialog box to select time domain synchronous and asynchronous MEIXs.

12. Press the '(12) Filter out TDom Asynchronous MEIXs' button. This will reorder the list, placing synchronous transfers first, in order of MEIX UID, with asynchronous second, in order of MEIX UID. The tool will copy those the synchronous transfers onto the *Potential Transfers* sheet and redirect you to that sheet where the next step is located. Figure 3.8 shows how the *Prospective Transfers* sheet will appear after step 12 has been performed.

MEIX UID	Source UID	Source	Bearer UID	Bearer	Sink UID	Sink	Transfer Type	TDom Synchronous
MEIX03	SR21	Cubicle	BE36	Radar Command	SN43	Cubicle	Material	Yes
MEIX05	SR28	AftDeck	BE34	Launcher Power Cable EM Conductivity	SN36	Launcher	Material	Yes
MEIX07	SR46	MissLift	BE49	Launcher Power	SN50	Missile	Energy	Yes
MEIX12	SR52	MissMag	BE62	Radar Data FOptic Mech Connection	SN71	Tower	Energy	Yes
MEIX17	SR11	ShipSup	BE17	DALP Command Cable EM Conductivity	SN29	Launcher	Information	Yes
MEIX04	SR12	Cubicle	BE14	Cubicle Power Cable Mech Connection	SN17	AftDeck	Material	No
MEIX06	SR39	Launcher	BE41	Launcher Status Cable Mech Connection	SN44	Launcher	Energy	No
MEIX08	SR46	MissLift	BE49	Launcher Power	SN50	Missile	Energy	No
MEIX16	SR69	AftDeck	BE46	MissLift2Launcher Emag Transfer	SN59	Tower	Information	No

Figure 3.8 – *'Prospective Transfers'* after step 12 has been performed.

13. The tool should have redirected you to the *Potential Transfers* sheet where the next step is located. At this point, the maximum and used excursion information for each source, sink and bearer should be manually inputted into each individual cell, see section 1 for the definitions of these terms. Figure 3.9 below shows how the *Potential Transfers* sheet should appear after step 13 has been completed.

MEIX UID	Source UID	Source	SR Max Excursion	SR Used Excursion	Bearer UID	Bearer	BE Max Excursion	BE Used Excursion	Sink UID	Sink	SN Max Excursion	SN Used Excursion	Transfer Type	Frequency Domain Overhead
MEIX02	SR16	Cubicle	12 Kg	9 Kg	BE30	Launcher Command Cable EM Conductivity	50 Kg	46 Kg	SN37	Cubicle	8 Kg	8 Kg	Material	
MEIX06	SR47	Launcher Pcable	1400 J	700 J	BE50	MissMag MissLift Structure Support Emag	1400 J	700 J	SN47	Missile	1400 J	700 J	Energy	
MEIX14	SR30	Cubicle	1250 B	90 B	BE39	Launcher Status Cable EM Conductivity	4000 B	2560 B	SN44	Launcher	600 B	586 B	Information	

Figure 3.9 – *'Potential Transfers'* after step 13 has been actioned.

14. Press the '(14) Display Frequency Overhead' button located on the *Potential Transfers* sheet. This will show the frequency overhead in column O. Figure 3.10 below shows how *'Potential Transfers'* will appear when step 14 is complete.

MEIX UID	Source UID	Source	SR Max Excursion	SR Used Excursion	Bearer UID	Bearer	BE Max Excursion	BE Used Excursion	Sink UID	Sink	SN Max Excursion	SN Used Excursion	Transfer Type	Frequency Domain Overhead
MEIX02	SR16	Cubicle	12 Kg	9 Kg	BE30	Launcher Command Cable EM Conductivity	50 Kg	46 Kg	SN37	Cubicle	8 Kg	8 Kg	Material	0 to 10 Hz
MEIX06	SR47	Launcher Pcable	1400 J	700 J	BE50	MissMag MissLift Structure Support Emag	1400 J	700 J	SN47	Missile	1400 J	700 J	Energy	100 to 120000 Hz
MEIX14	SR30	Cubicle	1250 B	90 B	BE39	Launcher Status Cable EM Conductivity	4000 B	2560 B	SN44	Launcher	600 B	586 B	Information	100 to 120000 Hz

Figure 3.10 – *'Potential Transfers'* after step 14 has been actioned.

4 Visualising the Data in Cytoscape

This section outlines how to convert the data into a format compatible with the Cytoscape application, and how to utilise the Cytoscape application to perform visual analytics on the FFP data.

4.1 Converting the tool into Cytoscape compatible format

The file format of the tool is not compatible with Cytoscape, so a programme to convert the file format has been embedded in the tool. On the *'MEI Connections'*, *'Prospective Transfers'* and *'Potential Transfers'* sheets there is a button with the caption 'Convert to Cytoscape compatible format' to perform this action. Figure 4.1.1 shows an example of this button.

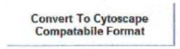
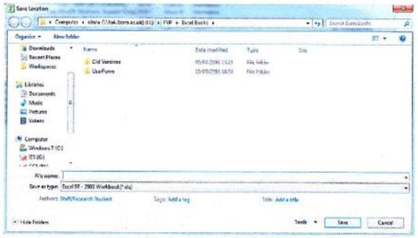


Figure 4.1.1 – The convert to Cytoscape compatible format button.

