UiO : Centre for Entrepreneurship
University of Oslo

The Relationship between Systems Engineering and Innovation

Empirical evidences from a large, novel subsea project in Norway

MSc in Innovation and Entrepreneurship

Felipe Santana Lima

2012-05-19

The Relationship between Systems Engineering and Innovation

Empirical evidences from a large, novel subsea project in Norway

Felipe Santana Lima

Supervisor: Prof. Tronn Skjerstad, PhD

Master of Science in Innovation and Entrepreneurship

Centre for Entrepreneurship

Faculty of Mathematics and Natural Sciences

University of Oslo

The Relationship between Systems Engineering and Innovation: Empirical evidences from a large, novel subsea project in Norway

Felipe Santana Lima

http://www.duo.uio.no/

University Print Centre, University of Oslo

Abstract

This study investigates the relationship between the practice of systems engineering and innovation and is intended to characterise the way they interact in a high-tech environment. The propositions are built upon two independent theoretical frameworks, namely process-oriented view and capability-oriented view. Two propositions aim at verifying the general alignment of their processes and capabilities and another two aim at identifying particular elements of misalignment. The probe is carried out as a case study in Åsgard Subsea Compression Project, and the research is based on qualitative analyses of primary data acquired through questionnaires and interviews. Åsgard is considered a highly innovative project in the global oil and gas industry; utilises intensively systems engineering concepts and methods; and is contemporary to this study.

The inquiry articulates the analyses and anchors the findings by establishing triangulations in multiple dimensions: theoretical frameworks, data collection methods and data collection units. The concurrent perspectives, methods and data collection units evolve independently throughout the research and in the end converge to a few consistent and reliable conclusions.

The empirical evidences consistently indicate that there are general synergies between the processes of systems engineering and innovation; and that whilst the capabilities necessary for the practice of the former are not the same as for the latter, they are mutually supportive. Nevertheless a particularly controversial relationship between the contemporary innovation's time-based strategy and the systems engineering capabilities emerge as a provocative question mark.

Acknowledgements

I am grateful to a number of people who contributed directly or indirectly to the completion of this academic work; nonetheless I wish to express special thanks:

To my supervisor, who combined professional attitude and friendship from the first to the last days of this research, keeping up his support even when his private life challenged his ultimate strength.

To all teachers whom I had the pleasure to meet during this Master's programme and in my previous studies; who shaped my academic knowledge and ability without which I would not have reached this stage.

To my colleagues at Aker Solutions who provided me with a priceless contribution in the data collection stage.

To Aker Solutions, for giving me permission to undertake the present study in Åsgard project.

And finally to my wife, who has been my unconditional supporter at all times.

Table of Contents

Table of Figures

Table of Tables

1 Introduction

1.1 Background

The decades that followed the Second World War were marked by accelerated technology progress in virtually all industries. There was the emergence of new technology-based industries such as semiconductors, pharmaceuticals, electronic computing and synthetic and composite materials; and in the same period was the technology-driven regeneration of existing sectors such as textiles, steel and agriculture, mainly in the pursuit of efficiency and productivity (Rothwell, 1994). The consequence is that firms' ability to innovate has become gradually the competition engine in the marketplace, requiring that organisations establish effective and efficient processes to ensure competitiveness and long-term survival in such rapidly changing business climate (Hippel, 1988, 2005). In line with that notion, Drucker (1974) dares to suggest that business has only two basic functions: marketing and innovation; marketing and innovation produce results, whilst all the rest are costs.

In the race for creating and marketing new products, services and processes ahead of the competition, firms have been naturally forced to face more complex technological challenges and at the same time ensure a better control of their processes than ever before. The 1940s are said to have contained the beginning of the end of the Machine Age and the beginning of the Systems Age. This new age is the product of a new intellectual framework in which the paradigms of reductionism and mechanism and the analytical type of thinking are supplemented by the paradigms of expansionism and a new synthetic type of thinking (Blanchard & Fabrycky, 2006). This new type of thinking so-called "systems thinking", in turn, gave origin to a new approach to engineering, which recognises all the important relationships between technical specialties and economic factors, ecological factors, political factors and societal factors.

However, the relationship between systems engineering and innovation is not as smooth and straight forward as it may seem. Besides, misconceptions around both topics often create noise in the dialogue and the way people and organisations perceive their interaction. The fact is that the academia, the organisations and some professionals realise that the established systems engineering practice and innovation management have some common characteristics and objectives, but in many circumstances they are perceived, or at least suspected, to counteract each other.

Blanchard & Fabrycky (2006) proposes a different construct on this relationship. They advocate that the thorough application of the system engineering process can lead to reduction of total life-cycle cost; reduction in system acquisition and/or realisation time; and more visibility and reduction in the risk associated with the design decision making process. However, without the proper organisational emphasis from the top-down, the establishment of an environment that will allow for creativity and innovation, a leadership style that will promote a “team” approach to design and so on, the implementation of the systems engineering concepts and methodologies will not occur. In other words, the practice of system engineering itself as well as its potential benefits depends on an innovative environment.

Hence this complex relationship has become an increasingly popular topic between scholars and managers. According to Walden (1998), both innovation and systems engineering are concerned with translating a concept or need into a deliverable entity. Innovation’s emphasis is translating an idea into a marketable product, whilst systems engineering’s emphasis is translating a user need into an operational system that satisfies that need. However, whereas creativity is typically mentioned as one of the first and most important steps in the innovation process (Meredith & Mantel, 1995), systems engineering puts a great deal of emphasis on discipline and control. A number of authors, mostly technologists (e.g. Walden, 1998, 1999; Schoening & Miller, 1993; Cropley & Cropley, 2000; Stajnko & Doukas, 2001), have written about this rather controversial and pervasive relationship but so far little empirical evidence is documented supporting any conclusion.

Innovation process studies have been conducted in a variety of research fields across the management sciences, but economists have repeatedly black-boxed the process of technical transformation whilst technologists often fail to take the external forces of the marketplace into consideration (Kline & Rosenberg, 1986; Hoholm & Olsen, 2012). It is not very likely, however, that researchers and managers will ever agree in a conclusive manner that systems engineering fosters innovation or that it inhibits innovation; and giving a conclusive ending to this controversy is, needless to say, not the ambition of this study. Nonetheless much has been studied on both topics in an attempt to better understand how the systems engineering and the innovation take place in practice. These studies offer a theoretical basis which, combined with relevant empirical data, may provide some additional information about how these two phenomena interact, the expected outcome of this interaction and how to manage it under different circumstances.

The present study is, therefore, an attempt to provide a contribution to the rather young body of knowledge on the interaction between systems engineering and innovation. Top-level questions to be answered are “at what extent they are consistent” and “which of their elements pull on the same direction and which counteract each other”.

An intuitive proposition for this research would be that the practice of systems engineering has a causal relationship with innovation performance. However, innovation performance itself is a pervasive concept to which no broadly accepted definition exists. Many researchers in the field of entrepreneurship might define innovation performance as speed to market. Economists would typically define it as the economic profit from the exploitation of products, services or processes originating from new ideas. Engineers, in turn, would define it as the flow of good ideas that a certain organisation transforms into functioning products, services or processes. Overall there is no consensus on the definition of innovation performance and most often it depends on the background of who is writing. Besides, trying to establish a causal relationship between the practice of systems engineering and innovation performance would mean taking the innovation process, again, as a black box. In other words, a research that is based on the said relationship would tend to regard the systems engineering process as the input and innovation performance as the output. Even if the empirical data showed a strong positive (or negative) correlation, the process which transforms the former into the latter would remain unknown.

1.2 Research problem and strategy

The utmost objective of this study is to investigate the **interaction between systems engineering practice and innovation** rather than trying to establish an overall cause-and-effect relationship. The motivation behind this inquiry has arisen from the researcher’s own professional experience on development and marketing of emerging technologies in the oil and gas industry’s subsea sector. It has been noted that there are circumstances where these two core concepts operate cooperatively, and there are others where they seem to be in conflict. This dually behaved relationship might be due to intrinsic factors, i.e. inherent characteristics of the two core entities, or might be caused by external factors. Although it would be impossible to identify all the external factors that might affect the strength and direction of the relationship, some candidate factors might be identified and introduced as moderators in the research construct. Nevertheless the key relationship systems engineering – innovation is yet too unknown and deserves further investigation before moderators and potentially mediators are introduced in the construct.

Walden's papers "Innovation in the Context of Systems Engineering" (1998) and "The Impact of Systems Engineering Capability Maturity on Innovation" (1999) depict some attempts to describe this relationship. In the former, Walden (1998) introduces the topic stating that "innovation is essential in high technology companies", however "systems engineering's emphasis on process, documentation and control is often perceived to inhibit innovation". In the latter, Walden (1999) he resumes the topic with the same proposition and carry out a reassessment, now of quantitative type, using the Systems Engineering Capability Maturity Model (EIA 731.1) and his summary on key innovation characteristics based on Katz (1988), Tushmann & Moore (1988), Humphrey (1987), Shenhar (1996), Gaynor (1996) and Dorf (1998). In both works, his conclusion is that "there is nothing inherently inconsistent between innovation and systems engineering; however one should be careful when attempting to introduce radical innovation into a process-based systems engineering organization". Even though the two capability assessment models used in his latter paper (Walden, 1999) contribute to a robust research design and his conclusion seems plausible (although controversial and rather simplistic) the limited source of data unfortunately threats the reliability of his conclusions. In the 1998 paper he articulates his own ideas on the central relationship using the literature to support them. In the 1999 paper he limits the quantitative data acquisition to his own perception of each variable, i.e. the researcher himself filled out the only questionnaire used to substantiate the conclusion.

Once the key research inquiry has been clarified, the strategy is to detach from any existing study focused on the same question, conduct an independent literature review, acquire original empirical data, analyse it and reach a conclusion which may be either supportive or conflicting with these previous studies.

Given the comprehensiveness of both key concepts, the characterisation of the relationship between them is not obvious, and incautious simplifications might threat the validity of the whole study. In other words, trying to describe the relationship without a supportive theoretical framework, or without carefully selected standpoints, would yield a study of limited scientific relevance. Therefore, both key concepts and the relationship between them are analysed herein from two independent perspectives, namely process-oriented view and capability-oriented view. In the diagram below (Figure 1), the bold arrow illustrates the fundamental relationship which is this research's object of study. The thin arrows illustrate the various angles of sight that are explored throughout the study. In other words, in the various parts of this study there are moments where innovation alone is analysed from a process perspective (i.e. process-oriented view), moments where systems engineering alone is analysed from a process perspective, and moments where the relationship between them are analysed from a process perspective. The same are analysed, likewise, from a capability perspective, i.e. capability-oriented view. In a timely line, the study starts from the outer thin arrows, gradually moves towards the inner vertical arrows, and these, finally, characterise the horizontal, bold arrow. This construct is intended to secure that the study finds support on a double-grounded theoretical framework and that the conclusions are based on the triangulation of two independent analyses, enhancing the research reliability.

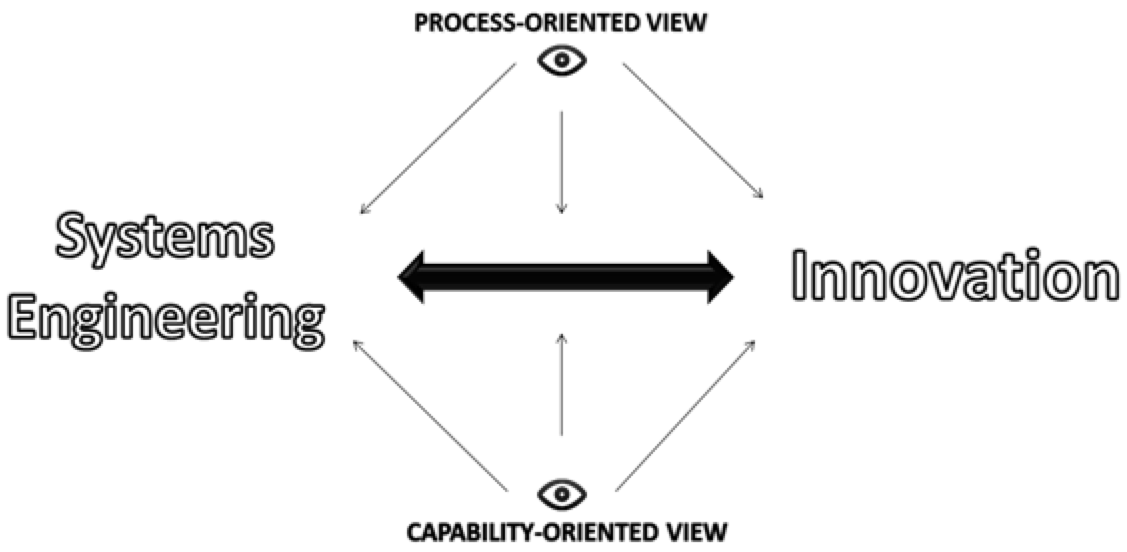

Figure 1 Research construct

In chapter 2, the two perspectives are better described and a review of what has been written about systems engineering and innovation is carried out. Chapter 3 presents the overall research design. Chapter 4 describes in detail what empirical data is collected and how the collection is carried out. Chapter 5 reports the content of the data analysis. Chapter 6 presents the overall conclusions and discussions.

2 Literature review

The literature review of both topics of interest, notably innovation and systems engineering, is presented in three parts: essential definitions, a process-oriented view and a capability-oriented view. The essential definitions section is aimed for making an early “agreement” with the reader on what is meant by innovation and by systems engineering. The process-oriented view section is intended to explore some of the models proposed by the relevant literature describing how systems engineering and innovation take place in practice. Finally, the capability-oriented view presents “soft resources” identified by the relevant literature as key enablers in order for systems engineering and for innovation to be put in practice by organisations.

In general, the systems engineering related literature used in this study is taken from researchers and societies related to this specific professional area, i.e. typically written by technologists. The innovation literature presented herein, in turn, is taken mainly from journals in various fields of business research.

2.1 Essential definitions

2.1.1 Definitions of systems and systems engineering

The fundamental element explored in this section is highlighted in Figure 2.

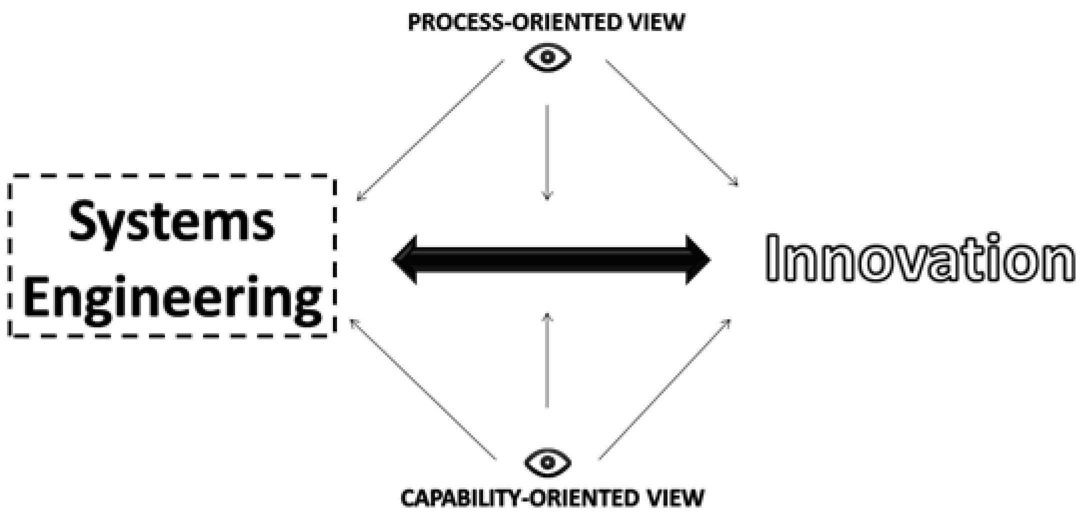

Figure 2 Fundamental element: Systems Engineering

As well as for most of the other engineering fields, there is no unarguable definition for systems engineering. The difference is that the object of study of the other engineering disciplines (e.g. mechanical engineering, chemical engineering, naval engineering, etc.) is either more concrete or better understood by the general public, if compared to “systems”. For this reason most of people perceive to have a better understanding of what these other professional areas are. For example, it is easy for the public to understand and visualise what solid bodies are, their differences, behaviour and properties. The same holds for fluids. Hence their understanding on solid mechanics, fluid mechanics and therefore mechanical engineering become natural. When it comes to systems engineering, the definition of “system” is itself beyond the understanding of most of the general public.

According to Blanchard & Fabrycky (2006), a system is: *an assemblage or combination of elements or parts forming a complex or unitary whole, such as a river system of a transportation system; any assemblage or set of correlated members, such as a system of currency; an ordered and comprehensive assemblage of facts, principles, or doctrines in a particular field of knowledge or thought, such as a system of philosophy; a coordinated body of methods or a complex scheme or plan of procedure, such as a system of organization and management; or any regular or special method or plan of procedure, such as a system of marking, numbering or measuring. Not every set of items, facts, methods, or procedures is a system. A random group of items in a room would constitute a set with definite relationships between the items, but it would not qualify as a system because of the absence of unity, functional relationship and useful purpose.*

In the real world there are various types of systems and various different dichotomies intended to classify them. For example, Blanchard & Fabrycky (2006) classify the systems as natural versus human-made, physical versus conceptual, static versus dynamic, closed versus open. Not all the types of systems are of the same degree of interest of systems engineering and not all are relevant in every instance. According to ISO/IEC 15288:2008 Systems and software engineering - System life cycle processes, the systems that are of special interest of systems engineering are man-made, created and utilised to provide products and/or services in defined environments for the benefit of users and other stakeholders. These systems may be configured with one or more of the following system elements: hardware, software, data, humans, processes (e.g., processes for providing services to others), procedures (e.g., operator instructions), facilities, materials and naturally occurring entities. In practice, they are thought of as products or services.

A brief definition of "systems" being given, it is possible to explore some definitions of systems engineering.

The Systems Engineering Handbook version 3.2.2 (INCOSE, 2011), published by the International Council on Systems Engineering, describes systems engineering as a perspective, a process and a profession, as illustrated by the three following representative definitions:

Systems engineering is a discipline that concentrates on the design and application of the whole system as distinct from the parts. It involves looking at a problem in its entirety, taking into account all the facets and all the variables and relating the social to the technical aspect.

Systems engineering is an iterative process of top-down synthesis, development, and operation of a real-world system that satisfies, in a near optimal manner, the full range of requirements for the system.

Systems engineering is an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, and then proceeding with design synthesis and system validation while considering the complete problem: operations, cost and schedule, performance, training and support, test, manufacturing, and disposal. Systems engineering considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs.

Blanchard & Fabrycky (2006) add the following, equally relevant definitions:

An interdisciplinary approach encompassing the entire technical effort to evolve into and verify an integrated and life-cycle balanced set of system people, product, and process solutions that satisfy customer needs. Systems engineering encompasses (a) the technical efforts related to the development, manufacturing, verification, deployment, operations, support, disposal of, and user training for, system products and services; (b) the definition and management of the system configuration; (c) the translation of the system definition into work breakdown structures; and (d) development of information for management decision making. (EIA/IS 632, 1994)

The application of scientific and engineering efforts to (a) transform an operational need into a description of system performance parameters and a system configuration through the use of an iterative process of definition, synthesis, analysis, design, test and evaluation; (b) integrate related technical parameters and ensure compatibility of all *physical, functional, and program interfaces in a manner that optimizes the total system definition and design; and (c) integrate reliability, maintainability, safety, survivability, human engineering, and other such factors into the total engineering effort to meet cost, schedule, supportability, and technical performance objectives.* (DSMC, 1990)

An interdisciplinary, collaborative approach to derive, evolve, and verify a life-cycle balanced system solution which satisfies customer expectations and meets public acceptability. (IEEE P1220, 1994)

An approach to translate operational needs and requirements into operationally suitable blocks of systems. The approach shall consist of a top-down, iterative process of requirement analysis, functional analysis and allocation, design synthesis and verification, and system analysis and control. Systems engineering shall permeate design, manufacturing, test and evaluation, and support of the product. Systems engineering principles shall influence the balance between performance, risk cost, and schedule. (DoD, 2002)

From the definitions compiled by Blanchard & Fabrycky (2006) and INCOSE, one can notice the constant emphasis on understanding the entire system life-cycle for a balanced solution. According to Blanchard & Fabrycky (2006), emphasis in the past has been placed primarily on design and system acquisition activities, with little (if any) consideration given to their impact on production, operations, maintenance, support, and disposal. If one is to adequately identify risks associated with the upfront decision-making process, then such decisions must be based on life-cycle considerations.

This strong life-cycle orientation has led the International Organization for Standardization (ISO) and the Electronics Industries Alliance (EIA) to join efforts with the Institute of Electrical and Electronics Engineers to write the ISO/IEC 15288:2008 / IEEE Std 15288-2008 "Systems and software engineering – System life-cycle processes", on which INCOSE has based the latest revisions of its Systems Engineering Handbook (INCOSE, 2011) and is gradually becoming an established international standard on system lifecycle approach across various industries. The standard intends to establish "*a common process framework for describing the life cycle of man-made systems. It defines a set of processes and associated terminology for the full life cycle, including conception, development, production, utilization, support and retirement*" (ISO/IEC 15288:2008).

INCOSE's Systems Engineering Handbook compares ISO/IEC 15288:2008 generic life-cycle to other life-cycle models. Although they differ in number and definition of stages to suit their owners' or originators' convenience, each providing insight into their own project management and execution model, they are clearly nothing but different perspectives of the same overall philosophy, as shown in Figure 3.

