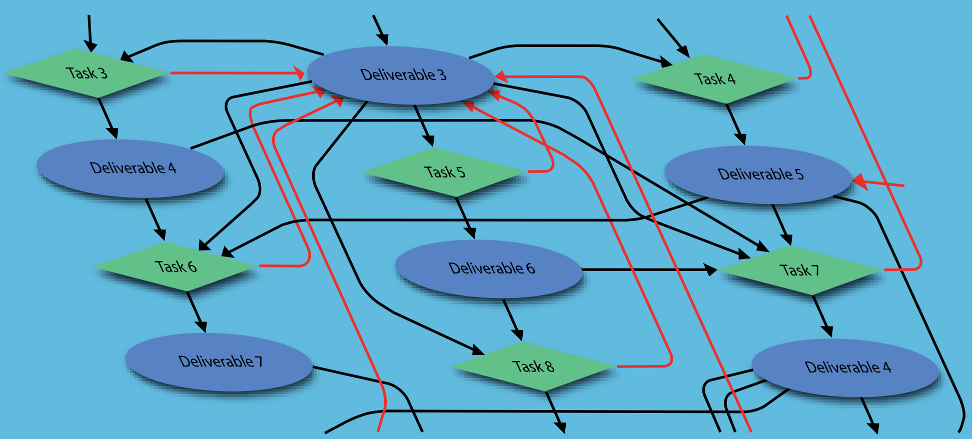
Modelling and Management of Engineering Processes

Concepts, Tools and Case Studies



Peter Heisig and
John Clarkson (Eds)

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Department of Engineering, University of Cambridge
Cambridge, United Kingdom

Peter Heisig and P. John Clarkson (Eds.)

Dr. Peter Heisig
University of Leeds
Socio-Technical Centre
Leeds University Business School
Leeds LS2 9JT

Prof. P. John Clarkson
University of Cambridge
Cambridge Engineering Design Centre
Department of Engineering
Cambridge CB2 1PZ

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Engineering Design Centre, University of Cambridge, UK

Preface

The importance of innovative processes for design and engineering in ensuring business success is increasingly recognised in today's competitive environment. However, academia and management need to gain a more profound understanding of these processes and develop better management approaches to exploit such business potential.

The aim of this *Second International Workshop on the Modelling and Management of Engineering Processes* is to showcase recent trends in the modelling and management of engineering processes, explore potential synergies between different modelling approaches, gather and discuss future challenges for the management of engineering processes and identify future research directions.

This International Workshop on Modelling and Management of Engineering Processes (MMEP) is being organised by the Engineering Design Centre at the University of Cambridge, the Socio-Technical Centre at Leeds University Business School and the Chair for Information Technologies in Mechanical Engineering at the Otto-von-Guericke-Universität in Magdeburg on behalf of the Design Society's Special Interest Group of the same name.

This workshop aims to continue working along the research roadmap for the Modelling and Management of Engineering Processes. During March 2009 a series of industry workshops were held in the UK, Sweden and Germany in order to identify future research needs, assisted by representatives from 27 companies from within the manufacturing, service and healthcare sectors. A preliminary roadmap was presented to and discussed with the research community in August 2009 at the ICED Conference in the US, and a joint white paper drafted (Heisig *et al.* 2009)[1].

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[1] Heisig P, Clarkson PJ, Hemphälä J, Wadell C, Norell-Bergendahl M, Roelofsen J, Kreimeyer M, Lindemann U (2009) Challenges and future fields of research for modelling and management of engineering processes, 2nd edn. Workshop Report CUED/C-EDC/TR 148, Cambridge Engineering Design Centre, Department of Engineering, University of Cambridge, UK

This first MMEP conference was launched in 2010 as a bi-annual series providing an international platform to highlight and discuss industry best practice alongside leading edge academic research.

The papers in the proceedings have been submitted and undergone a double-blind review and discussed at the Workshop. Based on this feedback, each author has revised their paper and contributed to this final edition of the workshop proceedings. They represent a sample of leading national and international research in the fields of engineering design, process modelling in engineering design and product development, and areas addressing the following topics:

Albers, Braun and Pinner describe the Integrated Product Engineering Model (iPeM) aimed to handle the complexity of engineering processes through modelling information based on a prototypic implementation.

Campean and Henshal present an integrated framework for systems engineering design based on a Failure Mode Avoidance (FMA) framework underpinned by a structured approach to function analysis of complex multi-disciplinary systems with an example from automotive systems design.