Pressing this button will bring up a dialog box, shown below in Figure 3.14, enabling you to select the file save location and name. The file format is locked as an Excel 97 – 2003 workbook as this is the file format compatible with Cytoscape.



Choose an appropriate file location and name, and press save. Excel will alert you to a loss of functionality; this is to do with the additional functionality added into create the tool and is not important. Press continue, and a copy of the desired sheet should open on the screen. Check the copied sheet contains the desired information, and proceed to the next section.

4.2 Creating a visualisation

This section will instruct the user how produce a basic visualisation of the data in the Cytoscape application.

Start the Cytoscape programme by selecting the cytoscape.exe application from the Cytoscape folder as shown in figure 4.2.1 below.

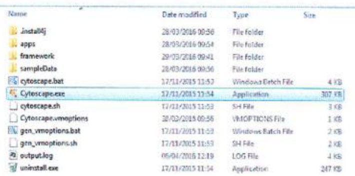
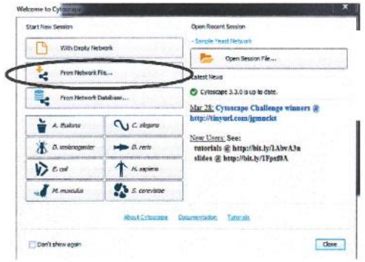


Figure 4.2.1 – how to start the Cytoscape application

A dialog box similar to figure 4.2.2 will open as the Cytoscape application loads; select the second button titled 'From Network File'.



Another dialog box will open allowing you to select a file; choose the file created in section 4.1, the copy of the desired sheet from the tool.

Once selected, a dialog box similar to figure 4.2.3 will open. This is the dialog box where Cytoscape allows you to format the data prior to creating the visualisation.

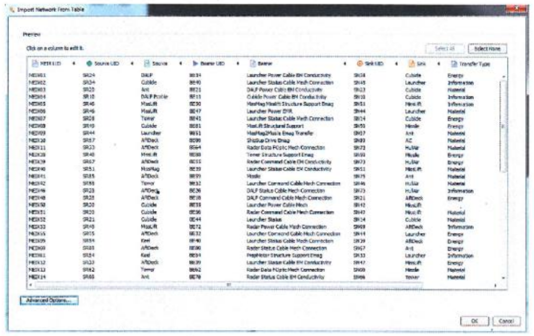
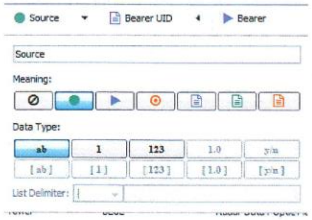


Figure 4.2.3 – Cytoscape dialog box to categorise columns prior to visualisation

Cytoscape will detect the column headings from the Excel sheet automatically, however you must first categorise each column to enable the visualisation characteristics to be accurate. Clicking the arrow on the right side of the column title will bring down a dialog box similar to the one shown in Figure 4.2.4.



There are 6 types of column category; Source Node (green circle), Source Node Attribute (green sheet), Interaction Type (purple arrow), Interaction Attribute (purple sheet), Target Node (orange circle) and Target Node Attribute (orange sheet). The attribute columns do not affect the visualisation; however it is important to set them correctly so that if information is required at a later time, it is available to the user. The nodes and interactions are what Cytoscape uses to build the visualisation, so it is important to ensure they are set correctly.

Setting the UID columns or the actual SSB data columns can have a drastic effect on the layout for several reasons, including if there are duplicated names for sources, sinks or bearers among others. It is up to the user to decide which columns to use as the nodes and interactions, however there must be consistency to avoid Cytoscape errors. Table 4.2.1 shows the two ways to categorise the columns.

Method 1		Method 2	
Source Node	Source UID	Source Node	Source
Interaction	Bearer UID	Interaction	Bearer
Target Node	Sink UID	Target Node	Sink

Table 4.2.1 – the two column categorisation methods to create a Cytoscape visualisation of the FFP data.

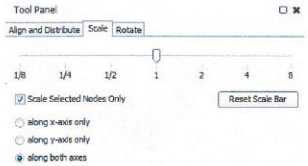
Once the columns have been categorised, use the OK button to produce the visualisation.

4.3 Improving the layout

It is highly unlikely that the default layout produced by Cytoscape will be in an acceptable format for the user, so this section aims to suggest layouts and changes to Cytoscape that can be used to enhance the visualisation.

4.3.1 Scale

Cytoscape frequently sets the nodes (sources and sinks) very close together, so using the scaling tool can be very useful to provide a better visualisation. To access the scaling tool go to LAYOUT-->SCALE.



Increasing the scaling (moving to the right) will pull the nodes further apart, but will make it more difficult to fit the entire image on one screen. Decreasing the scaling (moving to the left) will pull the nodes closer together. Resetting the scale bar can allow even greater scaling to be added.