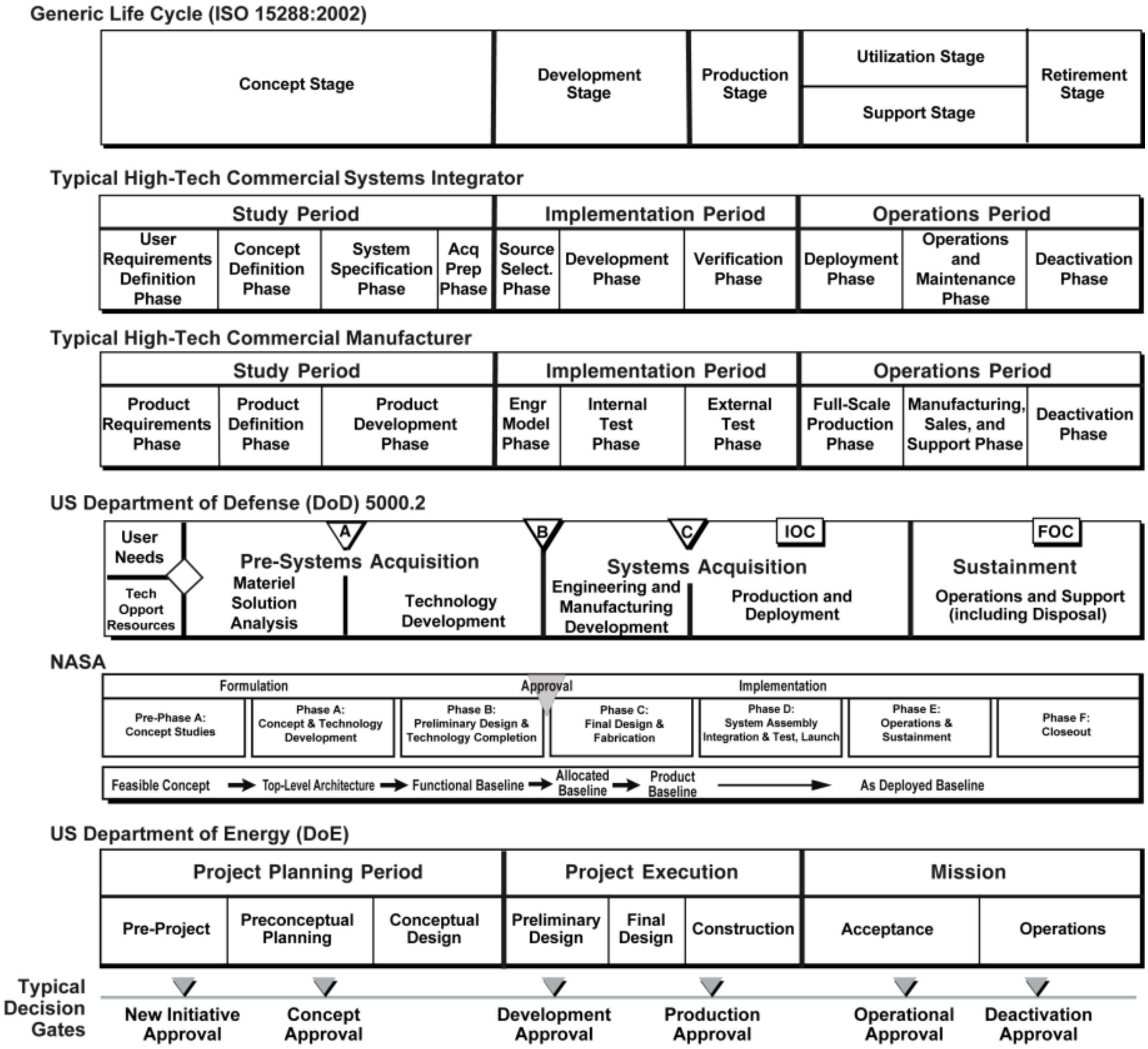

Figure 3 Various life-cycle models (source: INCOSE, 2011)

The Systems Engineering Handbook (INCOSE, 2011) proposes an additional stage which precedes the conceptual, called Exploratory Research Stage. Although this is not often mentioned as a typical life-cycle stage from a systems engineering perspective, many industries indeed employ it, in a structured or non-structured fashion, to study new ideas or enabling technologies and capabilities. Besides, given the freedom with which activities are typically carried out in this stage, is might potentially be of great value for the development of an organisation’s innovation capabilities.

2.1.2 Application domains of systems engineering

Human made systems exist everywhere, although very often this is not realised even by those involved in their development and design. That being said, it is natural that the systems engineering approach is applicable in every domain, and consequently every industry, where systems are developed. Moreover, the higher the complexity of the systems in a given industry the greater is the need for systems engineering.

Blanchard & Fabrycky (2006) exemplified eight typical applications where the need for systems engineering is particularly strong:

- Large-scale systems with many components, such as in aerospace, urban transportation and hydroelectric power generation.
- Small-scale systems with relatively few components, such as local area communication, computers, hydraulic mechanisms and mechanical braking systems.
- Manufacturing or production systems where there are input-output relationships, processes, processors, control software, facilities and people.
- Systems where a great deal of engineering and development is required, particularly when the new design or design elements depend on the introduction and qualification of novel technologies.
- Systems where the architecture is based on the use of existing commercial off-the-shelf components.
- Systems which are highly equipment-, software-, facilities- or data intensive.
- Systems where there are several suppliers involved in the design and development process at the national and possibly international level.
- Systems being designed and developed for use in the defence, civilian, commercial or private sectors, separately or jointly.

Although systems engineering is an industry-independent approach and its principles and practices are applicable to any conceivable area of human-made systems, in reality it is possible to observe a higher concentration in a few industries and in general these very industries show an overall superior maturity in the related methodologies and techniques.

By reading technical papers, participating in professional symposia/conferences or just looking at INCOSE's list of systems engineering processionals, it is unarguable that the majority of systems engineers and related works produced in this field come from the defence industry, aerospace industry, software industry and car industry.

The notion that system's thinking or systems engineering practices are limited or more suitable for these industries, however, does not hold true. Although fewer, there are also systems engineering professionals in a number of other industries, this researcher inclusive. Besides, and even more important, there is not one single scientific evidence that systems engineering is only applicable to the industries mentioned above, or even that it is less suitable for other industries.

Based on that, there must be a reason why systems engineering is in general concentrated in those four industries. One possibility is that by coincidence they started developing the specific practices and techniques earlier than other industries and this gave them an advantage so that to date they have been able to reach a higher professional maturity and attract more systems engineering professionals. Another possibility is that given the commonly accepted benefits of systems engineering (reduced life-cycle cost, reduced acquisition/development time, better managed risks, higher quality and reliability, etc.) industries that are more sensitive to these factors tend to be more receptive to this engineering approach. Nonetheless, this specific question is not the focus of this research and therefore is left aside for future studies.

2.1.3 Definitions of innovation

The fundamental element explored in this section is highlighted in Figure 4.

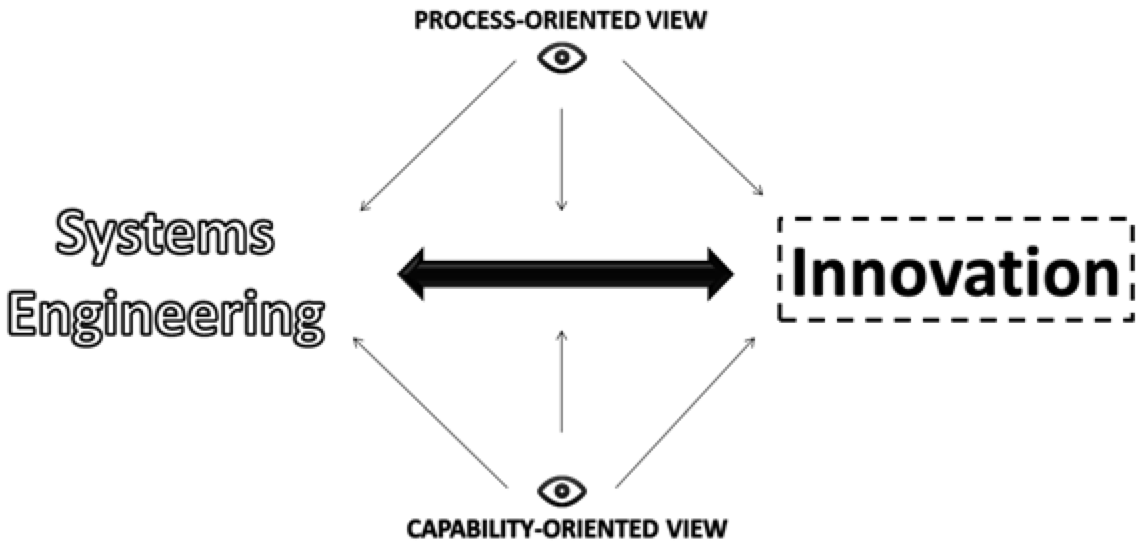

Figure 4 Fundamental element: Innovation

As well as in systems engineering, when dealing with innovation its conceptual definition does not come straight forward. Misconceptions and biased or one-sided views often take their roles in the dialogue. Therefore taking some time to minimise these misunderstandings is worthwhile given that this concept is in the focus point of the present study.

A typical thought that arises when the discussion is about innovation within organisations is that when a firm does something different, it is doing innovation. In line with the pre-Socratic Greek philosopher Heraclitus of Ephesus and his famous sayings that "*all things come to pass*" and that "*no man ever steps in the same river twice*", Oppenheimer (1955) postulated: "*In an important sense this world of ours is a new world, in which the unity of knowledge, the nature of human communities, the order of society, the order of ideas, the very notions of society and culture have changed and will not return to what they have been in the past*". Oppenheimer (1955) continued characterising the concept of newness with the idea that "*what is new is new not because it has never been there before, but because it has changed in quality*". Whilst the concept of newness is not the wrong path when trying to define innovation, it captures only one of its aspects and therefore is not complete.

Knight (1967) takes the idea of newness and proposes that "an innovation is the adoption of a change which is new to an organisation and to the relevant environment". Although not explicitly, Knight (1967) introduced in his definition the essence of what innovation actually is. In line, to qualify as an innovation, it is not enough to have some degree of newness, but it also needs to be adopted by both the organisation and the environment. The adoption by the organisation implies that the organisation took some action to materialise the new product, or put in practice the new process, or to adapt to a new structure, etc. The adoption by the environment infers, first of all, that the new thing, whatever that is, crossed the boundaries of the originating organisation. By "environment" one can understand as the industry, the market, the state, etc. In sum, when an organisation has something that contains some degree of newness; takes actions to materialise it as a product, a process, a structure, etc; brings it to the external world and the external world adopts it directly or indirectly; an innovation is configured.

Given the comprehensiveness of the concept of innovation, it can be viewed from a number of different perspectives; and every standpoint will naturally propose a different definition depending on what elements of the innovation "phenomenon" they find most relevant. Psychologists typically emphasise two aspects; creativity and change in individuals' behaviour and beliefs. Cropley et al. (1995, 1997, 1998, 1999), for example, shed light on the creativity aspect. Economists, in turn have typically emphasised the external elements rather than the innovation process itself, e.g. the impact of innovation on economic growth (Abramowitz, 1956; Denison, 1962; Griliches, 1958; Nelson, 1959; Solow, 1957), the role of governments on the definition of policies that affect innovation (Jaffe, 2000; Nelson, 1959); the spillover of government-run R&D into civilian endeavours (Solow, 1962; Welles et al., 1963) and the sources of innovation in terms of innovators and teams characteristics (Howell & Boies, 2004; MacKinnon, 1962; Schlaifer & Heron, 1950; Souitaris & Maestro, 2010; Heirman & Clarysse, 2007). Sociologists have focused on technological developments and their impact on social structure and behaviours of our society (Carter & Williams, 1959; Ogburn, 1953; Salter, 1960) and the creation of positive approaches and steps that facilitate change (Dewey, 1935; Durkheim, 1938, Gouldner, 1957).

More recently, attempts have been made to synthesise the various standpoints in comprehensive views and models. Galanakis (2006), for instance, explains that the complexity of the innovation concept often makes managers take decisions whose outcomes contradicts their original aims; and proposes a synthesised view, systems-thinking flavoured, to communicate an innovation theory to the different actors under a common perspective to reveal the complexity of innovation systems.

2.1.4 Innovation typology

Innovation can be categorised in a number of different dimensions. A few of them are explored in the following paragraphs.

The first and perhaps one of the most discussed ways of classifying innovation types is by the following categories: product, service, process, organisational structure and people. **Product** and **service** innovations are those which take place when the element of newness, whether it is product or service, is directly traded in the market. In a **process** innovation, the newness element is not directly traded in the marker, but the outcome of its process instead. Classic examples were the various models of industrial production, e.g. Taylorism, Fordism, Toyotism, etc. Process innovation is typically aimed for efficiency and productivity improvements, but not necessarily (although it may be associated with) the final product or service. **Organisational structure** type of innovation does not necessarily introduce a change in the final product or service, but the way the firm is organised instead. It can be and typically is combined with a process innovation, but not necessarily. For example, a firm undertaking an organisational structure innovation will typically change the teams structures, the lines of reporting, the accountabilities, and yet may or may not change the way its manufacturing plant operates in practice. **People** innovation happens when the organisation promotes a qualitative change in the nature of its stakeholders, particularly its employees. This change can be undertaken by dismissing and/or hiring personnel, or by developing people's competences, behaviours and attitudes with training, campaigns, etc.

Second, innovation can be classified by its scale and scope of change, being either radical or incremental. **Radical** innovations are those that introduce elements (products, services, processes, people, etc) completely new or unknown. This type of innovation is typically associated with inventions rather than improvements and often has the potential to create new, previously non existing markets. When the market newly created by a radical innovation destroys an established one, the innovation can be called **disruptive** innovation. Nonetheless there are sufficient empirical evidences showing that disruptive innovations are most often radical, but radical innovations are not necessarily disruptive. **Incremental** innovations are characterised by modifications, normally improvements of existing designs, techniques, etc. Whereas radical innovations have the power to generate enormous gains to whoever undertakes them, incremental innovations take place in disproportionally higher frequency.

A third innovation typology is concerning the degree of openness and categorises them as **open** or **closed**. These terms are often used wrongly in non-academic discussions; it is not uncommon that people use the term open innovation to describe the product of an innovation that is open for the public, such as a freeware or a service for which the provider does not charge. However, the innovation element that defines whether it is open or closed is its origin rather than distribution. Closed innovation was the ruling paradigm until the 1970s, when organisations ran their innovation-related functions (marketing, R&D, product development, etc.) within their own boundaries as a sealed process, and counting only on their own capabilities. The paradigm of open innovation started in the 1980s (and is still very alive), when firms started to drive their innovations in many different forms of joint efforts, such as strategic alliances, subcontracting, hiring external consultants, etc. Furthermore, the idea behind the open innovation is that those ideas of any interest for the firm should be taken into its business (no matter where it was originated), and those which are not interesting for the firm should be taken out of its business. Thus, innovations created and protected by external parties which are of any interest for a given firm can be taken in by licensing in their rights and making business exploiting their commercial value; whereas innovations created and protected by this very firm which are not commercially attractive for its own business can be licensed out so that other firms can exploit them commercially and all parties in this “network” get a share of the gains.

A fourth categorisation is between “good innovations” and “bad innovations”, although this is a vague, controversial and of little relevance for research. This type of discussion often arises when the ethical nature of an innovation is at stake. In an attempt to establish the difference between these two types in an unbiased manner, one can define a **good innovation** as those which offer a net positive gain for the society, whilst **bad innovations** are those which may even produce benefits for some parties, but overall brings a net loss for the society. To illustrate the difference, one can highlight the contrast between the atomic bomb and the penicillin. However, even examples like these, which in a first glance may seem unarguably bad and good, are not controversy free. The atomic bombs of Hiroshima and Nagasaki, combined, killed immediately 150 thousand people and caused the death of another hundreds of thousands in the following years due to radiation-related diseases. Some historians, however, argue that it started the end of the most widespread war in the history human kind, which had already claimed more than 50 million lives; and that the R&D programmes for military purposes which resulted in the “Little Boy” and the “Fat Man” (codenames of the two atomic bombs) laid the foundations of the nuclear energy, which constitutes one of the most important sources of energy nowadays. With no intention to take a position on such controversies, the example just shows that the good- versus bad innovation classification is highly subjective and does not contribute much to the research on innovation.

Beside the dimensions to which innovations can be classified, they can also be characterised by the industry where they take place. For example, the innovation cycles (from idea to business) in the ICT industry are extremely short; typically the time it takes for a product to be idealised and commercialised is in the order of few months. In the cars industry, which is characterised by fierce competition, though involves a great concern with human safety, the time it takes from start of development to launch of a new model is in the order of one year. When taking the examples of the aviation- and the oil and gas industries, the innovation cycle often takes several years. The aviation industry is marked by the receptiveness towards new technologies whereas the oil and gas industry is one of the most conservative towards new technologies, but both deals with ultra-complex technologies and have great concern with human and environmental safety, which leads to equally lengthy product qualification programmes. In sum, factors such as the concentration/competition, risk aversion and technology complexity and other characteristics do shape the way innovations take place in different industries.

2.2 A process-oriented view

Process can be defined as the series of actions, changes or functions intended to transform an input into an output. Whilst systems engineering is interested in transforming a user need (input) into a functioning system (output), the innovation concern is to transform an idea (input) into a marketable product (output). Describing how these transformations actually take place, i.e. mapping the processes, is arguably a matter of empirical observation rather than exact science. For both systems engineering and innovation there are several models trying to illustrate their respective processes, hardly any of them being applicable to every conceivable instance, but most of them applicable to a broad spectrum of cases.

2.2.1 Process models of systems engineering

The perspective explored in this section is highlighted in Figure 4.

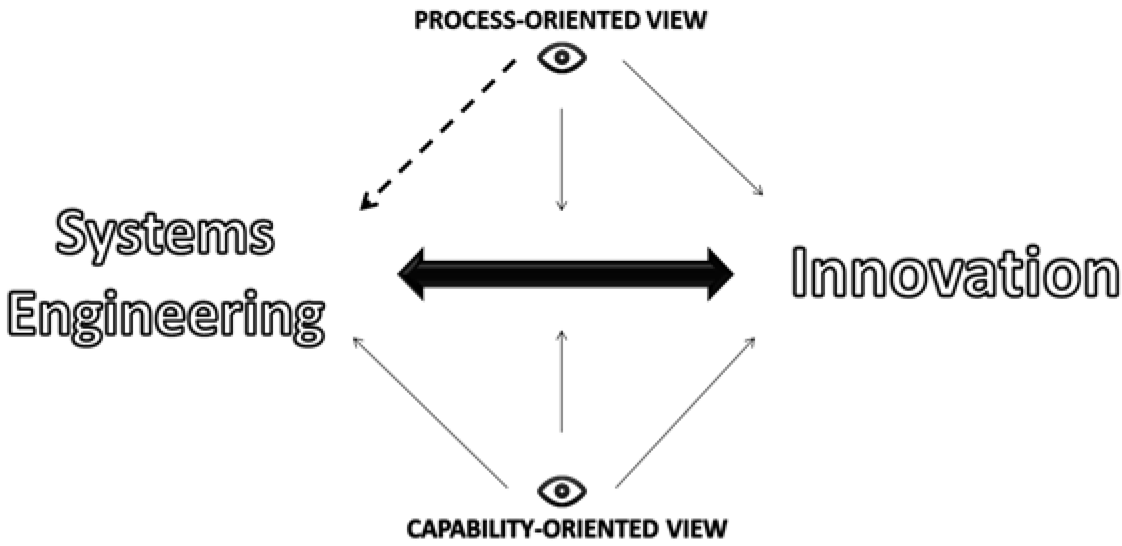

Figure 5 Systems engineering from a process-oriented view

Whilst there may be observed a common understanding about the objectives and principles of systems engineering, the processes through which it is implemented vary substantially. According to Blanchard & Fabrycky (2006), the process approach and steps to be fulfilled depend on the background and experiences of individuals involved.

One of the most basic systems engineering process models, which is arguably the backbone of all the others, is the five-step paradigm described by Shoening & Miller (1993), illustrated in Figure 6.

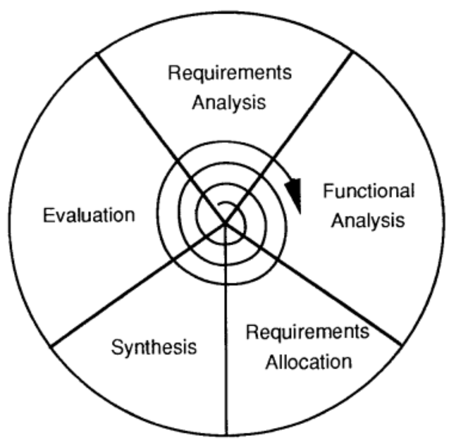

Figure 6 Five-step systems engineering paradigm (source: Shoening & Miller, 1993)

According to Shoening & Miller (1993), the five-step paradigm "*can be thought of in two parts; the iterative sequence of five activities and the spiraling level of detail beginning with very top-level information and then broadening the level of detail with each succeeding iteration towards the bottom-level*".

The "Requirement Analysis" is concerned with translating the user need into technical requirements, i.e. technical demands to be met by technical solutions. For every iteration, the documented requirements should be at an appropriate level of detail. The captured requirements are then divided in two groups: (a) those not more detailed than the level just set and (b) those that are more detailed and should be set aside for considerations during a later, lower level iteration.

The "Functional Analysis" translates the requirements identified and documented in the previous step into a functional description. Functions are typically actions to be performed by the system, which are organised in some type of behavioural model. There are a number of tools to illustrate these models and the most popular is the functional block diagram. The set of functions to be defined in this step should describe what the system element does, but not yet how it does.

The "Requirement Allocation" is when the requirements documented in the first step are distributed, or allocated, to the functions documented in the second step. This activity describes how much emphasis, cost, or weight should be attributed to the functions already defined in the iterative process.

The "Synthesis" consists of developing a practical solution, i.e. finding an existing element or creating a new element which is able to perform the functions defined in the second step, meeting the requirements allocated to them in the third step. It can be said that whilst the first, second and third steps are consist of an exploration and characterisation of the "problem", the synthesis is the identification or development of a solution.

The "Evaluation" includes all the activities necessary to verify and prove that the synthesised system elements perform successfully the functions assigned to them and meet the group "a" requirements allocated to their functions.

Although the five-step paradigm is consistent enough to apply to almost any system of interest, it lacks detailed instructions on how to put the systems engineering process in practice. Based on the same logic, the waterfall model was introduced in the early 70s, initially used for software development. This model depicts the system or software development using five to seven series of steps or phases. Ideally, each phase is carried out to completion in sequence until the product is delivered. However, this is rarely the case; when deficiencies are found phases must be repeated until the product is correct (Blanchard & Fabrycky, 2006) as illustrated in Figure 7.