Capjon and Hjelseth describe an simulation solution called Plant of Collaborative Conceptualisation (PoCC) supporting human ideation and participative design using a 360 degree simulator applied to maritime design.

Da Silva Vieira explores the interrelations between ambiguity, risk and change and their influence towards the completion of design issues in design meetings.

Gericke and Moser provide a case study from a small engineering company on how the engineers adopt design methodologies to different projects as a contribution for tailoring of a branch specific design approach.

Helten and Lindemann report on the first results from developing an instrument to assess the success of the introduction process of Lean Development.

Meboldt, Matthiesen and Lohmeyer draw from their industry experience to review the dilemma of managing iterations in product development processes and suggest strategies to deal with iterations under time pressure.

Oehmen and Ben-Daya propose a taxonomy for risks in product design and development which are prioritised based on an industry survey.

Szélig, Schabacker and Vajna describe a Tri-Process Modeling Tool for process optimization in product development projects.

Tahera, Earl and Eckert study focuses on the integration of physical and virtual testing to support the testing and subsequent design phases of product development.

Yang, Benjamin and Roberts reports research findings of innovation management of small and medium sized enterprises in the home healthcare sector identifying opportunities for improvement by better understanding the needs of users and carers.

Finally, we would like to thank all those authors and reviewers who have contributed to the preparation of this book, and also Anna Walczyk and Mari Huhtala who transformed a disparate set of initial drafts into a coherent and attractive book.

Peter Heisig and John Clarkson
The MMEP 2012 Editorial Committee, March 2013

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Part I

Conceptual Papers

Chapter 1

Developing a Taxonomy for Risks in Product Design and Development

J. Oehmen and M. Ben-Daya

1.1 Introduction

It is generally acknowledged that risks and their (mis-)management play a very significant role in the management of large-scale design, product development and engineering programs. When reviewing struggling or failed programs, “risks” are generally cited as one of the main reasons for those troubles (GAO, 2006; Oehmen *et al.*, 2012).

However, there exists no clear framework to discuss and describe these risks, as well as no quantified overview of the significance of different types of risks.

This paper makes a contribution to both areas: It begins with a literature review and discussion on risk definitions that apply to engineering programs, as well as an overview of existing taxonomies. Then, a comprehensive framework for describing engineering program risks is developed. It is based on the definition of risk as the effect of uncertainty on objectives (ISO, 2009), as well as the assumption that the overall objective of engineering programs is to deliver stakeholder value (Murman *et al.*, 2002). This framework is then applied to develop a taxonomy of engineering program risks. The main elements of the taxonomy are the distinction between uncertainties that primarily affect stakeholder needs, thus leading to the “risk of wrong objectives”, as well as uncertainties affecting the engineering program execution, creating “risk of missing objectives”.

In the following part of this paper, a number of those risks are prioritised based on the results of an industry survey. The main risks that are identified are related to customer requirements stability and clarity, as well as suppliers of designs and components.

The paper concludes with a discussion of the contributions and limitations of this paper.

1.2 Overview of Definitions of Risk

Risk is both an every-day as well as a technical term. Colloquially, risk refers to the possibility of a loss (Merriam-Webster, 2014). Table 1.1 summarises a number of risk definitions that apply to product design and development:

Table 1.1. Overview of definitions of risk

Source of definition	Definition of risk
(Kaplan and Garrick, 1981)	Risk is the triplet of (causal) scenario, likelihood and consequence.
(Dezfuli *et al*., 2010)	Risk is the potential for performance shortfalls, which may be realised in the future, with respect to achieving explicitly, established and stated performance requirements.
(Smith and Merritt, 2002)	Risks are defined a simple cause-and-effect chains of events.
(Oehmen *et al*., 2009)	Risks are defined within complex and dynamic causal networks.
(DoD, 2006)	Risk is a measure of future uncertainties in achieving program performance goals and objectives within defined cost, schedule and performance constraints.
(PMI, 2008)	Risk is an uncertain event or condition that, if it occurs, has an effect on at least one project objective: scope, schedule, cost, and quality
(INCOSE, 2007)	Risk is a measure of the uncertainty of attaining a goal, objective, or requirement pertaining to technical performance, cost, and schedule
(ISO, 2009)	Risk is the effect of uncertainty on objectives.