4.3.2 Style

The default style for Cytoscape is fairly basic and contains little information, although it is a good starting point for making the visualisation clearer. Cytoscape has many other styles with different characteristics that can be used to effectively visualise an imported file. Figure 4.3.2 shows the style editor. Pressing the drop down menu at the top allows you to select from the predesigned styles in Cytoscape, or you can use the properties to customise your own style.

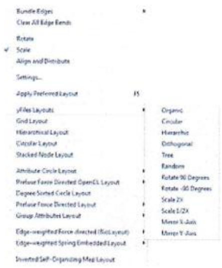
4.3.3 Layout Algorithm

Cytoscape has many built in layout algorithms to change how the visualisation appears, the full list is shown in figure 4.3.3. Each algorithm will affect an import file differently, however some of the following algorithms have proved useful during the creation of this user manual. To access them to go layout at the top of the screen then select the desired algorithm.

yFiles Layout --> Circular
yFiles Layout --> Organic
Edge Weighted Spring Embedded Layout
Circular Layout

Prefuse Force Directed Layout --> EdgeBetweeness

It is often necessary to increase the scaling after using these algorithms, refer to section 4.3.1 on how to adjust the scaling.



4.4 Manually altering the layout

It is also possible to manually alter the layout of the visualisation image by clicking on a node and dragging it around the screen. Similarly a node or connection can be moved or even deleted by selecting it and performing the desired action.

5 Useful Websites

Cytoscape User Manual:

http://wiki.cytoscape.org/Cytoscape_3/UserManual

Excel Troubleshooting:

www.excelhelpdesk.com

https://support.microsoft.com/en-us/kb/280504

https://support.microsoft.com/en-gb/kb/2758592

Appendix 6 – Frequency Domain Analysis of all SSBs Code

```
Public Sub FrequencyAnalysis()
    Dim SRCHi As Double, SNKHi As Double, SRCLo As Double, SNKLo As Double
    Dim BERHi As Double, BERLo As Double
    Dim MtchUIDs As String
    Dim i As Long, j As Long, k As Long
    Dim SRCUID As String, SNKUID As String, BERUID As String
    Dim LastRow As Long, LastRow1 As Long, LastRow2 As Long, LastRowSh3 As Long
    Dim MinHi As Double, MaxLo As Double
    'Declaring variables
    MtchUIDs = ""  'Sets the string blank'
   With ActiveSheet
        LastRow = .Cells(.Rows.Count, "A").End(xlUp).Row
    End With
    'finds the first empty row in column B from the top
    With ActiveSheet
        LastRow1 = .Cells(.Rows.Count, "F").End(xlUp).Row
    End With
     'finds the first empty row in column G from the top
     With ActiveSheet
        LastRow2 = .Cells(.Rows.Count, "K").End(xlUp).Row
    End With
     With Sheet3
        LastRowSh3 = .Cells(.Rows.Count, "A").End(xlUp).Row
    End With
     'finds the first empty row in column A from the top on sheet
    LastRowSh3 = LastRowSh3 + 1
For i = 2 To LastRow
    For j = 2 To LastRow1
        For k = 2 To LastRow2
        SRCHi = Range("D" & i).Value  'Source Fb Hi
        SRCLo = Range("C" & i).Value 'Source Fb Lo
        BERHi = Range("I" & j).Value  'Bearer Fb Hi
        BERLo = Range("H" & j).Value 'Bearer Fb Lo
        SNKHi = Range("N" & k).Value 'Sink Fb Hi
        SNKLo = Range("M" & k).Value 'Sink Fb Lo
        SRCUID = Range("A" & i).Value  'Source UID
        BERUID = Range("F" & j).Value  'Bearer UID
        SNKUID = Range("K" & k).Value  'Sink UID

        MinHi = WorksheetFunction.Min(SRCHi, BERHi, SNKHi) 'find the value of the lowest Fb Hi
        MaxLo = WorksheetFunction.Max(SRCLo, BERLo, SNKLo) 'finds the value of the highest Fb Lo

        If MinHi > MaxLo Then
        MtchUIDs = SRCUID & BERUID & SNKUID
        'sets the string as the combined UIDs
           Sheet3.Range("a" & LastRowSh3).Value = MtchUIDs
           'Prints the MtchUIDs string on the first available row in Sheet3
            MtchUIDs = ""
           'Sets the string back to blank for the next loop
            LastRowSh3 = LastRowSh3 + 1
            'Increases the lastrow on sheet 3 value by one
        End If
        Next k
    Next j
```

Appendix 7 – VBA code to remove the letters from an alphanumeric string

```
Function onlyDigits(s As String) As String

    Dim retval As String     ' This is the return string.      '
    Dim i As Integer         ' Counter for character position. '

    ' Initialise return string to empty                        '
    retval = ""

    ' For every character in input string, copy digits to     '
    '   return string.                                         '
    For i = 1 To Len(s)
        If Mid(s, i, 1) >= "0" And Mid(s, i, 1) <= "9" Then
            retval = retval + Mid(s, i, 1)
        End If
    Next

    ' Then return the return string.                           '
    onlyDigits = retval
End Function
```