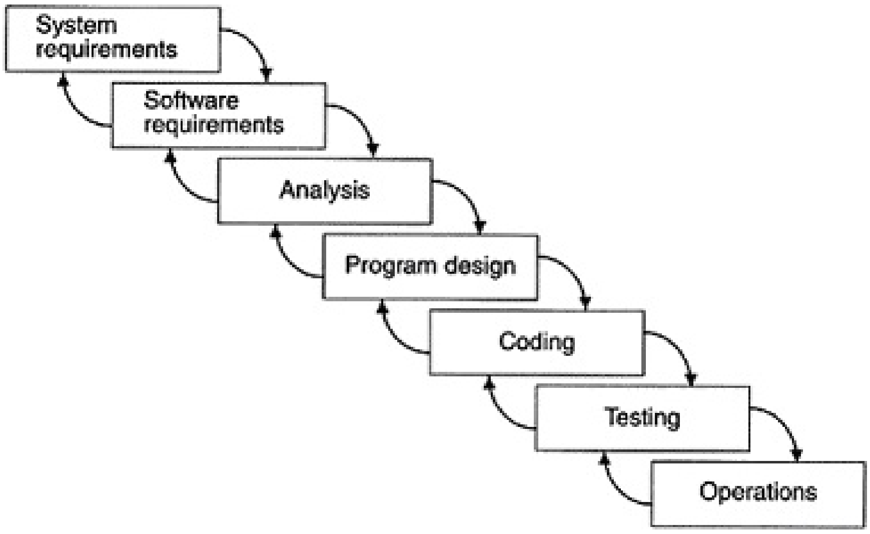

Figure 7 Waterfall model (source: Wideman, 2004)

The spiral process model (Figure 8) was introduced in the 80s in an attempt to promote a risk-driven approach for the development of products. This model is an adaption of the waterfall model, which does not prescribe the use of prototypes. In addition, the spiral model illustrates with more clarity the iterative aspect of the development process and the feedback loops. The application of the spiral model is iterative and proceeds through the several phases every time a prototype is designed and built. The use of prototypes allows for the reduction of the uncertainties associated with any design before proceeding to a subsequent phase (Blanchard & Fabrycky, 2006).

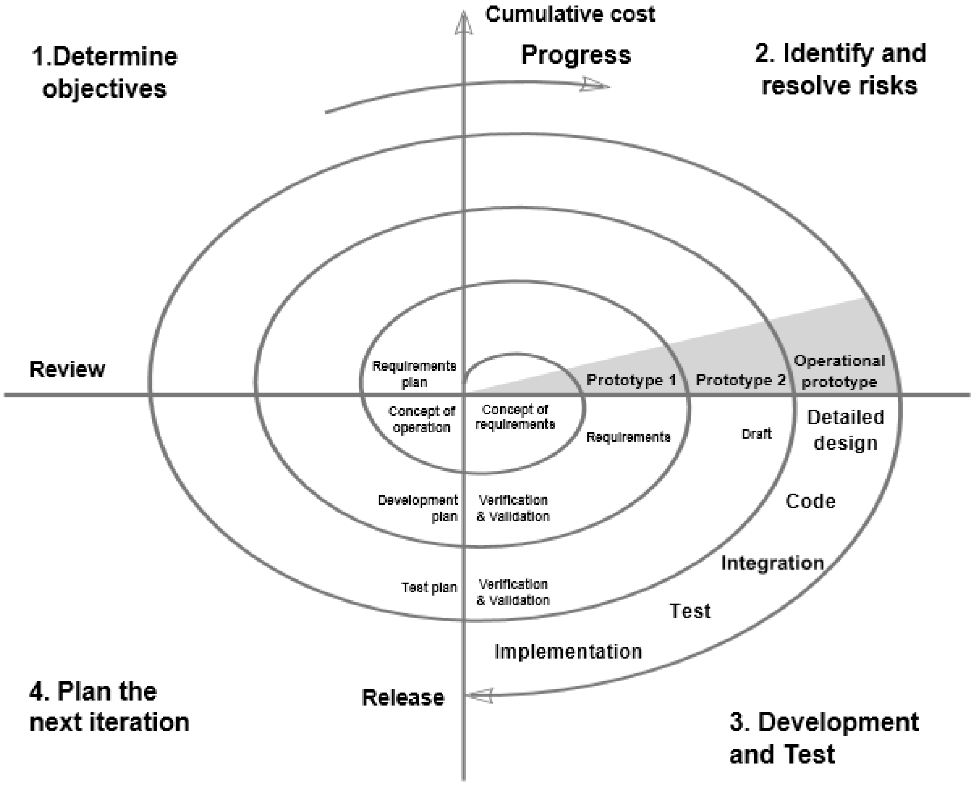

Figure 8 Spiral model (source: Boehm, 1986)

The Vee model (Figure 9) was introduced to describe "the technical aspect of the project cycle". This model departs from a user need on the upper left corner, goes through the engineering processes all the way down into the various system levels and ends with a fully validated and functioning system on the upper right corner (top-down followed by bottom-up). On the left side, analysis and synthesis resolve the system architecture. Integration and verification goes up on the right side as successively higher levels of subsystems are verified, culminating at the system top-level. At every level, the originating specifications are re-visited and the performance verified to ensure that the system meets all the requirements (Blanchard & Fabrycky, 2006).

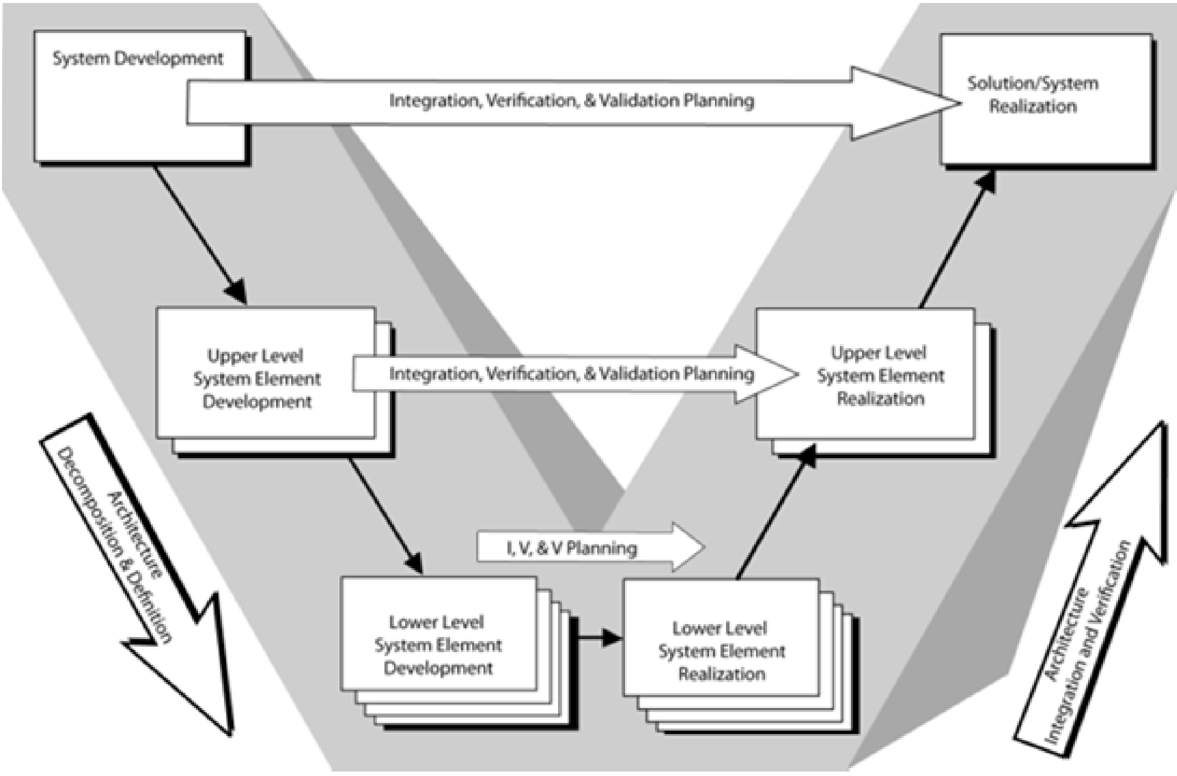

Figure 9 Vee model (source: INCOSE, 2011)

The systems engineering engine (Figure 10) developed by NASA is primarily intended to guide the development of space systems. NASA's systems engineering engine takes a more comprehensive standpoint, grouping the various processes by "system design", "technical management" and "product realisation". It may be argued that the NASA's engine, compared to the typical systems engineering models, includes new dimensions such as various interactions between the process elements as well and between the process and the external environment. According to NASA, "*Systems engineering is the art and science of developing an operable system capable of meeting requirements within often opposed constraints*". Yet, "*it is about looking at the big picture and not only ensuring that they get the design right (meet requirements) but that they get the right design*" (NASA, 2007).

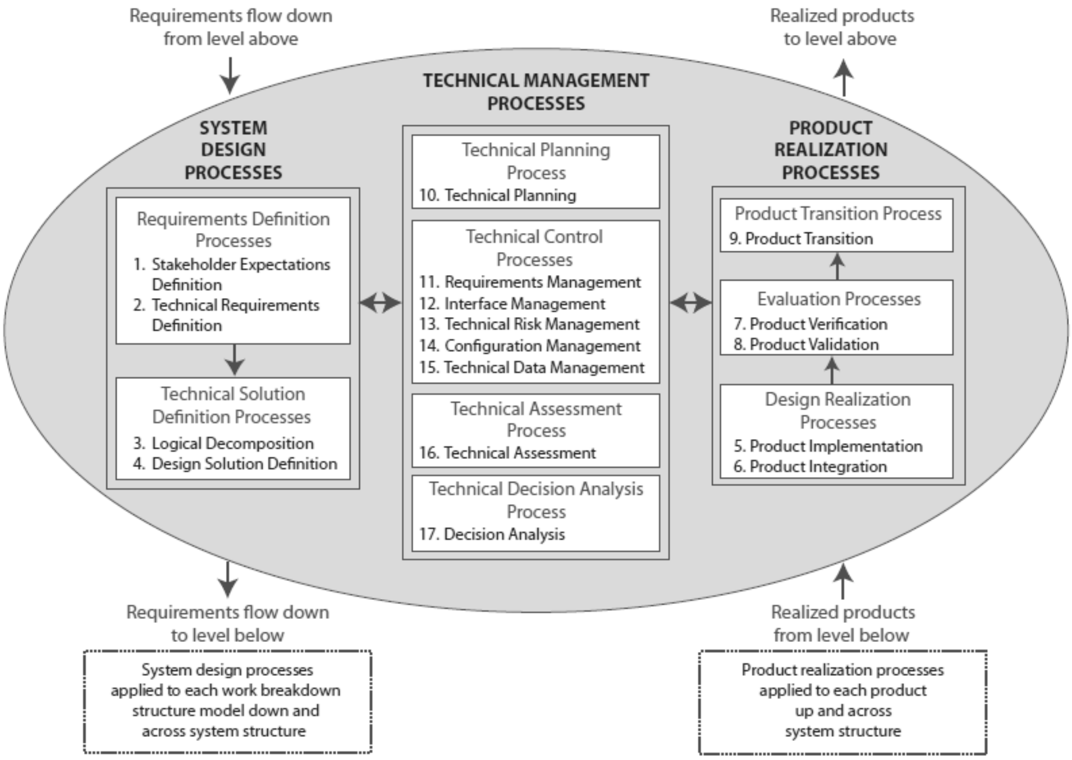

Figure 10 NASA's systems engineering engine (source: NASA, 2007)

2.2.2 Process models of innovation

The perspective explored in this section is highlighted in Figure 11.

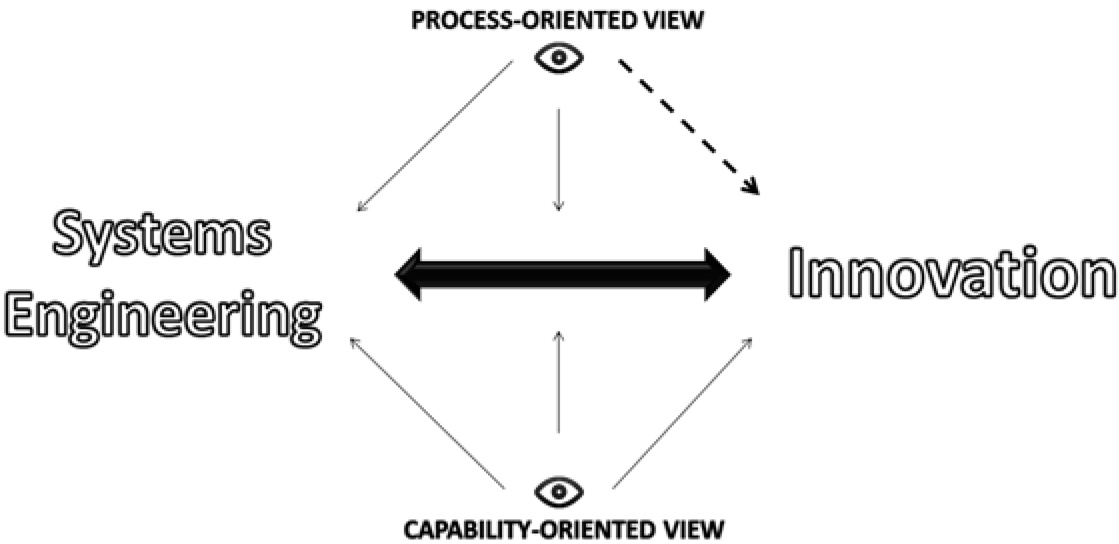

Figure 11 Innovation from a process-oriented view

Although it is unarguable that innovations do differ across industries and that models will neither capture all their relevant aspects nor illustrate flawlessly the way the process takes place, models yet provide a great help on the study of innovation. Rothwell (1994) presents a remarkable longitudinal analysis on how the innovation process evolved from the post Second World War to the 90s, which is the main reference for the process models described herein.

The first-generation innovation process was shaped by the accelerated economic growth caused by the rapid industrial expansion that took place in the 50s and early 60s. The period which followed the Marshall Plan and the Mutual Security Plan witnessed the recovery of Europe and levels of market demand as high as never before. The emergence of new technology-based industries associated with the re-generation of existing ones and the increased deployment of technology to enhance productivity and quality resulted in rapid job creation, rising prosperity and an associated consumer boom, leading to rapid growth of the consumer white goods, electronics and cars, with demand often exceeding production capacity (Freeman et al., 1992). During this period there was a great deal of optimism and euphoria towards scientific advance and industrial innovation and the common belief was that technology could solve all the world's problems. Since the market demand was peaking, marketing and sales was not a big issue; the challenge stood in raising supply of existing products and creating new ones, and for that the world had learnt that the only way was through technology innovation. This attitude was reflected on the public policies and great support to scientific development in universities and government laboratories, the supply of skilled manpower and financial support for major R&D programmes in private companies. Not coincidently the perceived innovation process in that period was focused on internal factors and technology push rather than the marketplace (Rothwell, 1994). The market was perceived to be able to absorb the products as a natural and unquestionable consequence; the problem lied on how to create products and make them reach the market in sufficient supply. This linear process pushed by technology inferred that more R&D in resulted in more sales out. The first-generation innovation process is illustrated in Figure 12.

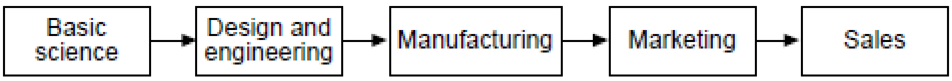

Figure 12 First-generation innovation process (source: Rothwell, 1994)

Whereas the 50s innovation process took sufficient demand as granted, the reality from the second half of the 60s was not quite so. As industrial productivity continued to grow, employment started to stabilise or grow at a much reduced rate (Rothwell & Soete, 1983). Manufacturing output continued to rise and the job creation grew in a much lower rate, making the demand and supply, once disproportional, start to balance out. With excessive supply to the relatively stable demand (at least compared to the previous decade), competition started to heat up and investment emphasis began to switch from new product and related expansionary change to rationalisation technological change (Clark, 1979; Mensch et al., 1980). As companies had to fight for market share, demand was no longer taken for granted and the innovation process began to change towards emphasising demand side factors, i.e. the marketplace. (Rothwell, 1994). The sale was no longer perceived as a natural consequence of the product development, but the product development itself became dependent on an identified market need. In other words, the former technology push had been replaced by a market pull, which characterised the second-generation innovation process. In this model, the process is pulled by the market need, making the technology change a consequence, or at most a merely reactive function. Rothwell's (1994) second-generation innovation process is illustrated in Figure 13.

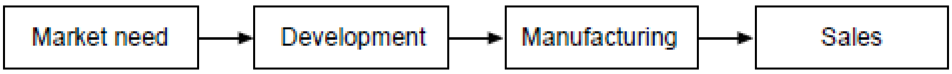

Figure 13 Second-generation innovation process (source: Rothwell, 1994)

The early 70s inherited from the previous decades an accelerated supply trend and the levels of demand gradually lagging behind. This unfavourable trend, combined with two major oil crises, led the economy to high rates of inflation and demand saturation; the so-called stagflation. If in the previous decades organisations had just to start considering the marketplace and not only look at their internal product development process, in the 70s the competition in the marketplace became the ultimate ruling force. Organisations were forced to adopt strategies of consolidation and rationalisation, with growing emphasis on economies of scale, and there was a growing concern with accountancy and financing issues leading to a strategic focus on cost reduction and control (Rothwell, 1994). During difficult times, with scarce resources and fierce competition, it became increasingly important to develop a more comprehensive understanding of the innovation process, leaving behind the short-sighted, one-sided views of technology push and market pull. A number of studies on innovation process carried out mainly during the 70s give empirical evidences that both the technology push and market pull models were extreme and atypical examples of a more general process of interaction between, on one hand, technological capabilities and, on the other, market needs (Mowery & Rosenberg, 1978). Compared to the first and second models from the 50s and 60s, the third-generation was aimed for providing a comprehensive and unbiased understanding of how the innovation process actually takes place, recognising the confluence of both driving factors within the framework of the innovating firm as one integrated engine (Rothwell, 1994). This rather comprehensive model showed that success depended neither on strong R&D effort alone or on market demand alone, but instead on doing all the tasks within the process and respecting the feedback loops (the two-way arrows) competently and in a balanced and well coordinated manner. Rothwell's third-generation innovation process is illustrated in Figure 14.

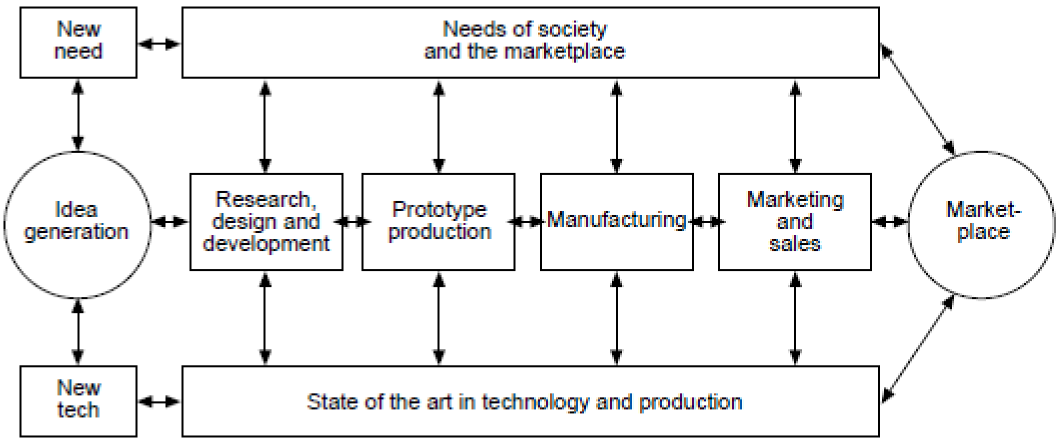

Figure 14 Third-generation innovation model (source: Rothwell, 1994)

The 80s, which followed two major oil crises, initiated a period of economic recovery with organisations concentrating their efforts on core businesses and core technologies (Peters & Waterman, 1982). The market demand showed favourable trends, but at the same time the industry was populated with competitive and well prepared organisations. In that decade the ICT industry became a driving engine in the marketplace, and the shortening product life-cycles transformed speed of development into an increasingly important factor in competition, leading organisations to adopt the so-called time-based strategies (Dumaine, 1989). From this period on, speed to market was no longer a strategic differentiation, but a mandatory requirement for those who wished to survive in the marketplace. The sequential models of innovation rapidly became obsolete, being replaced by a new paradigm of concurrent marketing, R&D, product, production and distribution development. Western firms visibly started to lag behind their Japanese counterparts in speed to market capabilities. Rothwell (1994) and Graves (1991) show that in the eighties, the Japanese firms outperformed the American firms because whilst the former had spotted the new paradigms of the fourth-generation innovation and started developing their capabilities accordingly, the latter were still operating in the third generation paradigms. Graves (1991) presents strong supportive evidences of this proposition from the automobile industry.

According to Rothwell (1994), the main features that allowed leading Japanese organisations to innovate more rapidly than their Western counterparts, are integration and parallel (or concurrent) development. It was the advent of the so-called "Integrated Product and Process Development" (IPPD), although this concept focuses on the technical aspects rather than the whole innovation process. Rothwell's fourth-generation innovation process is illustrated by Nissan's (Japanese car maker) new product development process as shown in Figure 15.