Appendix 8 –VBA code to reorder and filter out MEIXs with no FDom headroom

```
Sub TimeDomainAnalysis()
Range("I2").Select
    Selection.Sort Key1:=Range("I2"), Order1:=xlDescending, Key2:=Range("A2") _
        , Order2:=xlYes, Header:=xlGuess, OrderCustom:=1, MatchCase:= _
        False, Orientation:=xlTopToBottom
'Orders the data based on column I values first, then column A values second
Dim LastRow As Integer, i As Integer, CompareVal As Integer
Dim colB As String, colC As String, colD As String
Dim colE As String, colF As String, colG As String
Dim ParentStr As String, CellStr As String

     With ActiveSheet
        LastRow = .Cells(.Rows.Count, "B").End(xlUp).Row
    End With
'Finds the first available row in column B from the top
  For i = 2 To LastRow

        ParentString = "Yes"
        CellString = Range("I" & i).Value
        CompareVal = StrComp(ParentString, CellString, vbTextCompare)
        'Compares to see if the cell string (Source & Sink UIDs)
        'is yes or no using the vbTextCompare function
        If CompareVal = 0 Then

        Sheet4.Range("A" & i).Value = Range("A" & i).Value
        Sheet4.Range("B" & i).Value = Range("B" & i).Value
        Sheet4.Range("C" & i).Value = Range("C" & i).Value
        Sheet4.Range("D" & i).Value = Range("D" & i).Value
        Sheet4.Range("E" & i).Value = Range("E" & i).Value
        Sheet4.Range("F" & i).Value = Range("F" & i).Value
        Sheet4.Range("G" & i).Value = Range("G" & i).Value
        Sheet4.Range("H" & i).Value = Range("H" & i).Value
        'copies the information from each column to the same column
        'on sheet 4
        End If

        CellString = ""
        'returns the cellstring to blank
    Next i

 Sheet4.Activate
 'takes the user to sheet4 where the next step is located
End Sub
```

Appendix 9 – VBA code to display the frequency overhead

```
Public Sub FrequencyOverhead()
Dim SRDigStr As String, BEDigStr As String, SNDigStr As String
Dim SRDig As Double, BEDig As Double, SNDig As Double
Dim SRUID As String, BEUID As String, SNUID As String
Dim i As Long, LastRow As Long
Dim SRFreqHi As Long, SRFreqLo As Long, BEFreqHi As Long, BEFreqLo As Long
Dim SNFreqHi As Long, SNFreqLo As Long
Dim FreqOvhd As String

With ActiveSheet
    LastRow = .Cells(.Rows.Count, "B").End(xlUp).Row
End With
'finds the first empty row in column b on the active worksheet
For i = 2 To LastRow
SRUID = Sheet5.Range("B" & i).Value
BEUID = Sheet5.Range("F" & i).Value
SNUID = Sheet5.Range("J" & i).Value
'extracts the UIDs from the relevant columns on the potential transfers sheet

SRDigStr = onlyDigits(SRUID)
BEDigStr = onlyDigits(BEUID)
SNDigStr = onlyDigits(SNUID)
'using the onlyDigits function removes the letters from the alphanumeric string
SRDig = Val(SRDigStr) + 1
BEDig = Val(BEDigStr) + 1
SNDig = Val(SNDigStr) + 1
'increases the numeric value of the string by one to deal with the mismatch on row count
SRFreqHi = Sheet1.Range("D" & SRDig).Value
SRFreqLo = Sheet1.Range("C" & SRDig).Value
BEFreqHi = Sheet1.Range("I" & BEDig).Value
BEFreqLo = Sheet1.Range("H" & BEDig).Value
SNFreqHi = Sheet1.Range("N" & SNDig).Value
SNFreqLo = Sheet1.Range("M" & SNDig).Value
'pulls the frequency characteristics from the Sources,Sinks & Bearers worksheets

MinHi = WorksheetFunction.Min(SRFreqHi, BEFreqHi, SNFreqHi)
MaxLo = WorksheetFunction.Max(SRFreqLo, BEFreqLo, SNFreqLo)
'works out the lowest Fb Hi and highest Fb Lo
FreqOvhd = MaxLo & " to " & MinHi & " Hz"
'creates a string with the lowest Fb Hi and highest Fb Lo
Sheet5.Range("O" & i).Value = FreqOvhd
'displays the combined string
Next i


End Sub
```


Appendix 10 – Example VBA code to convert the FFP analysis tool to a format compatible with Cytoscape

```
Sub CytoscapeConvertSheet4()
Dim FilePath As String
FilePath = Application.GetSaveAsFilename(FileFilter:= _
    "Excel 97 - 2003 Workbook(*.xls),*.xls", Title:="Save Location")
'Allows the user to choose a file name and location
'and limits the user to only the Excel 97-2003 format
Sheet4.Copy
'copies the entire sheet
ActiveSheet.SaveAs& FilePath, FileFormat:=56

End Sub
```

A11: Concept Demonstrator Development ME(I) Transfers

UID	Source	SRC Fb Lo	SRC Fb Hi	Bearer	BER Fb Lo	BER Fb Hi	BER/SNK Gain	Sink	SNK Fb Lo	SNK Fb Hi	SNK/BER Gain	MEI	Type
MEIX1	DALP	1.00E+12	1.00E+13	WO Signal Beam IR								E	Inh
MEIX2	DALP	0.00E+00	1.00E+04	WO Signal	0.00E+00	0.00E+00	8.00E-01	AC	0.00E+00	0.00E+00	8.00E-01	I	Int
MEIX3	DALP	1.00E+12	1.00E+13	WO Signal Beam Light			5.00E-01	AC				E	Int
MEIX4	Keel	0.00E+00	2.00E+06	AftDeck Structure Support Emag	0.00E+00	1.60E+06	9.80E-01	AftDeck	1.00E+02	1.20E+06	8.82E-01	E	Inh
MEIX5	AftDeck	0.00E+00	5.00E+02	DALP Structural Support	0.00E+00	0.00E+00	1.00E+00	DALP	0.00E+00	0.00E+00	9.80E-01	E	Int
MEIX6	Keel	0.00E+00	2.00E+06	AftDeck Structure Support Emag	0.00E+00	1.60E+06	9.50E-01	MissMag	1.00E+02	1.20E+06	8.55E-01	E	Inh
MEIX7	DALP	0.00E+00	1.00E+03	DALP Status	0.00E+00	0.00E+00	1.00E+00	Cubicle	0.00E+00	0.00E+00	1.00E+00	I	Int
MEIX8	Tower	0.00E+00	2.00E+06	Ant Structure Support Emag	0.00E+00	1.60E+06	9.80E-01	Ant	1.00E+02	1.20E+06	8.82E-01	E	Inh
MEIX9	AftDeck	0.00E+00	2.00E+06	Cabin Structure Support Emag	0.00E+00	1.60E+06	9.90E-01	CabBase	1.00E+02	1.20E+06	8.91E-01	E	Inh
MEIX10	DALP Pcable	2.00E+01	1.00E+08	DALP Power EMR	2.00E+01	1.00E+08	7.00E-01	HullAir	2.00E+01	1.00E+08	7.00E-01	E	Ind
MEIX11	ShipSup	0.00E+00	2.00E+06	Cubicle Power Cable EM Conductivity	0.00E+00	1.60E+06	9.90E-01	Cubicle	1.00E+02	1.20E+06	8.91E-01	E	Inh
MEIX12	Cubicle	0.00E+00	1.00E+03	DALP Power	0.00E+00	0.00E+00	9.80E-01	DALP	0.00E+00	0.00E+00	9.80E-01	E	Int
MEIX13	Cubicle	0.00E+00	1.00E+02	Cubicle Power Cable Mech Connection	0.00E+00	8.00E+01	1.00E+00	AftDeck	1.00E+02	6.00E+01	9.00E-01	E	Inh
MEIX14	AftDeck	0.00E+00	1.00E+02	Cubicle Power Cable Mech Connection	0.00E+00	8.00E+01	9.80E-01	ShipSup	1.00E+02	6.00E+01	8.82E-01	E	Inh
MEIX15	CabBase	0.00E+00	2.00E+06	Cubicle Structure Support Emag	0.00E+00	1.60E+06	9.80E-01	Cubicle	1.00E+02	1.20E+06	8.82E-01	E	Inh
MEIX16	Cubicle	0.00E+00	1.00E+01	DALP Command	0.00E+00	0.00E+00	9.60E-01	DALP	0.00E+00	0.00E+00	1.00E+00	I	Int
MEIX17	Cubicle	0.00E+00	2.00E+06	DALP Command Cable EM Conductivity	0.00E+00	1.60E+06	1.00E+00	DALP	1.00E+02	1.20E+06	9.00E-01	E	Inh
MEIX18	Cubicle	0.00E+00	1.00E+02	DALP Command Cable Mech Connection	0.00E+00	8.00E+01	9.50E-01	AftDeck	1.00E+02	6.00E+01	8.55E-01	E	Inh
MEIX19	AftDeck	0.00E+00	1.00E+02	DALP Command Cable Mech Connection	0.00E+00	8.00E+01	1.00E+00	DALP	1.00E+02	6.00E+01	9.00E-01	E	Inh
MEIX20	Ant	0.00E+00	1.00E+03	Radar Data	0.00E+00	0.00E+00	9.80E-01	Cubicle	0.00E+00	0.00E+00	9.90E-01	I	Int
MEIX21	Cubicle	0.00E+00	2.00E+06	DALP Power Cable EM Conductivity	0.00E+00	1.60E+06	1.00E+00	DALP	1.00E+02	1.20E+06	9.00E-01	E	Inh
MEIX22	Cubicle	0.00E+00	1.00E+02	DALP Power Cable Mech Connection	0.00E+00	8.00E+01	9.80E-01	AftDeck	1.00E+02	6.00E+01	8.82E-01	E	Inh
MEIX23	AftDeck	0.00E+00	1.00E+02	DALP Power Cable Mech Connection	0.00E+00	8.00E+01	1.00E+00	DALP	1.00E+02	6.00E+01	9.00E-01	E	Inh
MEIX24	DALP	0.00E+00	2.00E+06	DALP Status Cable EM Conductivity	0.00E+00	1.60E+06	9.90E-01	Cubicle	1.00E+02	1.20E+06	8.91E-01	E	Inh