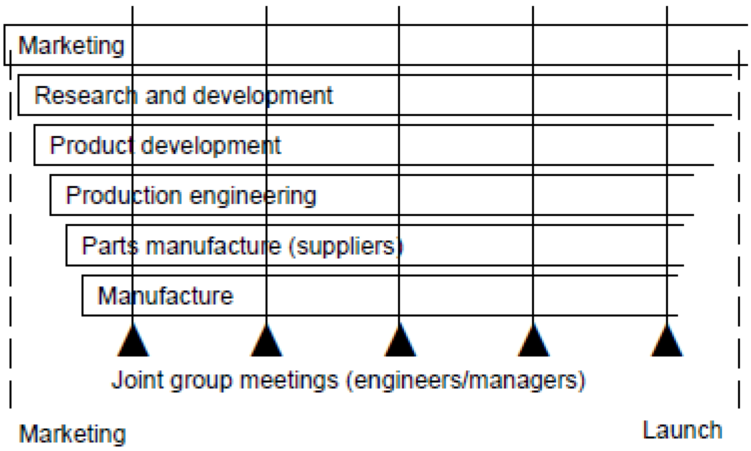

Figure 15 Fourth-generation innovation process (source: Graves, 1987)

Rothwell's (1994) yet indicates a trend towards a fifth-generation innovation process starting from the early 90s which was essentially a development of the fourth generation. Whilst the same paradigms of technological accumulation and strategic networking remained of equal importance, the competition pushed organisations to get increasingly better in integrated product and manufacturing strategies (or IPPD), flexibility and adaptability; and product development strategies gained an increasingly emphasis on quality and performance requirements. Whereas speed to market maintained its position as one of the most important requirements in the marketplace, the price paid by organisations for a outstanding performance in product development speed in order to "be the first" started to be challenged.

According to Graves (1989), compressing the development time by 1% can lead to a cost increase of more than 2%. Gupta & Wileman (1990) said that although Japanese firms operate at a more efficient time/cost curve than their American counterparts, they are willing to allocate twice as many resources to accomplish time reduction; therefore the trade-off between cost and time based on expected future profitability of innovation becomes an important issue. At the same time, increasing emphasis started to be placed on horizontal linkages, such as collaborative pre-competitive research, joint R&D ventures and R&D-based strategic alliances, therefore networking became an inherent part of the innovation process. Rothwell (1994) proposes six important (but not the only) factors to be considered in the time/cost trade-off: (1) the direct benefits of being first to market, (2) the direct costs of accelerating product development, (3) the indirect costs of accelerating product development, (4) the influence of timeliness on customer satisfaction, (5) the penalties accompanying lateness and (6) the short-term versus long-term perspective. On recognising the time/cost trade-off, these six factors and adopting appropriate strategies, Rothwell (1994) suggested that from the early 90s a number of leading innovators started shifting towards an even more efficient curve, as shown in Figure 16.

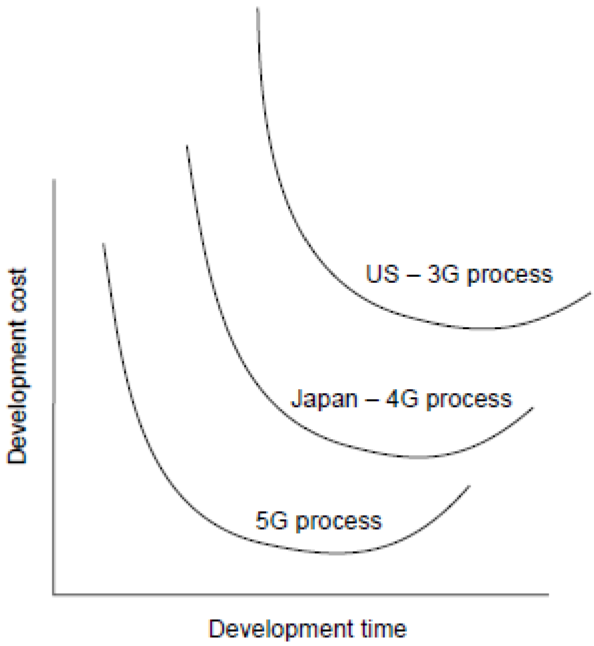

Figure 16 Product development time/cost trade-off curves (source: Rothwell, 1994)

A number of other authors have developed process models to capture how innovation takes place, including Schoening & Miller (1993), Cropley & Cropley (2000) and Walden (1998).

Schoening & Miller's model (1993), despite having being proposed in the same historical context as Rothwell's (1994) fifth generation, appear to be to a great extent aligned with the latter's first generation, i.e. based on the paradigm of technology push from the 50s and mid-60s. Schoening & Miller's top-level functional flow of the innovation process is illustrated in Figure 17.

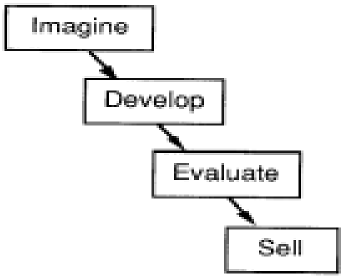

Figure 17 Schoening and Miller's innovation process (source: Schoening and Miller, 1993)

Cropley & Cropley's (2000) proposition is that the process of creativity and innovation is poorly understood and that educational institutions place too little emphasis on creativity and innovation in engineering undergraduate programmes. Not surprisingly, their main focus is the creativity aspect of the innovation phenomenon and this is what underlies their innovation process model. Their model comprises a starting point called "Preparation" followed by six stages namely (1) "Information", (2) "Incubation", (3) "Illumination", (4) "Verification", (5) "Communication" and (6) "Validation". The model is illustrated in Figure 18.

Figure 18 Cropley and Cropley's innovation process

Walden's (1998) "linear creative process", adapted from Shapero (1988) and Humphrey (1987) ideas, also places great emphasis on the creativity aspect. The model is illustrated in Figure 19.

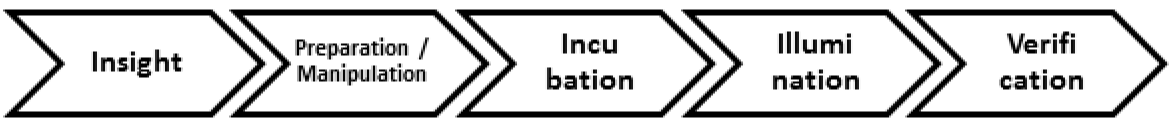

Figure 19 Walden's linear creative process

Cooper's (1988) "seven-stage game plan", also described by Stajnko & Doukas (2001) treats innovation from the risk management perspective, where the risk is gradually reduced as the process unfolds. The model is illustrated in Figure 20.

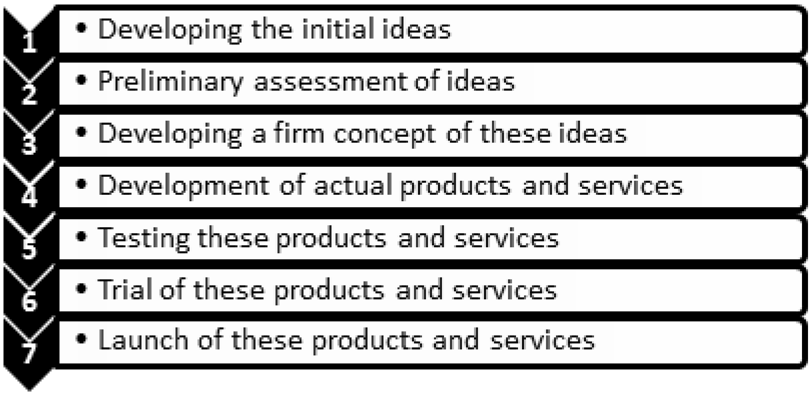

Figure 20 Cooper's seven-stage game plan

2.3 A capability-oriented view

One of the most popular theories in strategy research (and not less in practical strategic management) is the competition-based theory, which looks at how the industry is organised to find the causes of why some firms outperform the others. This framework has emerged as a response to Adam Smith's (1776) model of perfect competition, where entries and exits are relatively easy and all firms merely take the price as granted by a so-called "invisible hand", which was the market. In the 30s, the field of industrial economics emerged with the structure-conduct-performance model. According to Peng (2009), structure refers to the structural attributes of an industry such as costs of entry and exit; conduct is the firms' actions, i.e. how it deliberately (whether proactively or reactively) behaves to outstand from the others; and performance is the result of firms' conduct in response to the industry structure. In sum, the competition-based theory explains the firms' level of performance pointing to the industry structure as the fundamental cause.

A rival perspective is the institution-based theory, which became increasingly popular from the 90s looking at the "rules of the game" in an attempt to explain why the firms' performances differ so much. According to Peng (2009), institutions are "humanly devised constraints that structure human interaction" and they can be regulatory, normative or cognitive. As well as the competition-based theory, the institution-based theory explains firms' performance by looking at the external factors. Whilst the former focus on how the industry is organised, the latter focus on the explicit or implicit rules that shape the industry structure.

Yet another alternative to the two perspectives discussed above is the resource-based theory described by Barney and Clark (2007). Far from being mutually exclusive, these three theories looks at the same object and question, but focusing on different aspects of the problem. The resource-based theory emphasises on the assets that a firm owns or has access to as the fundamental cause of differences between firms' performance. A number of studies have been carried out in an attempt to classify and characterise these assets in various dimensions. In the 90s much was written about the difference between tangible and intangible assets and the different effects they have in firms' competitiveness. Prahalad and Hamel (1990), based on Selznick (1957) introduced the concept of "core competences" in the resource-based theory. Stalk et al. (1992), in the same context, argued that there is a non-negligible difference between competences and capabilities, thus adding his second term to the resource-based framework. Later, Teece, Pisano and Shuen (1997) highlighted the importance of firms' ability to develop their own capabilities, namely "dynamic capabilities" rather than simply buying them from the market; a perspective also shared by Barney and Clark (2007) when discussing strategic factor markets and sustained competitive advantage. Based on Teece, Pisano and Shuen's (1997) propositions, Makadok (2001) discussed the interaction of the two forms of rent creation, namely resource-picking (from the strategic factor markets) and capability-building (i.e. dynamic capabilities).

Whilst Barney and Clark (2007) argue that, in principle, distinctions among terms like "resources", "competences", "capabilities", "dynamic capabilities" and "knowledge" can be drawn, the authors also recognise that they all share the same underlying theoretical structure; all focus on similar kinds of firm attributes as critical independent variables and specify about the same conditions under which these firms attributes will generate persistent superior performance. For the present work, these typologies are not relevant and will not be utilised. Therefore, by the term "capability" this study refers to any "soft resource" or "intangible asset", whether acquired from the factor market or developed by the own organisation, which are sources of superior performance.

Whereas the competition-based theory and institution-based theory have equal importance for strategic management and research as the resource-based theory, they are not as suitable for the present work. The reason is because this study is intended to investigate the interaction between innovation and systems engineering from a practical standpoint, i.e. how they happen and affect each other rather than why they happen and their underlying causes. Therefore it becomes appropriate to support the research on a theoretical framework that focus on organisations' internal aspects, resources, processes and phenomena. Trying to carry out this investigation in a competition-based or institution-based framework would be confusing and might mislead the work.

2.3.1 Systems engineering capabilities

Built on the definition of "capability" presented, by systems engineering capability it is meant any "soft resource" (as discussed above) owned by an organisation which can be pointed out as a cause of superior performance on the practice of systems engineering (note that this differs from the broad concept of business performance). The perspective explored in this section is highlighted in Figure 21.

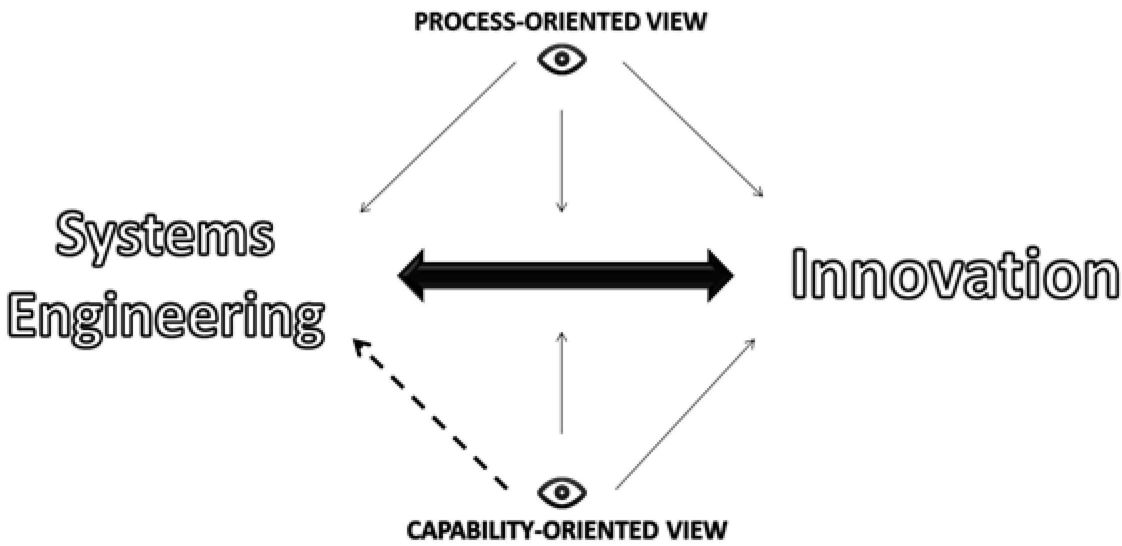

Figure 21 Systems engineering from a capability-oriented view

In 1995, a collaborative effort of six companies (Hughes Space and Communications, Hughes Telecommunications and Space, Lockheed Martin, Software Engineering Institute, Software Productivity Consortium, and Texas Instruments Incorporated), sponsored by the U.S. Department of Defense, produced the most well known capability model in the field of systems engineering, called Systems Engineering Capability Maturity Model, which later became the EIA 731.1 standard, or simply SE-CMM.

Based on the notion that success in the market if often determined by how efficiently an organisation translates customer needs into a functioning product (systems engineering's view) having the appropriate capabilities, in a sufficient maturity level, becomes essential for the successful practice of systems engineering. In order to create a model that can be used as a tool by organisations in any industry to assess their maturity level on these capabilities, the SE-CMM was created. In other words, the model is not intended to identify which capabilities are important, instead it already contains a list of important capabilities and gives a procedure on how to measure an organisation's level in each and every of them, according to an established grading scale.

The capabilities described in the SE-CMM are process-oriented and capture "how well" the organisation performs the various so-called "processes areas". The process areas are:

PA 01: Analyze Candidate Solutions

PA 02: Derive and Allocate Requirements

PA 03: Evolve System Architecture

PA 04: Integrate Disciplines

PA 05: Integrate System

PA 06: Understand Customer Needs and Expectations

PA 07: Verify and Validate System

PA 08: Ensure Quality

PA 09: Manage Configurations

PA 10: Manage Risk

PA 11: Monitor and Control Technical Effort

PA 12: Plan Technical Effort

PA 13: Define Organization's Systems Engineering Process

PA 14: Improve Organization's Systems Engineering Processes

PA 15: Manage Product Line Evolution

PA 16: Manage Systems Engineering Support Environment

PA 17: Provide Ongoing Skills and Knowledge

PA 18: Coordinate with Suppliers

The ability to perform the eighteen process areas in an effective, efficient and controlled manner is measured according to a six-level framework, from the least mature to the most mature, as shown in Figure 22.

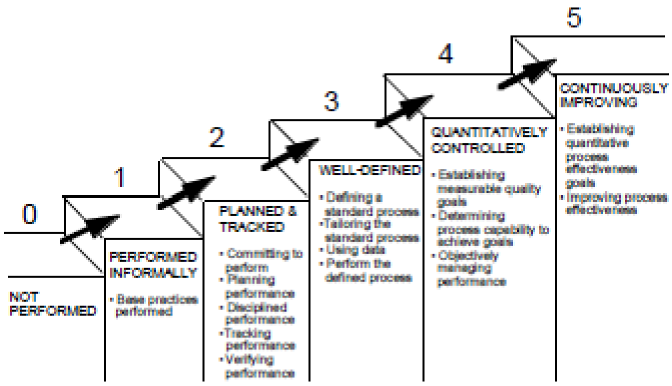

Figure 22 Capability maturity levels (source: SECMM)

Given the process areas and the maturity levels, the organisation's systems engineering maturity an infinite number of analyses can be performed.

Although other authors have written about systems engineering capabilities under a number or labels such as "SE features", "SE best practices", etc, no other model developed to date is comparable to the SE-CMM in terms of comprehensiveness, applicability across different industries and consistency and none has been tested to the same extent as the SE-CMM.

2.3.2 Innovation capabilities

In line with the previous section, by innovation capabilities it is meant any "soft resources" owned by an organisation which can be pointed out as the causes of superior innovativeness performance (again, note that this differs from the broad concept of business performance). The perspective explored in this section is highlighted in Figure 23.

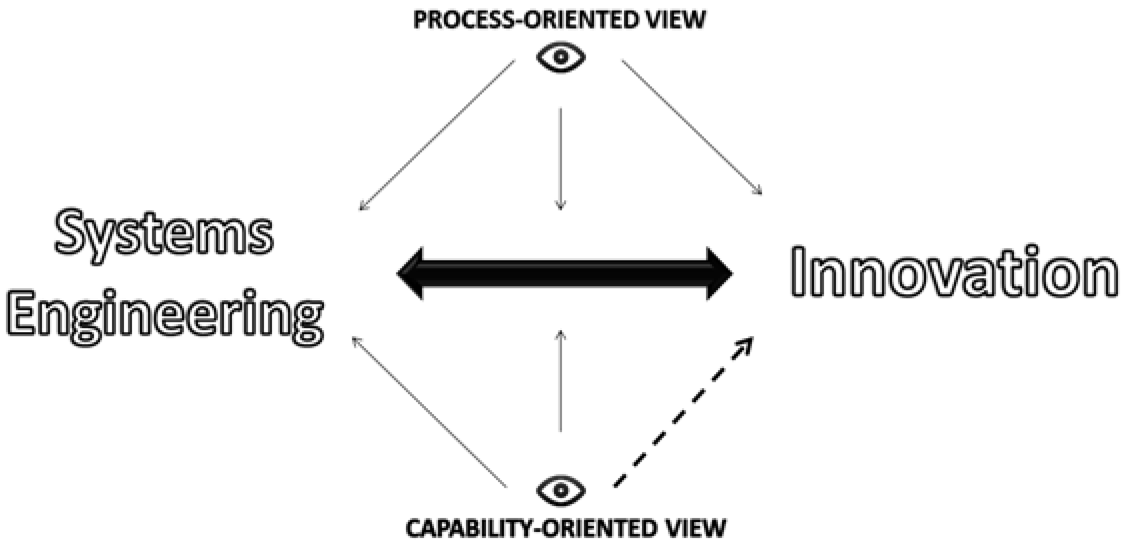

Figure 23 Innovation from a capability-oriented view

Rothwell (1994), when trying to settle the ground for his fifth-generation innovation process, argues that this is essentially a development of the fourth-generation (parallel, integrated) process in which technology of technological change is itself changing. In this context, where both development speed and resource utilisation efficiency are the very key innovation attributes, Rothwell (1994) proposes a list of twenty four factors involved in increasing development speed and efficiency. Some of them have a greater impact on speed, others on efficiency, and yet others offer improvements on both dimensions. Whilst Rothwell (1994) calls these twenty four elements “factors”, in the light of the definition given to the term “capability” as applicable for this study, they are absolutely nothing but innovation capabilities. Yet, most of them are far from new in the literature on successful industrial innovation (Rothwell, 1992). They are:

- An explicit time-based strategy: being a fast innovator at the forefront of corporate strategy.
- Visible top management commitment and support (McDonough & Barczac, 1991; Gupta & Wileman, 1990).
- Adequate preparation: mobilising commitment and resources in a timely manner (Ansoff, 1992).

- Efficiency at indirect development activities: activities such as project control, administration and coordination, which may account for up to 50% of total project development time (Sommerlatte, 1990).

- Adopting a horizontal management style with increased decision making at lower levels: greater empowerment of managers at lower levels reduces the number of approvals required, and the reduction in hierarchy reduces approval delays (Dumaine, 1989).

- Committed and empowered product champions and project leaders: leaders with both technical and project management skills are essential for successful product development (Graves, 1991; Gupta & Wileman, 1990, Rothwell & Teubal, 1977; McDonough & Spital, 1984; McDonough & Barczac, 1991).

- High quality initial product specification: early emphasis on requirement analysis and definition in order to reduce unplanned scope changes during product development, which can be a major factor in delay (Gupta & Wileman, 1990).

- Use of integrated (cross-functional) teams during development and prototyping (concurrent engineering): parallel activities taking place within a cross-functional, interdisciplinary team and outside (e.g. by suppliers) in a parallel process, referred to as the “Rugby” approach (Imai et al., 1985; Clark and Fujimoto, 1991).

- Commitment to across-the-board quality control: never cut corners skipping early stage design activities in order to speed up product development as the harmful consequences often appear downstream in the process, often as late as after commercial launch (Hewlett Packard, 1988).

- Incremental development strategy: aim for small and frequent technological steps, in a continuous improvement process (Clark and Fujimoto, 1989; Crawford, 1992).

- Adopting a “carry-over” strategy: utilisation of established building blocks from earlier models in the most recent designs.

- Product design combining the old and the new.

- Designed-in flexibility: called by systems engineering "open architecture", this refers to the creation of designs that contain inherent flexibility or technological slack so that it can originate a "product family" or derive into new products (Rothwell and Gardiner, 1988).

- Economy in technology: related to the concept of economy of scope, it means designing core components and/or frames that can be used across an extended range of products (Ruffles, 1986).

- Close linkages with primary suppliers: close and early connection and cooperation with suppliers in order to reduce development costs and increase development speed (Lamming, 1992; Maier, 1988; Rothwell, 1989).

- Up-to-date component database: create and maintain a useful database of components and suppliers that can be used in future projects.

- Involving leading-edge users in the design and development activities: the involvement of end users in the product development process may enhance designers' access to design basis information, increasing development speed and reducing development costs (Hippel, 1988; Shaw, 1986; Rothwell, 1986).

- Accessing external know-how: as no organisation has complete in-house capabilities to perform all necessary activities and superior resources of the same type may often be found outside the organisation, firms should consider the option to outsource resources such as hiring expert consultants, licensing-in existing technologies, assigning the design of specific components to suppliers, etc. (Gold, 1987; Stalk and Hout, 1990; Mansfield, 1988; McDonough and Barczac, 1991).

- Use of computers for efficient intra-firm communication and data sharing: efficient information flows and integration of computerised design (CAD) and manufacturing (CAM) systems contribute to efficient product development (Millson et al., 1992; Stalt and Haut, 1990).