MEIX25	Ant	0.00E+00	5.00E+01	Radar Status	0.00E+00	0.00E+00	9.80E-01	Cubicle	0.00E+00	0.00E+00	1.00E+00	I	Int
MEIX26	DALP	0.00E+00	1.00E+02	DALP Status Cable Mech Connection	0.00E+00	8.00E+01	1.00E+00	AftDeck	1.00E+02	6.00E+01	9.00E-01	E	Inh
MEIX27	AftDeck	0.00E+00	1.00E+02	DALP Status Cable Mech Connection	0.00E+00	8.00E+01	1.00E+00	Cubicle	1.00E+02	6.00E+01	9.00E-01	E	Inh
MEIX28	AftDeck	0.00E+00	2.00E+06	DALP Support EM Conductivity	0.00E+00	1.60E+06	9.80E-01	DALP	1.00E+02	1.20E+06	8.82E-01	E	Inh
MEIX29	Radar Pcable	2.00E+01	1.00E+08	Radar Power EMR	2.00E+01	1.00E+08	7.00E-01	HullAir	2.00E+01	1.00E+08	7.00E-01	E	Ind
MEIX30	Cubicle	0.00E+00	2.00E+06	Launcher Command Cable EM Conductivity	0.00E+00	1.60E+06	9.80E-01	Launcher	1.00E+02	1.20E+06	8.82E-01	E	Inh
MEIX31	Cubicle	3.50E+02	4.50E+02	Radar Power	3.50E+02	2.80E+02	9.30E-01	Ant	0.00E+00	2.10E+02	9.80E-01	E	Int
MEIX32	Cubicle	0.00E+00	1.00E+02	Launcher Command Cable Mech Connection	0.00E+00	8.00E+01	9.80E-01	AftDeck	1.00E+02	6.00E+01	8.82E-01	E	Inh
MEIX33	AftDeck	0.00E+00	1.00E+02	Launcher Command Cable Mech Connection	0.00E+00	8.00E+01	9.80E-01	Launcher	1.00E+02	6.00E+01	8.82E-01	E	Inh
MEIX34	Cubicle	0.00E+00	2.00E+06	Launcher Power Cable EM Conductivity	0.00E+00	1.60E+06	1.00E+00	Launcher	1.00E+02	1.20E+06	9.00E-01	E	Inh
MEIX35	Cubicle	0.00E+00	1.00E+02	Launcher Power Cable Mech	0.00E+00	8.00E+01	9.50E-01	AftDeck	1.00E+02	6.00E+01	8.55E-01	E	Inh
MEIX36	Cubicle	0.00E+00	5.00E+01	Radar Command	0.00E+00	0.00E+00	8.00E-01	Ant	0.00E+00	0.00E+00	1.00E+00	I	Int
MEIX37	AftDeck	0.00E+00	1.00E+02	Launcher Power Cable Mech	0.00E+00	8.00E+01	1.00E+00	Launcher	1.00E+02	6.00E+01	9.00E-01	E	Inh
MEIX38	ShipSup	5.50E+01	6.50E+01	Cubicle Power	5.50E+01	4.40E+01	1.00E+00	Cubicle	0.00E+00	3.30E+01	9.80E-01	E	Int
MEIX39	Launcher	0.00E+00	2.00E+06	Launcher Status Cable EM Conductivity	0.00E+00	1.60E+06	9.80E-01	Cubicle	1.00E+02	1.20E+06	8.82E-01	E	Inh
MEIX40	Launcher	0.00E+00	1.00E+02	Launcher Status Cable Mech Connection	0.00E+00	8.00E+01	1.00E+00	AftDeck	1.00E+02	6.00E+01	9.00E-01	E	Inh
MEIX41	AftDeck	0.00E+00	1.00E+02	Launcher Status Cable Mech Connection	0.00E+00	8.00E+01	1.00E+00	Cubicle	1.00E+02	6.00E+01	9.00E-01	E	Inh
MEIX42	AftDeck	0.00E+00	2.00E+06	Launcher Structure Support Emag	0.00E+00	1.60E+06	9.80E-01	Launcher	1.00E+02	1.20E+06	8.82E-01	E	Inh
MEIX43	Keel	0.00E+00	2.00E+06	Missile Lift Structure Support Emag	0.00E+00	1.60E+06	9.80E-01	MissLift	1.00E+02	1.20E+06	8.82E-01	E	Inh
MEIX44	Launcher	0.00E+00	5.00E+02	Launcher Status	0.00E+00	0.00E+00	1.00E+00	Cubicle	2.40E+01	0.00E+00	1.00E+00	I	Int
MEIX45	MissLift	0.00E+00	2.00E+06	MissLift Launcher Structure Support Emag	0.00E+00	1.60E+06	9.80E-01	Launcher	1.00E+02	1.20E+06	8.82E-01	E	Inh
MEIX46	MissLift	0.00E+00	2.00E+06	MissLift2Launcher Emag Transfer	0.00E+00	1.60E+06	9.30E-01	Launcher	1.00E+02	1.20E+06	8.37E-01	E	Inh
MEIX47	Launcher Pcable	2.00E+01	1.00E+08	Launcher Power EMR	2.00E+01	1.00E+08	7.00E-01	HullAir	2.00E+01	1.00E+08	7.00E-01	E	Ind