- Use of linked CAD systems along production filière (suppliers, manufacturers, users): integration of CAD systems are not only important within the organisation boundaries, but also between organisations when concurrent engineering is taking place and/or when design and manufacturing are not performed by the same firm (Hewlett Packard, 1989).

- Use of fast prototyping techniques: fast prototyping reduces the lead time and costs for the design verification activities (Juster, 1992; Kruth, 1991)
- Use of simulation modelling instead of prototypes: although not always viable or even appropriate, use of simulation instead of prototypes (e.g. for design screening, first instance design verification and verification of minor changes) can increase development speed, reduce development cost and improve product quality.
- Creating technology demonstrators as an input to simulation: basic technological understanding and verification of concepts as foundations for product design enhances value and reduces development cost and time (Ruffles, 1986)
- Use of expert systems as a design aid: use of computer-based product design and simulation techniques enables organisations to embark on electronics-based heuristics (Rothwell, 1994; Feigenbaum et al., 1988).

In his study, Rothwell (1994) synthesises the twenty-four factors in eight “underlying strategy elements” and four “primary enabling features”, which can themselves also be considered innovation capabilities, though in a more aggregated level.

Underlying strategy elements:

- Time-based strategy (faster, more efficient product development)
- Development focus on quality and other non-price factors
- Emphasis on corporate flexibility and responsiveness
- Customer focus at the forefront of strategy
- Strategic integration with primary suppliers
- Strategies for horizontal technological collaboration
- Electronic data processing strategies

- Policy of total quality control

Primary enabling features:

- Greater overall organisational systems integration
- Flatter, more flexible organisational structures for rapid and effective decision making
- Fully deployed internal databases
- Effective external data link

Another model on innovation capability, though much simpler than Rothwell (1994), was compiled by Walden (1999). Based on Katz (1988), Tushman & Moore (1988), Humphrey (1987), Shenhar (1996), Gaynor (1996) and Dorf (1998), his work establishes six key innovation characteristics, or capabilities. They are:

- Strategic direction: refers to how clear the organisation knows where it stands, what it wishes to achieve and the roadmap.
- Innovative culture: comprises how the organisation values new ideas, its willingness to take risks in a controlled and intelligent manner and flexibility to welcome and support change.
- Stream of new ideas: continuous creation and processing of new ideas where creativity is the central point, in activities such as R&D, product design, marketing and even when cannibalising their own products at the suitable times.
- Innovation infrastructure: organisation functions that drive the process of transformation of ideas into marketable products and processes.
- Support infrastructure: all other organisation functions that are not directly involved in the innovation “engine” but supports it in one way or another.
- Continuous improvement: the permanent improvement of the innovation process.

3 Research design

The research design chapter is intended to establish a detailed framework that helps to guide the study through the research process, allowing a greater likelihood of achieving its objectives (Wilson, 2010). The research design is, in essence, the logical sequence that connects the empirical data to the initial research question and, ultimately, to the conclusions (Yin, 2009).

The first section revisits the fundamental research question and develops it into a small number of more tangible research propositions, therefore giving a more precise direction of “what” is to be investigated. The second part describes the selected research method. The third part describes the unit of analysis and unit of data collection.

3.1 Research direction

As stated in the beginning, the ultimate objective of this study is to investigate the interaction between the practice of systems engineering and innovation in a technology-based organisation in order to provide a better insight for decision makers. Chapter 2 clarified some fundamental definitions of systems engineering and innovation and compiled a brief review of what has been written on these two topics, from both process-oriented view and capability-oriented view.

From the process-oriented view, the few studies that have crossed these two concepts suggest that systems engineering and innovation have a great deal of alignment in terms of objectives, direction and elements (e.g. Shoening & Miller, 1993; Walden, 1998, 1999; Stajnko & Doukas, 2001; Cropley & Cropley, 2001). Based on that, the following proposition can be drawn:

Proposition 1: There are general synergies between the systems engineering- and the innovation processes.

Nevertheless, some authors (e.g. Walden, 1998, 1999) suggest that often “Systems Engineering’s emphasis on process, documentation and control is perceived to inhibit innovation”. If there is a general perception that some elements of the systems engineering process do not pull on the same direction as innovation, it is important to identify which elements are these. Therefore the second proposition can be drawn as follows:

Proposition 2: At least one element of the systems engineering process is conflicting with the innovation process.

Following the rationale given in chapter 2 that capabilities are a type of resource and that firms' performance is essentially determined by the possession (or use) of the appropriate resources at the sufficient level of maturity, it is important for decision makers to know which capabilities they should pursue. The capabilities required for systems engineering and for innovation are well explored in the previous studies, but how compatible they are in practice is not yet clear. In other words, are these sets of capabilities essentially the same? Are they not the same, but at least compatible so that an organisation can possess both sets and they will coexist “in peace”? Or are they simply incompatible and it is not possible for an organisation to have at the same time all the capabilities required for the practice of systems engineering and innovation? This can be translated into the following propositions:

Proposition 3: Most of the capabilities required for the practice of systems engineering are the same as those required for innovation.

Proposition 4: There are capabilities required for innovation that are incompatible with the practice of systems engineering.

3.2 Research method

According to Yin (2009), there are three fundamental conditions that will define the most appropriate research method for each study, namely (1) type of research question, (2) the extent of control that the researcher has over actual behavioural events and (3) the degree of focus on contemporary as opposed to historical events. The main available methods are action research, experiment, survey, archival analysis, history and case study (Yin, 2009; Wilson, 2010)

The fundamental research question behind this study is of “how” type, i.e. “how does the practice of systems engineering interact with innovation in an organisation”, as opposed to “why”, “how many”, “how much”, “who”, “when” and “where”. In other words, in an attempt to characterise the way one phenomenon (or practice, or technique, etc., depending on the perspective) interacts with another, the question being posed is predominantly of “how” type.

When evaluating the degree of control the researcher has over the behavioural events, the answer is “negligible”. Both innovation and systems engineering normally are phenomena that happen (or are promoted) in an organisation-wide dimension, if not industry-wide. It might be argued that high rank executives might have some control of how their firms exercise innovation and how they put systems engineering in practice, which is not totally incorrect. Moreover, if they had no control whatsoever over these two behavioural events it would be meaningless to study them in the first place, as the implications for the managers would be useless. But the degree of control that the researcher carrying our this study has over the interaction between systems engineering and innovation is close to none, as opposed to the degree he would have over, for instance, a chemical reaction which might be carried out in a laboratory, under fully controlled conditions.

The third condition, about the degree of focus on contemporary events, it may be said that the phenomena studied herein are completely contemporary. Even though innovation has been happening for centuries, it was about half a century ago that it started becoming a driving engine in the marketplace and business researchers started to shed lights on the subject. Likewise systems engineering has been put in practice for some decades, but it was not more than two decades ago that it started being organised as a formal engineering discipline; the related techniques being developed in a professional manner; and the practitioners establishing professional communities. When looking at the relationship between them very little has been studied and written, but related questions from organisations on the subject are increasingly frequent, although more implicit than explicit.

Although the various research methods are not mutually exclusive and often there are situations in which all methods are applicable; Yin (2009) argues that when “how” questions are asked, about a contemporary set of events, over which the researcher has little or no control, a case study has a distinct advantage.

According to Wilson's (2010) categorisation as exploratory, descriptive and causal, this study can be said to be predominantly descriptive. Although little has been written about the key relationship studied herein, much has been written about both topics separately, as presented in chapter 2, therefore this research does not lack a theoretical framework and is not intended ultimately to raise research questions for future studies, but to draw some conclusions instead; therefore it should not be described as exploratory. Likewise it is not a fundamentally causal study because the research question is not intended to establish a causal relationship between two events in the first place; instead it intends to describe the relationship, which is not necessarily causal.

A descriptive case study, therefore, is believed to establish an appropriate link between the research questions and a real-world source of evidences.

3.3 Unit of analysis and unit of data collection

The unit of analysis selected for this study is a large, novel project in the subsea sector of the oil and gas industry being executed as this study is carried out. The oil and gas industry has been selected because the main industry in Norway (where this studied is performed); and the subsea sector because it is technology intensive and because this is where the author has had all his professional experience and therefore is able to have a clearer and more robust insight into the studied phenomena than would have otherwise in other fields.

Although the selected case is not the only instance where innovation takes place and systems engineering is put in practice in the subsea sector, it is a critical and revelatory case in various aspects. It is a critical case because (1) it promotes a technology leap of such magnitude that has rarely (if ever) seen in the subsea history; (2) it is a major project management challenge given the number of people and disciplines involved and the geographical distribution; and (3) it is outstandingly large in cost and value, compared to an average subsea project (Lima et al., 2011).

The selected case, Åsgard project, consists of an engineering, procurement and construction contract signed by Statoil and Aker Solutions in which the latter is to develop and deliver the world's first subsea gas compression system. The system can be regarded as highly complex and challenging from an engineering standpoint since it depends on a number of new technologies and a number of technologies being modified for the subsea environment (called marinisation). In simple terms, it consists of designing and building an entire unmanned, highly automated platform to be installed on the seabed and operated from a remote unit. Recognising such technical challenge and considering the potential benefits from the practice of systems engineering discussed in chapter 2, the contractor has made a strategic decision to make intensive use of this engineering approach, despite the fact that in general it is much less used in the oil and gas industry than in others, as discussed in chapter 2. From a business standpoint it is a very promising case as it will increase the reservoir recovery by approximately 28 billion Sm3 (Statoil, 2010), and can be regarded as an outstanding example of innovation as it brings basic research all the way to the status of marketable product, and unlocks future, follower developments (Lima et al., 2011).

Therefore, Åsgard is the real world organisation from where the empirical data are collected for this study. One relevant fact to be observed is that this unit of analysis is not an permanent organisation as a firm, but a project instead. According to the Project Management Institute (PMI), “a project is a temporary endeavour undertaken to create a unique product, service or result” (PMI, 2004). From the definition one can extract a major difference between a project and an organisation. Whilst a firm is permanent, or at least planned to be and perceived as so during its lifetime, a project has its start and its end well both well defined, regardless of its success or failure. An important implication of this key difference is that firms base their priorities and decisions on long term objectives, whilst projects think in relatively shorter term. Firms plan, measure and report their results in quarters whereas projects manage their progress typically in weeks or, in some cases even days. In sum, firms and projects differ quite substantially in timing.

As Åsgard is the only unit of analysis covered in this research, it can be regarded as a single-case study. Although the reliability of single-case studies is often challenged, this is believed to be the appropriate design for this study. Given this combination of intensive use of systems engineering and outstanding example of innovation, Åsgard can be said to be a critical case. It is also to a great extent revelatory, since very little has been written about systems engineering in the oil and gas industry of academic relevance; and about innovation more has been written but most often with partial understanding of what it actually is. Besides, because the researcher is an active member of the project team and, he has a better knowledge and understanding of this case than would have of any other cases, if a multiple case-case design had been chosen. If a second or a third case had been included, the level of knowledge and insight that the author would have over the cases would be unbalanced, since he would be looking at one case from inside and to the others from outside; and that would likely introduce a bias. Another reason for not introducing more cases in this study is related to resource utilisation. Since the author is already involved in Åsgard, much more and richer data can be collected from this project than would be conceivably practicable from other projects with the same amount of resources deployed. In sum, a deliberate decision has been made to make an in-depth analysis of one single case instead of a shallow and unbalanced analysis of multiple-cases.

In order to address the threat to reliability that a single-case study inherently has, multiple sources of data are utilised. In other words, information is gathered from a number of people from different functional areas and level of seniority. Whilst the single unit of analysis is Åsgard Project, a number of different project team members are the units of data collection.

4 Data collection

This section is intended to define what data are collected, how they are collected and additional precautions and preparations prior to data collection. The main objective on doing so is to secure internal validity and reliability, i.e. to guarantee that the data measures what it is intended to measure and that the results are stable and consistent with the truth (Wilson, 2010).

4.1 Data type and data collection tools

This research, being a case study, analyses a contemporary phenomena, and therefore has the possibility to acquire primary- and/or secondary data. Primary data, which is all information gathered for the purpose of- and unique to this very study (Wilson, 2010), is believed to be the most appropriate because secondary data is not known to be available at an appropriate level of quality, accuracy, suitability and reliability for this study.

Yin (2009) and Wilson (2010) suggest and recommend the following sources of evidence, or primary data collection tools: documentation, archival records, interviews, observation and physical artefacts.

Documentation and archival records, despite existing in large volumes within the project boundaries and in the involved organisations (client, contractor, suppliers, etc), do not address this very research question and are not fully available. Physical artefacts tell very little about the research question and barely exist within the boundaries of the unit of analysis, in the current project stage.

According to Yin (2009), a major strength of the case study data collection is the opportunity to use many different sources of evidence, whilst the need to use multiple sources of evidence far exceeds that in other research methods such as experiments, surveys or histories. Therefore, two primary data collection tools namely interview and questionnaire are utilised in combination so that their results can be compared and validated.

A third data collection tool, observation, in theory would also be an option for this case study. However, the researcher has deliberately decided to not deploy this tool for two main reasons as follows. The first and most important is that although participant observation is a recognised legitimate data collection tool, it is highly likely to introduce some degree of researcher’s own opinions and other biases in the research data, and therefore in this case the researcher prefers to keep them outside the study. The second reason is that the larger number of data collection tools to be used the more time and resources are needed. Hence the researcher considers that the combination of two data collection tools (questionnaire and interview) is sufficient for a high quality, balanced study; and introducing a third one would divert time and resources from other parts of the study (e.g. data analysis, synthesis/conclusions, etc.) providing only marginal contribution to the study’s overall quality.

4.2 Question levels

The questions to be asked both in the questionnaires and interviews are the key to build the link between the research question and the research answers. A few clarifications are worth prior to the questions materialisation.

The first distinction to be made is between the types of questions. Yin (2010) discusses the five-level framework as follows:

- Level 1: questions asked of specific interviewees
- Level 2: questions asked of the individual case
- Level 3: questions asked of the pattern of findings across multiple cases
- Level 4: questions asked of an entire study – for example, calling on information beyond the case study evidence and including other literature or published data that may have been reviewed
- Level 5: normative questions about policy recommendations and conclusions, going beyond the narrow scope of study

In this framework, relevant level 5 questions would be “Can managers use systems engineering to enhance their firms' innovativeness?”, or “How can managers prevent systems engineering from threatening their innovation capabilities?”, or yet “Can managers do systems engineering without jeopardising their innovation process?”. These, however, are normative questions and cannot be answered by one single study; nonetheless they are relevant in the sense that they form the context for the present research.

Level 4 questions would be “How do the empirical evidences and conclusions from this study relate to the existing literature?” or “What contribution does this study add to the body of knowledge on innovation and systems engineering?”.

Level 3 questions are not applicable for this study since it is based on a single-case design. If it were a multiple case study, for instance across multiple subsea projects, relevant level 3 questions would be “Are systems engineering and innovation proven to be generally consistent across subsea projects?” or “What are the particular systems engineering process elements that repeatedly appear to inhibit innovation in subsea projects?”.

Level 2 questions, very relevant for this study, are “How does the systems engineering process interact with the innovation process in Åsgard project?”, or “How compatible are the systems engineering capabilities with the innovation capabilities in Åsgard project?”.

Level 1 questions are natural derivatives from the research propositions, and are designed to prove them true or false. For each proposition, however, a number of level 1 questions can and should be made. The fundamental difference between them is that questions for a questionnaire are as objective and self-administered as possible and do not require the assistance of a interviewer; whereas interview questions can be somewhat open-ended so that the interviewee reverts with more information than what has been asked, allowing the interviewer to gather information which “he does not even know that he does not know” (Wilson, 2010; Yin, 2009).

4.3 Linking research construct and research questions

As discussed in chapter 3, propositions 1 and 2 are related to the process-oriented view whilst propositions 3 and 4 are related to the capability-oriented view. In order to set a ground for the questions, it is necessary, firstly, to define one reference model for systems engineering process, one reference model for innovation process, one reference model for systems engineering capabilities and one reference model for innovation capabilities, based on the repertory of models discussed in chapter 2. The key requirements for the selection of the appropriate model to be used in this research are:

- Simplicity: it should be as simple and concise as possible, though yet maintaining its robustness
- Suitability: it should be applicable to the unit of analysis, i.e. it should capture the process and capabilities that are relevant for Åsgard project.

4.3.1 A systems engineering process model

Amongst the systems engineering process models described in chapter 2, the one that best fits the criteria of simplicity and suitability is the Vee Model.

In Åsgard, as in most of the subsea projects, the overall need is analysed, the general system architecture is defined, the requirements are allocated and the components are picked from the market (commercial off-the-shelf) or detail designed (tailor-made components) from the top level to the bottom level, as illustrated in the first leg of the Vee. In sequence, the system is integrated (or synthesised), verified and validated, as illustrated in the second leg of the Vee. In Åsgard, at the bottom of the Vee are the core functional components such as compressors, pumps, separators and heat exchangers; and the utility components such as instruments, connectors, piping and valves. On the second leg the core functional components and utility components are integrated into modules, followed by compression trains and at the top of the second leg the entire subsea compression system is fully assembled, verified and validated.

The key process elements to be used as basis for the data collection, therefore, are the six blocks from the Vee model illustrative diagram. The generic process elements are then translated into more tangible terms that illustrate how the process actually takes place, in practice, in Åsgard project, as shown in Table 1.

Table 1 Vee model applied to Åsgard project

	Generic process elements	Åsgard-specific process elements
1	System development	General system analyses and solution screening
2	Upper-level system element development	Analysis and design of process system, power system, control system and layout
3	Lower-level system element development	Detail design and qualification of individual components (compressors, pumps, separators, heat exchangers, instruments, connectors, etc)

4	Lower-level system element realisation	Procurement and/or construction and factory acceptance test of lower-level components
5	Upper-level system element realisation	Assembly, factory acceptance test and functional test (whenever applicable) of modules
6	System realisation	Assembly of compressor trains and system integration test

4.3.2 An innovation process model

The innovation process model that best fits the reality in Åsgard project is the Rothwell's (1994) fifth-generation innovation process. As discussed in chapter 2, it is built on the same building blocks as the fourth-generation process, also with great emphasis on product development speed, but with additional focus on resource utilisation efficiency. Therefore, the building blocks from the fourth-generation process are adapted to the fifth-generation and translated into Åsgard-specific terms as shown in Table 2.

Table 2 Fifth-generation innovation process model applied to Åsgard project

	Generic fourth-generation process elements	Åsgard-specific fifth-generation process elements
1	Marketing	Lean and swift tendering process
2	Research and development	Lean and swift research and development
3	Product development	Lean and swift component development and design
4	Production engineering	Lean and swift fabrication planning
5	Parts manufacture (suppliers)	Lean and swift procurement of components
6	Manufacture	Lean and swift construction and assembly

4.3.3 A systems engineering capability model

The systems engineering capability model selected to be the basis for the data collection is the only described in chapter 2, namely Systems Engineering Capability Maturity Model (SE-CMM). This model is selected not for lack of alternatives (indeed there are alternatives available), but because it is in general by far better than any other model developed to date, and because it fits Åsgard's reality.

The SE-CMM, however, is too lengthy and if all the 18 “process areas” are deployed individually in the questionnaire, this will likely become a major challenge to the respondents, threatening the response rate and the response quality. Hence the SE-CMM elements are aggregated in five categories as presented in Table 3.

Table 3 Systems Engineering Capability Maturity Model applied to Åsgard project

	Systems engineering capabilities
1	**Ability to explore the technical problem domain** • Understand customer needs and expectations • Derive and allocate requirements
2	**Ability to explore the technical solution domain** • Analyse candidate solutions • Evolve system architecture • Integrate system • Verify and validate system
3	**Ability to manage technical effort** • Integrate disciplines • Ensure quality • Manage risk • Manage configurations • Monitor and control technical effort • Plan technical effort
4	**Ability to continuously improve technical effort** • Define project's systems engineering process* • Improve project's systems engineering processes*
5	**Ability to manage interface engineering-business** • Manage product line evolution • Manage systems engineering support environment • Provide ongoing skills and knowledge • Coordinate with suppliers

* Phrase “organisation” replaced with “project”.

4.3.4 An innovation capability model

The innovation capability model selected to be the basis for the data collection is a modified version of Rothwell's (1994) twenty-four factors. Qualitatively, the model's essence meets Åsgard project's reality sufficiently well, but as well as the original SE-CMM it is too lengthy to be used in the data collection. Therefore the eight "underlying strategy elements", which are an aggregation of the twenty four factors, are utilised as presented in Table 4.

Table 4 Rothwell's innovation capability model applied to Åsgard project

	Innovation capabilities
1	**Time-based strategy (faster, more efficient product development)** • Top management's commitment to timely delivery • Visible top management commitment and support • Efficiency at project administration and control
2	**Development focus on quality and other non-price factors** • Motivated and empowered product specialists and project champions • Emphasis on early analysis and specification of equipment requirements prior to design • Use of fast prototyping and mock-ups • Maximum utilisation of qualified technology whenever possible and use of existing building blocks
3	**Emphasis on corporate flexibility and responsiveness** • Mobilising resources in a sufficient and timely manner • Empowered low-level managers and coordinators • Use of inter-disciplinary teams and integration with teams in other functions and/or or locations
4	**Customer focus at the forefront of strategy** • Involvement of external parties such as end users and external technical experts (consultants)
5	**Strategic integration with primary suppliers** • Close cooperation with strategic suppliers
6	**Strategies for horizontal technological collaboration** • Integration of CAD tools with external parties such as users and suppliers
7	**Electronic data processing strategies** • Use and maintenance of component database with parts used in

	previous projects and which can be used in future projects • Integration of CAD tools inside the project • Intensive use of computer simulation tools • Focus on the development of building blocks that can be reconfigured for future Åsgard life-cycle stages or future projects
8	**Policy of total quality control** • Commitment to quality assurance

4.4 Data collection tools

4.4.1 Questionnaire

The questionnaire is first tool utilised. According to Wilson (2010), a questionnaire comprises a set of questions designed to generate data suitable for achieving the objectives of a research project.

The target audience are team members in engineering and business functions, since they are in the key nodes in the systems engineering / innovation relationship. In order to test the propositions given in chapter 3 with empirical evidences, the questions are structured in form of two matrices as follows.

The first matrix is intended to test propositions 1 and 2 and is based on the process models of systems engineering and innovation selected for the data collection as described in this chapter. Since propositions 1 and 2 interrogate on the level of synergies between both processes, the respondents are therefore asked to measure to which level each pair of process elements (systems engineering vs. innovation) are mutually supportive in Åsgard project. The quantitative synergy measures assigned to each cell are as follows:

- +3 : One works as an engine for the other
- +2 : One often has a positive influence on the other
- +1 : One may eventually contribute to the other
- 0 : Both may coexist but they do not influence one another
- -1 : One may inhibit the other

- -2 : One often inhibits the other
- -3 : One always, invariably inhibits the other

For example, for each combination of systems engineering process element with innovation process element a measure of synergy level is assigned by the respondents as shown in illustrative Table 5.

Table 5 Illustration of synergy levels between systems engineering- and innovation process elements

	Lean and swift tendering process	Lean and swift research and development
General system analyses and solution screening	+3	1
Analysis and design of process system, power system, control system and layout	0	-2

The same measurement logic is applied to the levels of compatibility between the systems engineering capabilities and innovation capabilities, as addressed by propositions 3 and 4. The respondents are therefore asked to measure to which extent each pair of process elements (systems engineering vs. innovation) are compatible in Åsgard project. The levels of compatibility assigned to each cell are as follows:

- +3 : Are essentially the same thing
- +2 : Are not the same but support each other
- +1 : Often coexists in the same team but do not support each other
- 0 : May coexists in the same team but do not influence each other
- -1 : Are partially incompatible but often teams manage to conciliate both
- -2 : Are completely incompatible and a team will hardly manage to conciliate both

It is important, however, to keep the link to the unit of analysis, since most of the respondents have experiences from other projects, i.e. from outside the unit of analysis. As discussed by Yin (2009), when data is collected from people there is a degree of subjectivity in the answers because they are based on the respondents' perceptions and not necessarily on the fact itself. This deviation between the true facts and people perceptions about the facts is compensated by triangulating data from multiple sources, i.e. multiple respondents. But in order to ensure that the answers given by the questionnaire respondents and interviewees are at least mostly based on the unit of analysis, they need to be instructed to give their answers based on their experience in Åsgard project rather than their opinions about other projects that they know. In other words, when asked about the level of synergy between "upper-level system element development" (systems engineering process element) and "research and development" (innovation process element), the answer needs to be (to the practicable extent) exclusively within Åsgard's context. Making this clear to the respondents the necessary precaution is taken to ensure that the evidences gathered in this study are actually about the unit of analysis as intended.

In sum, the questionnaires used in this study are in form of two matrices; the first for the process-oriented view and the second for the capability-oriented view. The matrices delivered to the respondents are given in APPENDIX A.

In order to ensure that the respondents understand their task, the researcher reads through the matrices content together with them and explains any point that is not completely understood. The researcher is also available and ready to provide any further clarification while the respondents are filling out the matrices.

4.4.2 Interview

The interviews, in this research, are taken as a second source of empirical data. Thus, any bias introduced by the questionnaire, questions being misunderstood, "tick box syndrome", or any other problem inherent to questionnaires can be challenged and compensated.

Face-to-face interviews are considered the most appropriate for this case, as opposed to telephone and focus group interviews, since it offers a repertory of desired advantages and the circumstances happen to minimise its typical disadvantages. The main advantages of face-to interviews, according to Wilson (2010), are the possibility of engaging in both verbal and non-verbal communication, that the conversation can be taped, greater flexibility on delivery of questions and immediate completion. The disadvantages are mostly eliminated by the fact that the interviewer (i.e. the researcher) is a team member and knows well all the potential interviewees. In other words, it is easy to set up the meetings, to get access to the interviewees and to carry out the interviews; and embarrassing situations and cross-cultural issues are unlikely to emerge. Besides, other hassles commonly associated with face-to-face interviews such as dress-code uncertainties, address and access to the meeting venue, “hand-shaking” protocols and timing issues all become irrelevant.

The interviews are carried out using a semi-structured interview technique, which is a hybrid of structured and unstructured approaches (Wilson, 2010). The backbone of the conversations is the preliminary findings or indications from the questionnaire responses. Interviewees are team members holding key positions in the project connected to the relationship between systems engineering and innovation. Potential candidates to be interviewees are, for example, the system engineering lead, the project engineering manager, the project business manager and the project director. At least one and no more than three interviews of approximately one hour each are deemed appropriate, considering the need for data, the amount and quality of data that can be acquired in each interview and the time and resources available.

4.5 Ethical and reliability considerations

The researcher's position as an active member of the project team raises, naturally, questions about reliability and ethics. For the sake of clarity and transparency, the author is a senior subsea systems engineer that works for Aker Solutions, the engineering, procurement and construction (EPC) contractor of Åsgard project, and has been involved in this development since the front-end studies, taking part also in the tender stage and currently in the execution stage.

The threat to reliability comes from the fact that a participant normally has their own preconceptions and opinions about the unit of analysis, which is not a desirable characteristic for a researcher, which ideally should be completely unbiased. According to Becker (1958, 1967) and Yin (2009), case study investigators are especially prone to this problem because they must understand the issues beforehand. In this case, however, the researcher’s motivation is his own curiosity and not willingness to advocate any supposed preconceptions. In order to eliminate the inevitable suspicion from the reader, data is collected from multiple sources external to the researcher's observations (i.e. questionnaires and interviews) and a clear and transparent logic chain linking the research question to the empirical evidences and these to the conclusions are established throughout the present study.

Ethical questions may arise from the fact that being a project team member the researcher has privileged access to proprietary and classified information. Although this is not untrue, no empirical data is collected and no information about the project is included in this study without clearance from Aker Solutions. Besides the privacy and confidentiality of the respondents are fully respected to the degree desired by them, so that absolutely no one taking part in this study as a respondent or contributor is unduly exposed.

5 Data analysis

This chapter intends to report how the data collected is "decoded", i.e. how the data is interpreted and how the findings are connected to the overall research context. The first section elaborates on the strategy adopted to make this "decoding" in a reliable manner; and the following sections report the analysis of the two types of data available, respectively from the questionnaire responses and interviews.

5.1 Analytic strategy

The data analysis strategy adopted is "relying on the theoretical propositions" (Yin, 2009). This approach basically means going back to the research question following the same path which derived it into the propositions and data collection queries (questions level 1). As explained in chapter 4, the data collection has been formatted in such a way that the data provide evidences about the research propositions. Therefore, in this chapter, the data is analysed and interpreted so to conclude whether or not each proposition holds true. The data traceability context is illustrated in Figure 24.

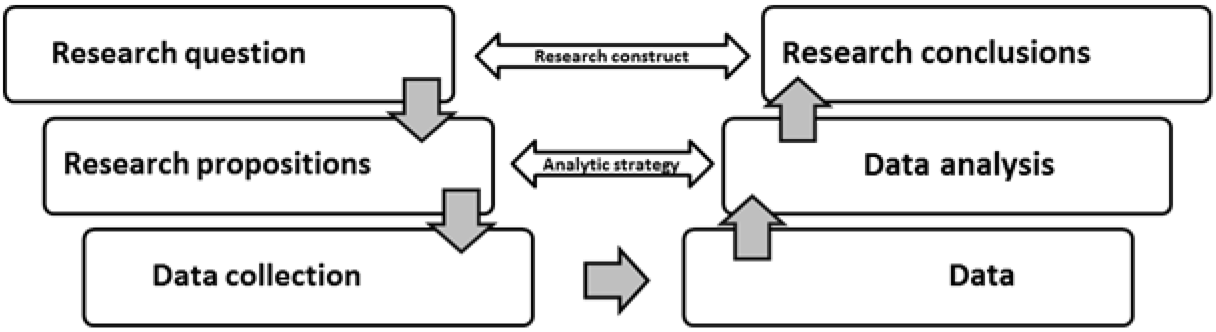

Figure 24 Data traceability flow diagram

Although relying on theoretical propositions is the most often preferred data analysis strategy, it is not the only available option (Yin, 2009). An alternative would be to develop a case study description. That strategy consists of using the collected data to build a description of the case. Whist it has its recognised value, it does not necessarily keep a clear traceability to the research question and propositions, and because of this loose chain of evidences it may lead to conclusions which do not provide a proper answer to the research question, i.e. it often puts the very research validity in risk. A second alternative is examining rival explanations. This option is more appropriate when the research question is of "why" type, as it analyses which of the proposed causal relationships is most strongly supported by the data. Because the present study is not based on a “why” type question and not based on a causal relationship, this analytic strategy is not the most appropriate.

A third alternative is using both qualitative and quantitative data, and this can be used in combination with any of the other strategies. Despite the fact that this option has the potential to yield appreciable benefits, it normally depends on the availability of a large amount of data to make the conclusions significant. In this study some simple quantitative analysis tools are utilised, particularly in the analysis of the questionnaire responses, but this is merely to support the qualitative analysis. Claiming any quantitative conclusion based on a too small sample, which is the case of this study, would risk undermining its reliability.

5.2 Analysis

5.2.1 Questionnaire

Data analysis method

A greater priority is placed on getting the right people to respond the questionnaire rather than getting a high quantity of people to respond. Therefore 10 project members considered good potential respondents were listed; eight were reached and although all of them showed willingness to contribute, only six told they would be able to return the questionnaire in time. Those six questionnaires (each comprising two matrices as explained in chapter 4) were filled out, returned to the researcher and used in the data analysis. The potential interviewees were not approached in the questionnaire stage, even though they would have been good respondents, because it was preferred to use a mutually exclusive approach towards the two data collection tools. In other words, those that responded the questionnaires were not interviewed and those that were considered as potential interviewees were not asked to respond the questionnaires.

The analysis of the data acquired through the questionnaires is qualitative, as explained previously, and so are the preliminary conclusions drawn from them. A few simple statistical methods are utilised for the interpreting the data, but given that the number of respondents in this case study is very limited compared to, for instance, what would be necessary for a survey study, no quantitative conclusion can be drawn from the data. In other words, the conclusions from the questionnaires are for instance “this element appears to be more significant that that element” rather than “element X has a Pearson product-moment correlation coefficient of 0.8 with element Y with an error of +/- 15%”.

Analysing the questionnaire data sample, the two basic attributes measured in every cell were the general tendency towards one value and dispersion. The central tendency indicates what the questionnaire is looking for, i.e. the strength of each relationship between a given row (systems engineering models) and a column (innovation models). Two typical statistical measures which capture central tendency are mean and mode (Wilson, 2010). When the sample size is substantially large (e.g. in a survey), both can be considered equally good methods of capturing the central tendency. However, when the sample size is as small as six, the mean may be greatly affected by one single response completely off the central tendency. Using the mode instead this effect can be avoided since this method takes into consideration only the most frequent response, not being affected by one or two responses completely off the pattern. Hence the mode is considered the most suitable method for this study. The matrices with the modes of every cell are given in Table 8 and Table 9 of APPENDIX B.

The dispersion indicates how much one can rely on the measured central tendency. In other words, a low dispersion means that most of the responses are close to the central tendency and the pattern can be considered strong, whilst a high dispersion means that the responses are distributed in a wide range of values and the pattern is considered weak or at least not well defined. Although a number of different methods are often utilised for measuring dispersion standard deviation the most commonly used (Wilson, 2010) and the one considered suitable for this study. The matrices with the standard deviation of every cell are given in Table 10 and Table 11 of APPENDIX B.

In order to identify the most significant relationships, the quantitative analysis of the questionnaire responses searched for relationships that had at the same time:

- Mode close to the extremes, i.e. highly positive or highly negative
- Low standard deviation

Therefore a third pair of matrices was produced with, for every cell, the product of mode and the inverse of standard deviation as given in the following equation:

$$f(x) = mode(x) \cdot [stdev(x)]^{-1}$$

The highest f(x) values indicate, therefore, the relationships that are at the same time strongest and most reliable from a statistical standpoint. These are the most interesting relationships for the study.

Data analysis results

Whilst the methods for refining the data sample are primarily based on statistical techniques and more typically used in quantitative analyses, the overall analysis and therefore the conclusions are qualitative.

The conclusions about the synergies between the systems engineering process and the innovation process that can be drawn from the scrutiny of Table 12 of APPENDIX B are as follows:

1. Overall, 19 cells have positive values, 11 cells are null and six are negative. This implies that in general the systems engineering processes have positive synergies with the innovation processes, although some elements can coexist without any synergy at all and some fewer actually inhibit one another.

2. There is a clear concentration of positive synergies along the principal diagonal, indicating that there is some degree of sequential synchrony between the systems engineering process and the innovation process.

3. There is a concentration of positive synergies of high significance on and around the lower end of the principal diagonal. This might imply that either the last steps in the systems engineering- and in the innovation processes have a stronger synergies than the first steps, or that both processes converge to a common end.

4. The second element of systems engineering process, namely analysis and design of upper-level subsystems (between the top-level system and the low-level subsystems/components) has an overall negative synergy (i.e. sum) with the innovation

process. This negative value, however, has the lowest significance modulus of all rows and therefore it is hard to be considered a reliable result.

Similarly, the conclusions about the compatibility between the systems engineering capabilities and the innovation capabilities drawn from the scrutiny of Table 13 of APPENDIX B are as follows:

1. Overall, there are 27 pairs of capabilities that not only can coexist but support each other, eight pairs of capabilities that can coexist without influencing each other and only five that are unlikely or impossible to coexist in the same team.

2. The technical-oriented systems engineering capabilities, namely ability to explore the technical domain and ability to explore the solution domain, seem to be more compatible with the innovation capabilities than the systems engineering management capabilities.

3. The time-based strategy appears to be consistently incompatible with the all systems engineering capabilities.

4. The customer focus at the forefront of strategy has a consistent neutral compatibility with the systems engineering capabilities, except with the particular system’s engineering ability to explore the technical problem domain, with which the relationship appears to be very strong.

5. Strategic integration with primary suppliers has a moderate, though positive compatibility with systems engineering capabilities.

6. The relationship between the ability to manage the engineering-business interface and the policy of total quality control is of particularly high significance, meaning that the two capabilities are either highly mutually supportive or essentially the same thing.

5.2.2 Interviews

Data analysis method

Two face-to-face interviews were conducted; the first with the project engineering manager and the second with the project business manager. Both interviewees combine academic education- and professional experience in engineering and in business management and/or economics.

The interviews we conducted, as planned, with a backbone based on the preliminary results of the questionnaires. The backbone questions are given in APPENDIX C. Not all the questions were made literally as they read in APPENDIX C; instead the underlying topics were explored as the conversations evolved. The main focus was (1) to challenge the indications from the questionnaires that appear to be in conflict with the literature or common sense, (2) to corroborate the results that are most significant and (3) to acquire any other information from the interviewees originally not taken into consideration by the researcher. Yet, some questions were made on the opposite of what the questionnaires indicated. For example, where the questionnaire indicated a significantly positive correlation between two elements, in some instances the interviewer stated that the said relationship was commonly perceived to be negative and asked whether or not interviewee agrees with such supposedly common perception.

The interviews were taped so that they could be listened to and scrutinised more thoroughly in the analysis stage. It was told to the interviewees, however, that the transcripts would not be documented, to ensure that they would speak more freely about the project and their opinions. Hence this report does not contain the literal interview transcripts. The analysis of the audio records is the basis for the qualitative conclusions that follow in the next sections.

Wilson (2010) recommends the four-step process for qualitative interview analysis as follows:

1. Transcribing data
2. Reading and generating categories, themes or codes
3. Interpreting the findings
4. Writing the report

The first step is not relevant in this study since it was agreed with the interviewees that the literal interview transcripts would not be included in the report. Listening to the audio records has equivalent effect for the researcher as reading the supposed transcripts. The main disadvantage of analysing the “raw” audio records is that the use of word analysis software packages such as NVivo and CAQDAS becomes unviable. Conversely the advantage is that it is possible to analyse the interviewees' timing, voice tone, etc., which may provide additional information about their degree of certainty and the strength of their opinions.

In the second step a priori coding, i.e. a deductive approach has been taken (Wilson, 2010). The pre-defined categories are the relationships indicated by the questionnaires to be the most interesting for further investigation.

The third and fourth steps are described in the next sections.

Interview with Project Engineering Manager

General understanding about innovation and systems engineering

According to the interviewee, his understanding of innovation in the subsea context is a combination of new technologies, new markers for workforce and new industries to buy from, both in the dimension of technology and work processes. Based on this, he considers Åsgard an innovative project because it contains new technology items and the use of existing technology items in new applications.

On systems engineering he showed a clear process-oriented view, very similar to the process model described in chapter 4, enumerating process elements such as requirement capture, systems analysis, design, integration and verification. He added that Åsgard does practice systems engineering, and this is in its own merit an innovation since systems engineering does not have an established footprint in the subsea sector. For this reason, it is not yet practiced to its full potential in this first project and the next project that uses this engineering discipline intensively will enjoy a higher maturity, nonetheless Åsgard utilises it to the practicable extent.

Systems engineering vs. swift and lean tendering process

Challenging the indication from the questionnaire that systems engineering does not have significant synergies with a lean and swift tendering process, the interviewee strongly disagreed. He argued that systems engineering is highly instrumental in the tender phase; a well managed tender phase tends to spend more resources on systems engineering than the execution phase, relatively to the total resources spent; and the reason is that the consequences of doing something wrong in the tender phase are so disastrous that an organisation cannot afford skipping a proper systems engineering process in that stage. With regard to the timing element, he supported that a multi-discipline approach makes the overall tendering process swifter and leaner, making the time spent on systems engineering a good “investment”.

Last systems engineering process stages vs. last innovation process stages

Exploring the significant synergy between the lean and swift fabrication planning and the lean and swift construction and assembly with the second leg of the Vee model of systems engineering process, focus was placed on the planning part. Asked whether the final assembly and system integration testing is highly dependent on a good planning process and a good engineering process beforehand, the interviewee strongly agreed, particularly when taking into consideration a non-conventional system such as Åsgard, because the requirements tend to exceed those of conventional systems and because the organisation’s experiences on such systems is limited.

Overall systems engineering process vs. overall innovation process

Overall, the interviewee said that as a whole the systems engineering process has a positive interaction with the innovation process. When dealing with new technologies and/or new application of existing technologies, there are always new requirements; the consequences of choosing “this instead of that” are not obvious; and there are always alternative solutions to solve the problem or to meet the new requirements; so therefore this calls for and gives room for the practice of systems engineering. He also added that in these situations there is always a great focus on measuring risks, trading off costs and benefits, understanding the consequences, appraising alternative opportunities, therefore investing in an early thorough system analysis and engineering process is the best approach. In line, according to the interviewee the first leg of the Vee model on systems engineering process (system analysis, requirements capture, and design) has the highest relevance to the innovation process.

Key systems engineering capabilities

When exploring the capability domain, the interviewee indicated multidiscipline competence as the key enabler for the practice of systems engineering, with a predominant importance on the attitude dimension, such that also the specialists are aware that the work within their own discipline is integrated with- and has a consequences on the rest of the system. The typical subsea products are isolated, autonomous pieces of technology that little interact with other products, and traditionally the clients themselves manage these interfaces; whilst in Åsgard the system complexity and the higher number of relationships and interfaces between the parts make the awareness that something and somebody is affected by your work clearly the key enabler for the systems engineering practice. A second important capability is the understanding that there are defined roles in the project so that various people do not end up doing the same thing, and that these defined roles are well integrated in the project processes. A third capability is a strong team that has not only the multidiscipline attitude but also strong multidiscipline skills, i.e. that has a high level of knowledge in all relevant technical and managerial disciplines.

Key innovation capabilities

Exploring the key innovation capabilities, the interviewee indicated that the very key is a good understanding of risk and reward. This means spotting not only the threats to the project (in various dimensions such as system performance, cost, schedule, quality, etc), but also all opportunities that may arise. In order to achieve this, one needs a great degree of flexibility to appreciate that changes may be beneficial and introducing novel solutions may be worth it. At the same time, the cost and benefit of every available option needs to be clearly appraised and understood so that good decisions can be made on what and when to adopt this or that solution.

Exploring the problem domain vs. time-based strategy

The controversial relationship between the early stages of systems engineering (which include system analysis, requirement capture, etc) with the time-based element of contemporary innovation was explored by stating that they are not compatible and not synergic and asking the interviewee if he agrees. His answer was that in commoditised markets where there is no need for product development because the product is already designed in detail, the main work to be done is in marketing and sales, therefore forcing a system analysis and requirement allocation is definitely a misallocation of time and resources. However where it comes to innovative products markets where something new needs to be developed, or something needs to be deployed in a different application, then he completely disagreed and argued that from the time invested in making a clear equipment specification the organisation can get a good factor of savings compared to leaving that step unresolved until when the system is built because a number of "nasty" fixes will need to be made. In tenders, particularly, investing time in finding a good technical solution to be offered is not more important than investing time in analysing the requirements, since it is the latter that will provide the understanding of the risks involved and the commercial exposure of the organisation towards the external parties.

Exploring the technical problem domain vs. exploring the technical solution domain

Comparing the ability to explore the problem domain to the ability to explore the solution domain, the interviewee was asked which one has a higher relevance to innovation. The answer was that "major inventions" tend to derive predominantly from the former whilst "improvements" tend to derive predominantly from the latter. In Åsgard, he added that one cannot go and plan for a "subsea gas platform" diving directly into how to "solve it", without exploring thoroughly the problem domain. Based on the concept of system-of-systems, the interviewee classified the overall subsea gas compression concept as a radical innovation, whilst in the lower levels of embedded systems and components there are all levels of innovation, from radical through barely incremental and even some commodity components.

Overall systems engineering capabilities vs. customer focus at the forefront of strategy

The low significance in the relationship between "customer focus at the forefront of strategy" and systems engineering capabilities in general was explored by asking how it is perceived in Åsgard context, i.e. if they have anything to do with each other whatsoever. The relationship was hard to be visualised, but the interviewee eventually brought back the requirements capture as the link in this relationship, meaning that it is by understanding the customer's need that one can keep customer focus at the forefront of the strategy.