MEIX48	MissLift	0.00E+00	2.00E+06	MissLift2Missile Emag Transfer	0.00E+00	1.60E+06	9.80E-01	Missile	1.00E+02	1.20E+06	8.82E-01	E	Inh
MEIX49	Cubicle	3.50E+02	4.50E+02	Launcher Power	3.50E+02	2.80E+02	9.60E-01	Launcher	0.00E+00	2.10E+02	9.80E-01	E	Int
MEIX50	MissMag	0.00E+00	2.00E+06	MissMag Misslift Structure Support Emag	0.00E+00	1.60E+06	9.80E-01	MissLift	1.00E+02	1.20E+06	8.82E-01	E	Inh
MEIX51	MissMag	0.00E+00	2.00E+06	MissMag2Missile Emag Transfer	0.00E+00	1.60E+06	9.80E-01	Missile	1.00E+02	1.20E+06	8.82E-01	E	Inh
MEIX52	MissMag	0.00E+00	2.00E+06	MissMag2MissLift Emag Transfer	0.00E+00	1.60E+06	9.80E-01	MissLift	1.00E+02	1.20E+06	8.82E-01	E	Inh
MEIX53	Cubicle	0.00E+00	1.00E+01	Launcher Command	0.00E+00	0.00E+00	9.80E-01	Launcher	0.00E+00	0.00E+00	1.00E+00	I	Int
MEIX54	Keel	0.00E+00	2.00E+06	PropMotor Structure Support Emag	0.00E+00	1.60E+06	9.60E-01	PropMotor	1.00E+02	1.20E+06	8.64E-01	E	Inh
MEIX55	Cubicle	0.00E+00	2.00E+06	Radar Command Cable EM Conductivity	0.00E+00	1.60E+06	9.80E-01	Ant	1.00E+02	1.20E+06	8.82E-01	E	Inh
MEIX56	AftDeck	0.00E+00	1.00E+02	Radar Command Cable Mech Connection	0.00E+00	8.00E+01	9.80E-01	Tower	1.00E+02	6.00E+01	8.82E-01	E	Inh
MEIX57	MissMag	0.00E+00	1.00E-01	MissMag2Missile Push	0.00E+00	0.00E+00	9.80E-01	Missile	0.00E+00	0.00E+00	9.60E-01	E	Int
MEIX58	Tower	0.00E+00	1.00E+02	Radar Command Cable Mech Connection	0.00E+00	8.00E+01	1.00E+00	Ant	1.00E+02	6.00E+01	9.00E-01	E	Inh
MEIX59	MissMag	0.00E+00	1.00E-01	Missile	0.00E+00	0.00E+00	9.80E-01	MissLift	6.60E+01	0.00E+00	1.00E+00	M	Int
MEIX60	Ant	0.00E+00	7.00E+01	Radar Data FOptic Mech Connection	0.00E+00	5.60E+01	9.80E-01	Tower	1.00E+02	4.20E+01	8.82E-01	E	Inh
MEIX61	MissLift	0.00E+00	1.00E-02	MissLift2Missile Push	0.00E+00	0.00E+00	9.80E-01	Missile	0.00E+00	0.00E+00	9.50E-01	E	Int
MEIX62	Tower	0.00E+00	7.00E+01	Radar Data FOptic Mech Connection	0.00E+00	5.60E+01	9.80E-01	AftDeck	1.00E+02	4.20E+01	8.82E-01	E	Inh
MEIX63	MissLift	0.00E+00	1.00E-02	Missile	0.00E+00	0.00E+00	9.80E-01	Launcher	0.00E+00	0.00E+00	1.00E+00	M	Int
MEIX64	AftDeck	0.00E+00	7.00E+01	Radar Data FOptic Mech Connection	0.00E+00	5.60E+01	9.80E-01	Cubicle	1.00E+02	4.20E+01	8.82E-01	E	Inh
MEIX65	Tower	0.00E+00	2.00E+02	Ant Structural Support	0.00E+00	0.00E+00	8.00E-01	Ant	0.00E+00	0.00E+00	9.80E-01	E	Int
MEIX66	Ant	0.00E+00	7.00E+01	Radar Data FOptic Transmissability	0.00E+00	5.60E+01	9.80E-01	Cubicle	1.00E+02	4.20E+01	8.82E-01	E	Inh
MEIX67	AftDeck	0.00E+00	3.00E+02	Tower Structural Support	0.00E+00	0.00E+00	1.00E+00	Tower	0.00E+00	0.00E+00	9.80E-01	E	Int
MEIX68	Cubicle	0.00E+00	1.00E+02	Radar Power Cable EM Conductivity	0.00E+00	8.00E+01	9.80E-01	Ant	1.00E+02	6.00E+01	8.82E-01	E	Inh
MEIX69	AftDeck	0.00E+00	5.00E+02	Cabin Structural Support	0.00E+00	0.00E+00	1.00E+00	CabBase	0.00E+00	0.00E+00	9.80E-01	E	Int
MEIX70	Cubicle	0.00E+00	1.00E+02	Radar Power Cable Mech Connection	0.00E+00	8.00E+01	9.80E-01	AftDeck	1.00E+02	6.00E+01	8.82E-01	E	Inh