Overall systems engineering capabilities vs. overall innovation capabilities

Compiling all the systems engineering capabilities in one "block" and all innovation capabilities in a second "block", the interviewee was asked if they are compatible and the answer was that they are clearly and strongly compatible and that the practice of systems engineering, in Åsgard project, fosters innovation. In a commoditised product area the need for systems engineering is however perceived to be much lower than in Åsgard-type projects, so are the benefits from the practice of systems engineering.

Asked if an innovative culture supports the practice of systems engineering, the interviewee said that an innovative culture in his opinion is the constant search for better solutions, out of handbooks and catalogues, and that this is an essential condition for the practice of systems engineering

Discipline vs. innovation

Asked if the additional discipline put forward by systems engineering in the product development process inhibits innovation, the interviewee strongly disagreed and added that this discipline is necessary for a streamlined innovation process. Without this discipline, the innovation would be not manageable and only by random chance it might be successful, which is to say that such additional discipline is the way to drive innovation and influence in an intentional and controlled manner its chances of success.

Interview with Project Business Manager

General understanding about innovation and systems engineering

Asked what the interviewee understands by innovation in the subsea context, he described it as “finding and verifying solutions that bring the technology forward and finding ways of implementing and succeeding with them” and that “it is not sufficient to have a good idea or a thought without having a structure around it, methods, etc. in order to succeed in implementing it”. He also made it clear that innovation does not involve only engineering, but also other capabilities and overall framework, including clients, confidence, support functions and management.

About Åsgard, the interviewee argued that the project is attempting to be less innovative than it actually is in the sense that it is trying to build something in a very tight schedule so that the room for exploring new ideas and testing new technologies is limited by the need for delivering it in time. In other words, Åsgard lives in a conflict between the technology enthusiasm and the absolute need to get it designed, built, tested and delivered in due time.

By systems engineering the interviewee understands as a group of professionals or a discipline that looks at the overall functionality and processes required to produce a total entity. Thus, in the subsea context systems engineering integrates and coordinates all relevant disciplines such as electrical, controls and instrumentation, process, piping, structures, tooling, tie-ins, etc. However, in the subsea sector systems engineering is living alongside the so-called “product engineering” and the former must direct the latter. Product engineering teams make decisions which affect other teams or work packages of product engineering, and in order to optimise these interactions and reach a balanced system there must be a group coordinating these interfaces. Asked if Åsgard is succeeding in this cross-discipline, cross-product integration, he said that the project team has done a surprisingly good job and, although there are minor corners wherever one looks, this is a continuous improvement processes in which one never quite arrives.

Early stages of systems engineering process vs. innovation

Discussing the early stages of the systems engineering process and suggested that often they are perceived to not have a positive synergy with the innovation process, he said that the whole engineering process definitely has a strong relationship with the innovation process, the early stages inclusive. He added that even though he has an execution, result orientation, he does not agree with this supposed perception and proceeded adding that the system analysis is indeed one of the necessary steps in the product realisation process. Further, he added that in a timeline there are a number of steps that depend on the previous steps to be completed, and any of these, if not performed and completed properly, has the potential to lock the innovation process. In Åsgard project, the process that we go through is: first we try to understand the requirements; then we look at the various ways of how they can be achieved, which is a period of creation; we move to the solution selection process which is followed by a period where the selected solutions are further improved and optimised whilst all the other alternative solutions are gradually abandoned.

Systems analysis vs. innovation

Making a comparison between the system analysis and system definition stages of the systems engineering process with regard to their relevance for the innovation process, the interviewee said that being able to see and understand the problem and therefore the requirements correctly and free of preconceptions is a necessary step for the innovation to be useful.

Key innovation capabilities

When asked what key capabilities Åsgard has or needs to have in order to be an innovative project, the interviewee highlighted that any project, including this, needs to have a framework that leads individuals to focus on what they are best at doing. In a project, this is materialised by well designed contractual conditions, commercial conditions and the project organisation.

Key systems engineering capabilities

The same question being made about systems engineering, he said that the key capabilities for the project to practice systems engineering are the knowledge that has been generated through a strong product focus in the subsea division combined with the knowledge that has been developed in the "topside" project execution, whose systems are typically larger, more complex, with more interfaces, etc. For the next Åsgard-type project, he added, our differential will be having not only the combination of people who have either approach (complex system vs. standalone product), but also people that learned in Åsgard to have the combination of both approaches.

Exploring the problem domain vs. time-based strategy

Discussing the compatibility of the time-based strategy with the practice of systems engineering, the interviewee was asked if the former supports or inhibits the latter, and if the latter supports or inhibits the former. He answered that performing systems engineering in an orderly and controlled manner is absolutely necessary to meet a timeline as that it disciplines the way and the order that people make decisions; and making right decisions at the right time is crucial for achieving the timeline. Similarly, he argued that a time-based strategy is absolutely necessary for a streamlined engineering process and without a schedule, the process does not function. In sum, according to the interviewee the compatibility is positive on both directions.

Exploring the technical problem domain vs. exploring the technical solution domain

Yet discussing capabilities, the interviewee was asked about the key capabilities necessary for Åsgard to be effective in exploring the problem domain. His answer is firstly a composite organisation that has all the necessary basic bits of knowledge, not a lot of the same ones, but the right mix of people that understand every bit. Secondly, experience. Asked if the same capabilities are also the key for developing the solution domain, his answer was yes, that the same combination of all bits of basic knowledge and experience are the keys with the addition of ability to make good decisions, which is also important for exploring the problem domain but even more for developing the solution.

Because the interviewee placed a strong emphasis on discussing the ability and the importance of making decisions, illustrating the decision making process as a tree from the fine branches to the routes and back, he was then asked what is needed for people to be a good decision makers. The answer was: ability to listen properly, to understand their surroundings, requirements and needs, the concept of overview and totality, understanding of the priorities, understanding of the problem to be solved and understanding of the consequences of their choices (in quality, time, safety, etc.). Provoked with the question if he was talking about understanding risk and reward (as thoroughly elaborated by the previous interviewee), he answered that this is an integral part of the decision making process, as well as many other things.

Systems engineering in general vs. innovation in general

Calling to his statement that in Åsgard systems engineering interacts positively with innovation, the interviewee was asked if that relationship might be different in another subsea project. His answer was that in the typical subsea standalone product "world" the concept of systems engineering still has not entered the scene as the products are simpler systems and normally can be handled without the so-called systems thinking, or more specifically systems engineering. However when the project involved larger number of components, technologies, interfaces, etc, the need for systems engineering pronounces itself more strongly.

Asked if Åsgard has an innovative culture, the answer was that we have pockets of very innovative culture and pockets that restrain the innovation activity. This happens not only within the contractor's project team, but also in the client's team, where there are as many technology enthusiasts as in "our team" but also people whose work is focused on ensuring that the project delivered in the right time, cost and particularly quality, which very often acts as an effective constraint to innovation.

Discipline vs. innovation

The final question was whether the greater deal of discipline that systems engineering introduces in the engineering process inhibits innovation in Åsgard project. The interviewee argued that not having this degree of discipline would lead to sub-optimalisation of the totality. In other words, if the various teams, work packages, etc. were free to optimise their bits independently from the others, the overall system would be unbalanced and perhaps not an optimal solution to the main problem. Further, he added that freedom is not about being allowed to do exactly what you wish in a given point in time, instead it is about smooth interaction and respect for the others' needs, and it applies in engineering as much as it does in life.

5.3 Synthesis of empirical data

Whilst section 5.2 is indented to dissect the questionnaire responses and the interviews, this section compiles their main highlights. As explained in the beginning of this chapter, the data analysis strategy is relying on theoretical propositions (Yin, 2009). The technique adopted for linking data to the propositions is pattern matching (Yin, 2009), which in this case means finding indications that consistently appear in the questionnaire responses and both interviews. This being said, this section synthesises the empirical evidences in the light of the research propositions given in chapter 3.

Proposition 1 states that there are general synergies between the systems engineering- and the innovation processes. In this respect, the analyses show that the matrix based on the process-oriented view (Table 8 of APPENDIX B), gives three times as many positive as negative indications and slightly more positive than non-positive indications. Amongst the six systems engineering process elements, only one appears to have a negative synergy with the overall innovation process (analysis of high-level sub-systems), though of negligible significance, whilst four have very significant positive synergies. Amongst the six innovation process elements, two have very significant positive synergies with the overall systems engineering process and no element show negative synergy. Furthermore, the concentration of significant synergies along the principal diagonal suggests that there is a significant synchrony between the systems engineering and the innovation processes.

From the first interview, what can be extracted in this respect is that (1) although otherwise indicated by the questionnaire, the practice of systems engineering plays an instrumental role in the lean and swift tendering process, (2) the success of the last stages of the innovation process depend largely on a proper systems engineering process beforehand and (3) the innovation process in general call for and gives room for the systems engineering process. From the second interview, what can be extracted at the light of proposition 1 is that (1) the early stages of the systems engineering process are indeed necessary for the whole innovation process to succeed and (2) both systems analysis and system definition are of equal importance for innovation.

Based on the questionnaire responses and both interviews, it can be said that proposition 1 finds strong support in the empirical data. The conclusion therefore is that in Åsgard project there are general synergies between the systems engineering- and the innovation processes and **Proposition 1** is proven true in the unit of analysis.

Proposition 2 states that at least one element of the systems engineering process is conflicting with the innovation process. This statement finds some support in the questionnaire responses (see Table 12), where it can be observed that the analysis and design of upper-level subsystems appears to have a negative synergy with the overall innovation process. Nevertheless the significance (combination of mode and standard deviation) of this negative synergy is very low. In the row that captures this specific process element, it can be observed that there are neutral synergies (i.e. no interaction) with three innovation process elements, one moderately positive synergy and two moderately negative synergies (i.e. conflicts). All three non-neutral synergies, however, have a substantially high standard deviation, meaning that the responses in those cells were highly mixed. When looking for evidences in the interviews, no support for this proposition can be found; on the contrary there are some moderate suggestions of the opposite. In sum, the evidences about supposed conflicts between one or more elements of the systems engineering process and the innovation process are mixed and too weak, therefore **Proposition 2** is neither proven true nor proven false by the research data.

Proposition 3 states that most of the capabilities required for the practice of systems engineering are the same as those required for innovation. Table 13 shows that amongst the 40 cells only one has a mode 3, i.e. the only capabilities that most of the questionnaire respondents consider essentially the same are “ability to explore the technical solution domain” and “customer focus at the forefront of strategy”.

In the first interview, the respondent highlighted as the very key capability for the practice of systems engineering a developed multidiscipline competence. As the key innovation capability he indicated the most important is a good risk and reward understanding. Although it can be easily argued that they are somewhat related to each other and not too far apart, they are definitely not the same thing.

The second interview pointed out to a particular case of ambidexterity as the key systems engineering capability which is very particular to Åsgard project context: the ability to combine a deep expertise both in standalone subsea products and the ability to handle complex systems in large projects. As the key innovation capability the interviewee mentioned that the project needs to have a framework that leads individuals to focus on what they are best at doing. Once again, in is not difficult to find a connection between these two capabilities, but they are essentially not the same thing.

In Table 9 and in both interviews it is possible to find evidences to prove proposition 3 not true, as discussed in the paragraphs above. Nonetheless, Table 9 shows that 19 of the 40 relationships are of type “not the same but support each other” (value 2). Table 11 shows that most of these 19 cells also have a considerably low standard deviation, i.e. there is some degree of consensus between the respondents. Both interviews give equivalent indication: the key capabilities are not quite the same but appear to have some connection with one another. The conclusion about **Proposition 3**, therefore, is that most of the capabilities required for the practice of systems engineering are not the same as those required for innovation, but according to the empirical evidences they are mutually supportive.

Proposition 4 states that there are capabilities required for innovation that are incompatible with the practice of systems engineering. The data acquired from the questionnaires give a very clear and significant indication that the time-based strategy is consistently incompatible with all the systems engineering capabilities, as can be observed in Table 13.

The interviews, however, give a mixed though clarifying indication. The first interviewee stated that in commoditised markets, trying to do systems engineering is a mistake and the main effort should be placed on marketing and sales, whereas in innovative products markets, such as the one where Åsgard project belongs, the systems engineering capabilities are absolutely in line with a time-based strategy and they have a relationship of mutual dependence. The second interviewee advocated that the relationship between systems engineering and the time-based strategy is of mutual dependence, such that without systems engineering any technology-based project will struggle to meet the milestones and deadlines and a proper schedule is necessary for the practice of engineering in general.

In sum, amongst all the data acquired in this research, there are strong evidences to prove proposition 4 true (mainly from the questionnaires) and also strong reasons to prove it false (mainly from the interviews). In this situation, the only viable conclusion is that the time-based strategy has a highly controversial relationship with the systems engineering capabilities and, if there is one innovation capability that is incompatible with the practice of systems engineering, this is the only potential candidate. **Proposition 4**, therefore, remains unproven.

6 Conclusion

6.1 Final conclusions

In order to investigate the relationship between systems engineering and innovation, this study adopted two perspectives; a process-oriented view and a capability-oriented view. In line with that, a theoretical framework based on four literature-based models was built; one for each of the two nodes of the relationship (innovation and systems engineering) and from both perspectives. Crossing the process-oriented model of systems engineering with the process-oriented model of innovation it was possible to investigate the relationship from the process-oriented perspective. Similarly, crossing the capability-oriented model of systems engineering with the capability-oriented model of innovation it was possible to analyse the relationship from the capability-oriented perspective. Each of these two crossings, in turn, is derived into two theoretical propositions. Propositions 1 and 3 were focused on the strength and nature of the key relationship whilst propositions 2 and 4 intended to identify any weaknesses in the relationship.

This research construct was applied in Åsgard subsea compression project, a large project currently in execution in Norway whose scope is the development and delivery of the first subsea system that will meet completely the need for an entire gas compression platform. Because this project is considered highly complex from a systems perspective and because it is considered highly innovative, it was chosen as the sole unit of analysis for the present investigation. The research, therefore, was carried out as a single case study in Åsgard project.

From the process-oriented view, the conclusion from the thorough analysis is that in Åsgard project the systems engineering and innovation processes are in general highly synergic. However, the data provided moderate evidences that in particular the second stage of the systems engineering process, namely “upper-level system element development” (which in Åsgard context has been rephrased as “analysis and design of process system, power system, control system and layout”), either has no synergy at all or a minor conflict with the innovation process.

From the capability-oriented view, the conclusion is that the capabilities required for the practice of systems engineering are not the same as those required for innovation, but the majority of them are mutually supportive. In the search for one innovation capability that is incompatible with the practice of systems engineering, the time-based strategy outstood as a controversial candidate, for which strong but mixed evidences were found, leading to the conclusion that there is something hidden in this particular relationship and this is probably a interesting object for future studies.

Overall, the first conclusion that can be drawn from this study is that in Åsgard project the practice of systems engineering supports innovation as well as its innovative culture supports the practice of systems engineering. A second conclusion is that it is possible for the project to build and sustain in the same team the capabilities necessary for the practice of systems engineering and the capabilities required for innovation, since most of them are mutually supportive. A third conclusion is that the very common preconception that the additional discipline introduced by systems engineering inhibits innovation, in Åsgard, is proven incorrect; on the contrary, this very discipline helps streamline the innovation process making it both more effective and more efficient.

Having these three major conclusions been drawn, it is of high importance to beware the difference between their internal and external validity (Yin, 2009; Wilson, 2010). Since this study has been performed in one single case, the conclusions are valid only for this particular study's unit of analysis, i.e. Åsgard project. In other words, the conclusions are backed by empirical evidences that guarantee their validity only within the boundaries of this project. Therefore no normative conclusion can be drawn from this study about the relationship between systems engineering and innovation in general or in other cases in particular.

6.2 Discussions and implications

A number of interesting discussions emerge from the conclusions of this study as much as from the points that remain inconclusive.

The first is the implications for professional managers. The conclusions that in Åsgard there are strong synergies between the systems engineering- and the innovation processes and that discipline does not inhibit innovation imply that the same may (though do not necessarily do) hold true for other projects, and therefore managers cannot take as granted that systems engineering is an inappropriate approach when the project needs to be innovative. The second implication is that systems engineering may be more important for projects involving novel technologies than projects involving established technologies.

A number of implications are also relevant for researchers. The first and probably most obvious is that if this study has been able to draw strong conclusions about Åsgard project, the same investigation can be carried out in other cases. With results from a number of cases, the case-specific conclusions that are consistent across the cases can be drawn as normative conclusions; and the reasons for the conflicting results, if any, can be investigated. A second interesting implication for researchers, which might lead to a more focused study, is the particular relationship between the time-based strategy and systems engineering. The evidences found in this study for this particular relationship, being at the same time strong and antagonistic, are provocative and calls for a separate study intended to better understand the nature and dynamics of this relationship.

When looking at the conclusions of this research in the light of the previous studies, a number of relevant references can be made. Walden (1998, 1999) concluded that systems engineering is basically consistent with innovation, with the recognition that radical innovation may require special consideration. Whilst the present study strongly supports the first part of his conclusion, it does not support the second. Åsgard project is considered a radical innovation in the sense that never in the oil and gas industry history the complete functionality of a platform had been replaced by a subsea system. Furthermore, if this technology becomes a trend and the gas platforms (and potentially oil platforms too) start being replaced by subsea systems, this would be a revolution in the oil and gas industry. That being said, systems engineering seems to be more important in Åsgard, a radical innovation project, than in conventional subsea projects where light incremental innovation takes place.

Stajnko & Doukas (2001) argued that because innovation is the way that a business turns its vision into reality and this often can be complex and limitless in its application and scope, systems engineering is critical in helping to aim the innovation effort in the right direction. The present study has found that understanding risk and reward and being good decision maker are some of the key capabilities for innovation. If the innovators' main challenge is steering their efforts in the right direction, understanding risk and reward and being good decision maker are certainly the most important capabilities. Furthermore, if this study has indicated that in Åsgard systems engineering supports the decision making process, then it does support innovation according to Stajnko and Doukas' (2001) logic.

Cropley & Cropley (2000) made a parallel between the systems engineering process and the innovation process, being the latter strongly focused on creativity. Their conclusion was that there is a strong alignment between the systems engineering- and innovation processes, the very same conclusion found by the present study.

Schoening & Miller (1993) defended that a disciplined use of the systems engineering process at the very beginning helps identify top-level changes in requirements allocation that lead to new and innovative solutions. All the data acquired from the questionnaires and both interviews carried out in the present study support the notion that the first steps of the systems engineering process, i.e. the top-level requirements capture and allocation, are crucial for understanding the problem and finding innovative solutions.

Blanchard & Fabrycky (2006) state that without a proper organisational emphasis from the top-down, the establishment of an environment that will allow for creativity and innovation, a leadership style that will promote a “team” approach to design and so on, the implementation of the systems engineering concepts and methodologies will not occur. The conclusion from the present study that the practice of systems engineering helps innovation performance as much as an innovative culture helps systems engineering supports Blanchard’s & Fabrycky’s proposition.

In sum, the key findings of the present study, in general, support the previous studies that investigated the relationship between systems engineering and innovation, with minor localised exceptions (e.g. Walden, 1998, 1999). Overall, this study contributes with further empirical evidences and case-specific conclusions to the body of knowledge on innovation and on systems engineering.

References

Abramowitz, W. (1956). Resource and output trends in the U.S. since 1870. *American Economic Review*, *May*.

Ansoff, H. I. (1992). Managing discontinuous strategic change. In H. I. Ansoff, A. Biseman & P. M. Storm (Eds.), *Understanding and managing strategic change*. Amsterdam: Noth-Holland Publishing Company.

Barney, J. B., & Clark, D. N. (2007). *Resource-based theory: creating and sustaining competitive advantage*. New York, NY: Oxford University Press Inc.

Becker, H. S. (1958). Problems of inference and proof in participant observation. *American Sociological Review, 23*, 652-660.

Becker, H. S. (1967). Whose side are we on? *Social Problems, 14*, 239-247.

Blanchard, B. S., & Fabrycky, W. J. (2006). *Systems engineering and analysis* (Fourth ed.). Upper Saddle River, NJ: Pearson Education Inc.

Boehm, B. W. (1986). A spiral model of software development and enhancement. *ACM SIGSOFT Software Engineering Notes 11*(4).

Carter, C. F., & Williams, B. R. (1959). *Science in industry policy for progress*. London: Oxford University Press.

Clark, J. (1979). A model of embodied technical change and employment. *Science Policy Research Unit*. Brighton: University of Sussex.

Clark, K. B., & Fujimoto, T. (1989). Lead time in automobile product development: exploring the Japanese advantage. *Journal of Engineering and Technology Management, 6*, 25-58.

Clark, K. B., & Fujimoto, T. (1991). *Product development performance*. Boston, MA: Harvard Business School Press.

Cooper, R. (1988). *Winning at new products*. London: Kogan Page.

Crawford, C. M. (1992). The hidden costs of accelerated product development. *Journal of Product Innovation Management, 9*, 188-199.

Cropley, A. J. (1995). "Kreativität" [Creativity]. In M. Amelang (Ed.), *Encyclopedia of Psychology v.8* (pp. 329-373). Göttingen: Hogrefe.

Cropley, A. J. (1999). Creativity and cognition: producing effective novelty. *Röper Review, 21*, 253-260.

Cropley, D. H., & Cropley, A. J. (1998). *Teaching engineering students to be creative: program and outcomes*. Paper presented at the Australasian Association for Engineering Education 10th Annual Conference.

Cropley, D. H., & Cropley, A. J. (2000). *Creativity and innovation in the systems engineering process*. Paper presented at the 10th Annual International Symposium of the International Council on Systems Engineering, Minneapolis, MN.

Cropley, D. H., Priest, S., & Cropley, A. J. (1997). *Fostering creativity and innovation in engineering students*. Paper presented at the Australasian Association for Engineering Education 9th Annual Conference.

Denilson, E. (1962). The source of economic growth in the United States. New York, NY: Comittee for Economic Development.

Dewey, J. (1935). *Liberalism and social action*. New York, NY: G. P. Putnam's Sons.

DoD, (2002), Mandatory procedures for major defense acquisition programs (mdaps) and major automated information system (mais) acquisition programs. U.S. Department of Defense.