MEIX71	CabBase	0.00E+00	1.00E+02	Cubicle Structural Support	0.00E+00	0.00E+00	1.00E+00	Cubicle	0.00E+00	0.00E+00	9.80E-01	E	Int
MEIX72	AftDeck	0.00E+00	1.00E+02	Radar Power Cable Mech Connection	0.00E+00	8.00E+01	9.80E-01	Tower	1.00E+02	6.00E+01	8.82E-01	E	Inh
MEIX73	Keel	0.00E+00	1.00E+03	AftDeck Structural Support	0.00E+00	0.00E+00	1.00E+00	AftDeck	0.00E+00	0.00E+00	9.80E-01	E	Int
MEIX74	PropMotAcou	20	2.00E+04	PropMotor Acoustics	20	2.00E+04	9.80E-01	HullAir	20	2.00E+04	9.80E-01	E	Ind
MEIX75	PropMotVibe	0.1	100	PropMotor Vibrations	0.1	100	8.00E-01	Keel	0.1	100	8.00E-01	E	Ind
MEIX76	Tower	0.00E+00	1.00E+02	Radar Power Cable Mech Connection	0.00E+00	8.00E+01	9.80E-01	Ant	1.00E+02	6.00E+01	8.82E-01	E	Inh
MEIX77	Keel	0.00E+00	1.00E+03	PropMotor Structural Support	0.00E+00	0.00E+00	1.00E+00	PropMotor	0.00E+00	0.00E+00	9.80E-01	E	Int
MEIX78	Ant	0.00E+00	1.00E+02	Radar Status Cable EM Conductivity	0.00E+00	8.00E+01	9.80E-01	Cubicle	1.00E+02	6.00E+01	8.82E-01	E	Inh
MEIX79	Keel	0.00E+00	3.00E+02	MissMag Structural Support	0.00E+00	0.00E+00	1.00E+00	MissMag	0.00E+00	0.00E+00	9.80E-01	E	Int
MEIX80	Ant	0.00E+00	1.00E+02	Radar Status Cable Mech Connection	0.00E+00	8.00E+01	9.80E-01	Tower	1.00E+02	6.00E+01	8.82E-01	E	Inh
MEIX81	Keel	0.00E+00	1.50E+02	MissLift Structural Support	0.00E+00	0.00E+00	1.00E+00	MissLift	0.00E+00	0.00E+00	9.80E-01	E	Int
MEIX82	Tower	0.00E+00	1.00E+02	Radar Status Cable Mech Connection	0.00E+00	8.00E+01	9.80E-01	AftDeck	1.00E+02	6.00E+01	8.82E-01	E	Inh
MEIX83	MissMag	0.00E+00	7.50E+02	MissMag Misslift Structural Support	0.00E+00	0.00E+00	9.80E-01	MissLift	0.00E+00	0.00E+00	9.80E-01	E	Int
MEIX84	AftDeck	0.00E+00	1.00E+02	Radar Status Cable Mech Connection	0.00E+00	8.00E+01	9.80E-01	Cubicle	1.00E+02	6.00E+01	8.82E-01	E	Inh
MEIX85	AftDeck	0.00E+00	3.00E+02	Launcher Structural Support	0.00E+00	0.00E+00	9.80E-01	Launcher	0.00E+00	0.00E+00	9.80E-01	E	Int
MEIX86	PropMotor	0.00E+00	2.00E+06	ShipSup Drive Emag	0.00E+00	1.60E+06	9.80E-01		1.00E+02	1.20E+06	8.82E-01	E	Inh
MEIX87	MissLift	0.00E+00	3.00E+02	MissLift Launcher Structural Support	0.00E+00	0.00E+00	9.80E-01	Launcher	0.00E+00	0.00E+00	9.80E-01	E	Int
MEIX88	AftDeck	0.00E+00	2.00E+06	Tower Structure Support Emag	0.00E+00	1.60E+06	9.80E-01	Tower	1.00E+02	1.20E+06	8.82E-01	E	Inh
MEIX89	PropMotor	5.50E+01	6.50E+01	ShipSup Drive	5.50E+01	4.40E+01	9.80E-01	ShipSup	0.00E+00	3.30E+01	9.30E-01	E	Int
MEIX90	DALP	0.00E+00	4.40E+14	WO Signal Beam Light	0.00E+00	3.52E+14	9.80E-01	AC	1.00E+02	2.64E+14	8.82E-01	E	Inh

A12: Publications

INCOSE INSIGHT 2017: “Maintaining Systems of Systems Fit-for-Purpose”. Accepted for publication May 2017 published in INSIGHT Issue 2 June 2017

IEEE Systems, Man and Cybernetics: “Maintaining Systems of Systems Fit-for-Purpose” 2015-08-0021.R1 January 2017

INCOSE IS 2016: Conference Paper and Presentation. 18/07/2016

INCOSE ASEC 2014: Academic Research Showcase Poster 20/05/2014

INCOSE IS2014: Key Reserve Paper and Showcase Poster 25/2/2014

This page is intentionally blank