Dorf, R. (Ed.). (1998). *Technology management handbook*. FL: CRC Press and IEEE Press.

Drucker, P. (1974). *Management, tasks, responsibilities, practices*. New York: Harper & Row.

DSMC. (1990). *Systems engineering management guide*. Defense Systems Management College, Superintendent of Documents. Washington, DC: U.S. Government Printing Office.

Dumaine, B. (1989). How managers can succeed through speed. *Fortune, 13.* .

Durkheim, É. (1938). *The rules of sociological method*. Chicago, IL: University of Chicago Press.

EIA. (2002). 731.1 Systems Engineering Capability Maturity Model (Vol. 1). Arlington, VA: Electronic Industries Alliance.

EIA/IS. (1994). 632 Systems Engineering. Arlington, VA: Electronic Industries Alliance.

Feigenbaum, E., McCorduck, P., & Nii, H. P. (1988). *The rise of the expert company*. London: Macmillan.

Freeman, C., Clark, J., & Soete, L. (1992). *Unemployment and technical innovation*. London: Frances Pinter.

Galanakis, K. (2006). Innovation process. Make sense using systems thinking. *Technovation, 26*, 1222-1232.

Gaynor, G. (Ed.). (1996). *Handbook of technology management*. New York, NY: McGraw-Hill.

Gold, B. (1987). Approaches to accelerating new product development. *Journal of Product Innovation Management, 4*, 81-88.

Gouldner, A. W. (1957). Theoretical requirements of the applied social sciences. *American Sociological Review, 22*(1), 92-102.

Graves, A. (1987). Comparative trends in automotive research and development. *Science Policy Research Unit*. Brighton: University of Sussex.

Graves, A. (1991). *International competitiveness and technology development in the world automobile industry.* D.Phil., University of Sussex, Brighton.

Griliches, Z. (1958). Research costs and social returns: hybrid corn and related innovations. *Journal of Political Economy, 66*(5), 419-431.

Gupta, A. S. K., & Wileman, D. L. (1990). Accelerating the development of technology-based new products. *California Management Review, 32*(2), 24-44.

Heirman, A., & Clarysse, B. (2007). Which tangible and intangible assets matter for innovation in start-ups? *The Journal of Product Innovation Management, 24*, 303-315.

Hippel, E. v. (1988). *The sources of innovation*. New York, NY: Oxford University Press.

Hippel, E. v. (2005). *Democratizing innovation*. Cambridge, MA: MIT Press.

Hoholm, T., & Olsen, P. I. (2012). The contrary forces of innovation: a conceptual model for studying networked innovation processes. *Industrial Marketing Management*.

Howell, J. M., & Boies, K. (2004). Champions of technological innovation: the influence of contextual knowledge, role orientation, idea generation, and idea promotion on champion emergence. *The Leadership Quarterly, 14*, 123-143.

Humphrey, W. S. (1987). *Managing for innovation: leading technical people*. NJ: Prentice-Hall.

IEEE. (1994). P1220 Standard for Application and Management of the Systems Engineering Process. New York, NY: Institute of Electrical and Electronic Engineers.

Imai, K., Nonaka, I., & Fakeuchi, H. (1985). Managing the new product development. In K. Clark & F. Hayed (Eds.), *The uneasy alliance*. Boston, MA: Harvard Business School Press.

INCOSE. (2011). TP-2003-002-03.2.2 Systems engineering handbook: a guide for system life cycle processes and activities (3.2.2 ed.).

ISO/IEC. (2008). 15288:2008 Systems and software engineering - System life cycle processes.

Jaffe, A. B. (2000). The U.S. patent system in transition: policy innovation and the innovation process. *Research Policy, 29*, 531-557.

Juster, N. P. (1992). A summary of rapid prototyping processes. *Computer aided Rapid Prototyping, Department of Mechanical Engineering*. Leeds: University of Leeds.

Katz, R. (Ed.). (1988). *Managing professionals in innovative organizations*. New York, NY: Harper.

Kline, S. J., & Rosenberg, N. (1986). An overview of innovation. In R. Landau & N. Rosenberg (Eds.), *The positive sum strategy*. Washington, DC: National Academy Press.

Knight, K. E. (1967). A descriptive model of the intra-firm innovation process. *The Journal of Business, 40*(4), 478-496.

Kruth, J. P. (1991). Material increase manufacturing by rapid prototyping techniques. *Annals of the CIRP (Collège International pour l'Étude Scientifique des Techniques de Production Méchanique), 40*(2), 603-614.

Lamming, R. (1992). *Supplier strategies in the automotive components industry: development towards lean production.* D.Phil., University of Sussex, Bighton.

Lima, F. S., Storstenvik, A., & Nyborg, K. O. (2011). *Subsea compression: a game changer*. Paper presented at the Offshore Technology Conference Brasil 2011, Rio de Janeiro.

MacKinnon, D. (1962). Intellect and motive in scientific inventors: implications for supply. *The rate and direction of inventive activity: economic and social factors*: Princeton University Press (for the National Bureau of Economic Research).

Maier, H. (1988). *Partnership between small and large firms: current trends and prospects*. Paper presented at the Conference on Partnerships between Small and Large Firms, Brussels.

Makadok, R. (2001). Towards a synthesis of the resource-based and dynamic-capability views of rent creation. *Strategic Management Journal, 22*, 387-401.

Mansfield, E. (1988). The speed and cost of industrial innovation in Japan and the United States: external vs. internal technology. *Management Science, 34*(19), 1157-1168.

McDonough, E. F., & Barczac, G. (1991). Speeding up new product development: the effects of leadership style and source of technology. *Journal of Product Innovation Management, 8*, 203-211.

McDonough, E. F., & Spital, F. C. (1984). Quick-response new product development. *Harvard Business Review, 62*, 52-53.

Mensch, G., Kaash, K., Kleinknecht, A., & Schnapps, R. (1980). Innovation trends and switching between full- and under-employment equilibrium. *International Institute of Management, Discussion Paper Series*. Berlin.

Meredith, J., & Mantel, S. (1995). *Project management* (Third ed.). New York, NY: John Wiley & Sons.

Millson, M. R., Raj, S. P., & Wileman, D. (1992). A survey of major approaches for accelerating new product development. *Journal of Product Innovation Management, 9*, 53-69.

Mowery, D. C., & Rosenberg, N. (1978). The influence of market demand upon innovation: a critical view of some recent empirical studies. *Research Policy, 8*.

NASA. (2007). SP-2007-6105 Systems Engineering Handbook.

Nelson, R. (1959). The economics of invention: a survey of the literature. *Journal of Business, 32*(2), 101-127.

Ogburn, W. F. (1953). *Social change*. New York, NY: Viking Press.

Oppenheimer, R. (1955). Prospects in the arts and science. *Perspectives USA, 5*, 10-11.

Packard, H. (1988). Hewlett Packard and engineering productivity. Palo Alto, CA: Hewlett Packard.

Packard, H. (1989). *The promise and measure of CAD*. Paper presented at the 1st Co. Graphics Symposium, Milano.

Peng, M. W. (2009). *Global strategic management* (Second ed.): Cengage Learning.

Peters, T. J., & Waterman, R. W. (1982). *In search for excellence*. New York, NY: Harper and Row.

PMI. (2004). A guide to the project management body of knowledge: PMBOK guide. Newtown Square, PA: Project Management Institute Inc.

Prahalad, C. K., & Hamel, G. (1990). The core competence of the corporation. *Harvard Business Review, June*, 79-91.

Rothwell, R. (1986). Innovation and re-innovation: a role for the user. *Journal of Marketing Management, 2*(2), 109-123.

Rothwell, R. (1989). SMFs, inter-firm relationships and technological change. *Entrepreneurship and Regional Development, 1*, 275-291.

Rothwell, R. (1994). Towards the fifth-generation innovation process. *International Marketing Review, 11*(1), 7-31.

Rothwell, R., & Gardiner, P. (1988). The strategic management of re-innovation. *R&D Management, 18*(2), 147-160.

Rothwell, R., & Soete, L. (1983). Technology and economic change. *Physics in Technology, 14*(6), 270-277.

Rothwell, R., & Teubal, M. (1977). SAPPHO revisited: a re-appraisal of the SAPPHO data. In K. A. Stroetman (Ed.), *Innovation, economic change and technology policies*. Basel and Stuttgart: Birkhäuser.

Ruffles, P. C. (1986). Reducing the cost of aero engine design. *Aerospace, 13*(9), 10-19.

Salter, W. E. G. (1960). *Productivity and technical change*. London: Cambridge University Press.

Schlaifer, R., & Heron, R. (1950). *The development of aircraft engines and fuels*. Cambridge, MA: Harvard Business School.

Schoening, W. W., & Miller, A. J. (1993). *Using systems engineering to expand opportunities for innovation*. Paper presented at the 3rd Annual International Symposium of the National Council on Systems Engineering, Arlington, VA.

Selznick, P. (1957). *Leadership in administration*. New York, NY: Harper and Row.

Shapero, A. (1988). Managing creative professionals. In R. Katz (Ed.), *Managing professionals in innovative organizations*. New York, NY: Harper.

Shaw, B. (1986). *The role of the interaction between the manufacturer and the user in the medical instrument manufacturing process.* D.Phil., University of Sussex, Brighton.

Shenhar, A. (1996). Management of technology and innovation: Course handouts, MOT 8232, University of Minnesota, Spring.

Smith, A. (1776). *An inquiry into the nature and causes of the wealth of nations*: Random House Inc.

Solow, R. (1957). Technical change and the aggregate production function. *Review of Economics and Statistics, 39*(3), 312-320.

Solow, R. (1962). Gearing military R&D to economic growth. *Harvard Business Review, December*.

Sommerlatte, T. (1990). Raising technology development productivity. Luxembourg.

Souitaris, V., & Maestro, B. W. M. (2010). Polychronicity in top management teams: the impact on strategic decision processes and performance of new technology ventures. *Strategic Management Journal, 31*, 652-678.

Stajnko, F., & Doukas, L. (2001). *Innovation and soft systems engineering*. Paper presented at the 11th Annual International Symposium of the International Council on Systems Engineering, Melbourne.

Stalk, G., Evans, P., & Shulman, L. E. (1992). Competing on capabilities: the new rules of corporate strategy. *Harvard Business Review, 70*(2), 57-69.

Stalk, G., & Hout, T. M. (1990). Competing against time. *Research Technology Management, March-April*, 19-24.

Statoil. (2010, December 1st). Statoil awards Åsgard contract. Retrieved February 25th, 2012, from http://www.statoil.com/en/NewsAndMedia/News/2010/Pages/01DecAasgardContract.aspx

Teece, D. L., Pisano, G., & Shuen, A. (1997). Dynamic capabilities and strategic management. *Strategic Management Journal, 18*, 509-533.

Tushman, M. L., & Moore, W. L. (Eds.). (1988). *Readings in the management of innovation* (Second ed.). New York, NY: Harper.

Walden, D. D. (1998). *Innovation in the context of systems engineering*. Paper presented at the 8th Annual International Symposium of the International Council on Systems Engineering, Vancouver, BC.

Walden, D. D. (1999). *The impact of Systems Engineering Capability Model on innovation*. Paper presented at the 9th Annual International Symposium of the International Council on Systems Engineering, Brighton.

Welles, J., Marts, L., Waterman, R., Gilmore, J., & Venuti, R. (1963). Commercial application of missile-space technology. Denver, CO: Denver Research Institute.

Wideman, R. M. (2004, February 1st). The role of project life cycle (life span) in project management. Retrieved February 18th, 2012, from http://www.maxwideman.com/papers/plc-models/1990s.htm

Wilson, J. (2010). *Essentials of business research: a guide to doing your research project*. London: SAGE Publications Ltd.

Yin, R. K. (2009). *Case study research: design and methods* (Fourth ed.). Thousand Oaks, CA: SAGE Publications Inc.

APPENDIX A BLANK MATRICES

Table 6 Synergies between systems engineering process and innovation process

SCALE: +3 : One works as an engine for the other +2 : One often has a positive influence on the other +1 : One may eventually contribute to the other 0 : Both may coexist but they do not influence one another -1 : One may inhibit the other -2 : One often inhibits the other -3 : One always, invariably inhibits the other	Lean and swift tendering process	Lean and swift research and development	Lean and swift component development and design	Lean and swift fabrication planning	Lean and swift procurement of components	Lean and swift construction and assembly
General system analyses and solution screening						
Analysis and design of process system, power system, control system and layout						
Detail design and qualification of individual components (compressors, pumps, separators, heat exchangers, instruments, connectors, etc)						
Procurement and/or construction and factory acceptance test of lower-level components						
Assembly and factory acceptance testing and functional testing (whenever applicable) of modules						
Assembly of compressor trains and system integration testing						

Table 7 Compatibility between systems engineering capabilities and innovation capabilities

SCALE: +3 : Are essentially the same thing +2 : Are not the same but support each other +1 : Often coexists in the same team but do not support each other 0 : May coexists in the same team but do not influence each other -1 : Are partially incompatible but often teams manage to conciliate both -2 : Are completely incompatible and a team will hardly manage to conciliate both	Time-based strategy (faster, more efficient product development)	Development focus on quality and other non-price factors	Emphasis on corporate flexibility and responsiveness	Customer focus at the forefront of strategy	Strategic integration with primary suppliers	Strategies for technological collaboration with external parties	Electronic data processing strategies (databases, CAD, CAM, FEM, CFD, etc)	Policy of total quality control
Ability to explore the technical problem domain								
Ability to explore the technical solution domain								
Ability to manage technical effort								
Ability to continuously improve technical effort								
Ability to manage the interface engineering-business								

APPENDIX B ANALYSES

B1 Mode

Table 8 Process-oriented view: mode

Synergies between systems engineering process and innovation process							
SCALE: +3 : One works as an engine for the other +2 : One often has a positive influence on the other +1 : One may eventually contribute to the other 0 : Both may coexist but they do not influence one another -1 : One may inhibit the other -2 : One often inhibits the other -3 : One always, invariably inhibits the other	Lean and swift tendering process	Lean and swift research and development	Lean and swift component development and design	Lean and swift fabrication planning	Lean and swift procurement of components	Lean and swift construction and assembly	∑
General system analyses and solution screening	3	2	1	0	1	2	9
Analysis and design of process system, power system, control system and layout	1	2	2	0	0	0	5
Detail design and qualification of individual components (compressors, pumps, separators, heat exchangers, instruments, connectors, etc)	1	3	3	1	2	2	12
Procurement and/or construction and factory acceptance test of lower-level components	0	1	1	2	3	2	9
Assembly and factory acceptance testing and functional testing (whenever applicable) of modules	0	1	-1	0	1	2	3
Assembly of compressor trains and system integration testing	0	0	-1	2	1	3	5
∑	5	9	5	5	8	11	

Table 9 Capability-oriented view: mode

Compatibility between systems engineering capabilities and innovation capabilities									
SCALE: +3 : Are essentially the same thing +2 : Are not the same but support each other +1 : Often coexists in the same team but do not support each other 0 : May coexists in the same team but do not influence each other -1 : Are partially incompatible but often teams manage to conciliate both -2 : Are completely incompatible and a team will hardly manage to conciliate both	**Time-based strategy (faster, more efficient product development)**	**Development focus on quality and other non-price factors**	**Emphasis on corporate flexibility and responsiveness**	**Customer focus at the forefront of strategy**	**Strategic integration with primary suppliers**	**Strategies for technological collaboration with external parties**	**Electronic data processing strategies (databases, CAD, CAM, FEM, CFD, etc)**	**Policy of total quality control**	∑
Ability to explore the technical problem domain	-1	1	2	3	2	2	2	1	12
Ability to explore the technical solution domain	-1	2	2	0	2	2	3	2	12
Ability to manage technical effort	-1	2	2	0	2	2	2	2	11
Ability to continuously improve technical effort	-1	2	0	0	1	0	2	2	6
Ability to manage the interface engineering-business	2	1	2	0	1	0	0	2	8
∑	-2	8	8	3	8	6	9	9	

B2 Standard deviation

Table 10 Process-oriented view: standard deviation

Synergies between systems engineering process and innovation process							
Standard deviation	Lean and swift tendering process	Lean and swift research and development	Lean and swift component development and design	Lean and swift fabrication planning	Lean and swift procurement of components	Lean and swift construction and assembly	∑
General system analyses and solution screening	1,7	0,9	0,7	1,1	1,2	1,3	6,9
Analysis and design of process system, power system, control system and layout	0,7	1,3	1,5	0,4	0,7	0,7	5,4
Detail design and qualification of individual components (compressors, pumps, separators, heat exchangers, instruments, connectors, etc)	1,3	1,9	0,8	1,5	1,3	1,3	8,3
Procurement and/or construction and factory acceptance test of lower-level components	1,1	1,4	1,5	0,7	0,9	1,6	7,3
Assembly and factory acceptance testing and functional testing (whenever applicable) of modules	1,3	1,3	1,3	1,1	0,8	0,7	6,6
Assembly of compressor trains and system integration testing	1,3	1,5	1,3	0,5	1,1	0,5	6,4
∑	7,5	8,4	7,2	5,5	6,1	6,2	

Table 11 Capability-oriented view: standard deviation

Compatibility between systems engineering capabilities and innovation capabilities									
Standard deviation	Time-based strategy (faster, more efficient product development)	Development focus on quality and other non-price factors	Emphasis on corporate flexibility and responsiveness	Customer focus at the forefront of strategy	Strategic integration with primary suppliers	Strategies for technological collaboration with external parties	Electronic data processing strategies (databases, CAD, CAM, FEM, CFD, etc)	Policy of total quality control	∑
Ability to explore the technical problem domain	1,5	0,8	0,4	1,3	1,3	0,7	0,7	1,1	8,0
Ability to explore the technical solution domain	1,5	0,4	0,5	1,0	1,5	0,4	0,5	1,3	7,3
Ability to manage technical effort	1,5	1,1	0,5	1,1	1,6	1,1	1,1	1,6	9,8
Ability to continuously improve technical effort	1,9	1,1	0,9	0,9	0,8	1,3	0,9	0,8	8,7
Ability to manage the interface engineering-business	1,6	0,7	0,9	1,3	0,8	0,8	1,1	0,4	7,8
∑	8,1	4,2	3,3	5,7	6,2	4,4	4,3	5,4	

B3 Significance

Table 12 Process-oriented view: significance

Synergies between systems engineering process and innovation process							
SIGNIFICANCE $f(x) = mode(x) \cdot [stdev(x)]^{-1}$	Lean and swift tendering process	Lean and swift research and development	Lean and swift component development and design	Lean and swift fabrication planning	Lean and swift procurement of components	Lean and swift construction and assembly	∑
General system analyses and solution screening	1,1	2,5	2,0	0,0	0,7	1,2	7,4
Analysis and design of process system, power system, control system and layout	2,0	1,2	0,9	0,0	0,0	0,0	4,0
Detail design and qualification of individual components (compressors, pumps, separators, heat exchangers, instruments, connectors, etc)	0,6	0,8	4,3	0,4	1,1	1,2	8,4
Procurement and/or construction and factory acceptance test of lower-level components	0,0	0,5	0,5	4,0	3,8	0,7	9,4
Assembly and factory acceptance testing and functional testing (whenever applicable) of modules	0,0	0,6	-0,6	0,0	1,4	4,0	5,4
Assembly of compressor trains and system integration testing	0,0	0,0	-0,6	6,7	0,8	10,0	16,8
∑	3,6	5,6	6,4	11,1	7,7	17,1	

Table 13 Capability-oriented view: significance

Compatibility between systems engineering capabilities and innovation capabilities									
SIGNIFICANCE $f(x) = mode(x) \cdot [stdev(x)]^{-1}$	Time-based strategy (faster, more efficient product development)	Development focus on quality and other non-price factors	Emphasis on corporate flexibility and responsiveness	Customer focus at the forefront of strategy	Strategic integration with primary suppliers	Strategies for technological collaboration with external parties	Electronic data processing strategies (databases, CAD, CAM, FEM, CFD, etc)	Policy of total quality control	∑
Ability to explore the technical problem domain	-0,4	1,4	10,0	1,8	1,1	4,0	4,0	0,8	22,6
Ability to explore the technical solution domain	-0,4	10,0	6,7	0,0	0,9	10,0	10,0	1,2	38,3
Ability to manage technical effort	-0,4	1,7	6,7	0,0	0,7	1,5	1,7	0,7	12,6
Ability to continuously improve technical effort	-0,3	1,5	0,0	0,0	1,4	0,0	2,5	2,9	8,0
Ability to manage the interface engineering-business	0,7	2,0	2,5	0,0	1,4	0,0	0,0	10,0	16,7
∑	-0,8	16,6	25,8	1,8	5,6	15,5	18,2	15,5	

APPENDIX C INTERVIEW BACKBONE

Introductory questions:

1. What do you understand by Innovation in the subsea context? Do you think Åsgard is an innovative project? Why?

2. What do you understand by Systems Engineering in the subsea context? Do you think we practice SE in Åsgard? How?

Process-oriented view:

1. Systems engineering processes in general does not have strong synergies with lean and swift tendering process innovation

2. System analysis does not have strong synergies with innovation in general

3. Detail design and qualification of components has some synergy with lean and swift component design and development

4. Assembly of trains and SIT have strong synergy with lean and swift fabrication planning

5. Assembly of trains and SIT have very strong synergy with lean and swift construction and assembly

6. Systems engineering processes have strong synergies with innovation processes (19x11x6)

Capability-oriented view:

1. What capabilities do you think an organisation should have to practice systems engineering?

2. What capabilities do you think an organisation should have to be innovative?

3. Time-based strategy (faster, more efficient product development) is not compatible with systems engineering capabilities.

4. The ability to explore the technical solution domain seems to be more compatible with innovation capabilities than the ability to explore the problem domain.

5. The systems engineering capabilities seem to have neutral compatibility with customer focus.

6. SE capabilities are strongly compatible with innovation capabilities (27x8x5)

Final questions:

1. What do you think systems engineering have to do with innovation in Åsgard context? Do you think this relationship would be different in other project?

2. Do you think the practice of systems engineering fosters innovation in Åsgard?

3. Do you think we have an innovative working environment and culture in Åsgard? Do you think it facilitates the practice of systems engineering?