For the purpose of this paper, we adapt the broadest definition (ISO, 2009) to our particular application, as all other definitions can be seen as subsets thereof. Risk in engineering programs is defined as the effect of uncertainties on understanding and delivering stakeholder value.

While other papers focus on the quantification of risks (see for example Kaplan and Garrick, 1981), this paper focuses on developing a taxonomy that allows risk- and program management professionals to capture, analyse and manage risks in a structured fashion.

1.3 Review of Risk Taxonomies in Engineering Programs

A number of structures to collect and describe risks in engineering programs have been put forward and are summarised in Table 1.2. Many standards do not explicitly develop a risk taxonomy, but list types of risks instead:

Table 1.2. Overview of risk taxonomies

Source	**Types of risks / Summary of risk taxonomy**
	Types of risks
(Dezfuli *et al.*, 2010)	Types of risk: safety, technical, cost, and schedule.
(DoD, 2006)	Types of risk: threat, requirements, technical baseline, test and evaluation, modelling and simulation, technology, logistics, production, facilities, concurrency, industrial capabilities, cost, management, schedule, external factors, budget, and earned value management system.
(PMI, 2008)	Types of risk: technical, external, organisational, and project management with their subcategories.
(INCOSE, 2007)	Types of risk: technical, cost, schedule and programmatic, and supportability.
(ISO, 2009)	No specific types or risk taxonomy, as the standard is generic.
(Jiang and Klein, 2000)	Types of risks: various, most significant: lack of expertise, intensity of conflicts, lack of clarity in role definition.
(Tiwana and Keil, 2006)	Types of risks: 1. related technical knowledge; 2. customer involvement; 3. requirements volatility; 4. development methodology fit; 5. formal project management practices; 6. project complexity.
(Sicotte and Bourgault, 2008)	Types of uncertainty: technical and project uncertainty, market uncertainty, fuzziness and complexity
(Keizer *et al.*, 2005)	Types of risks: 1. Commercial viability risks, 2. Competitor risks. 3. Consumer acceptance and marketing risks, 4. Public acceptance risks, 5. Intellectual property risks, 6. Manufacturing technology risks, 7. Organisation and Project management risks, 8. Product family and brand positioning risks, 9. Product technology risks, 10. Screening and appraisal risks, 11. Supply chain and sourcing risks, 12. Trade customer risks.
	Taxonomies
(Yeo and Ren, 2008)	Taxonomy: Project management processes; organisational context; technical content; environment.
(Persson *et al.*, 2009)	Taxonomy: Task, structure, actor, technology.
(Lyytinen *et al.*, 1998)	Taxonomy: Task, actor, structure, technology and their relationship.

The review of the literature clearly shows that there is no clear taxonomy currently available to describe risks in engineering programs in a structured fashion. Existing "taxonomies" are not linked to clear definitions of risks, and most literature sources only present (semi)-structured collections of risks that are neither mutually exclusive nor cumulatively exhaustive.

1.4 Developing a Taxonomy for Engineering Program Risks

For developing a risk taxonomy, we start with the definition of risk as the effect of uncertainty on objectives (see Section 1.2). That leads to the three obvious question: What objectives? What uncertainties? And: What effects?

1.4.1 Objectives of Engineering Programs

While the discussion of the "right objectives" of engineering programs and product development would probably easily fill a book, for our purpose we define the overall objective of product development in the most general terms as generating value for the engineering program stakeholders (Murman *et al.*, 2002).

Value itself can be interpreted in a number of ways, for example as profitable products, cost effectiveness production systems and usable knowledge (Ward, 2007), willingness to pay (Mascitelli, 2006), as the quotient of benefit and cost (Welo, 2011), as the generation of information and reduction of uncertainty (Browning *et al.*, 2002) or as an aggregated function of importance of need, degree of need fulfilment, timeliness and cost (Slack, 1998). For building the risk taxonomy, we define generating value (*i.e.* the overall objective of engineering programs) as fulfilling stakeholder needs (Norman and Draper, 1986; Griffin and Hauser, 1993; Ulrich and Eppinger, 1995).

To operationalize this definition (also see Figure 1.1), we decompose program outcomes into distinct categories in such a way that allows us to describe all relevant programs outcomes in a structured fashion where the different categories are a mutually exclusive and cumulatively exhaustive.

Based on this structure, all relevant engineering program outcomes are captured. In our example, the two top-level categories are program execution attributes (*e.g.* program schedule, program cost), and artefact attributes (*i.e.* attributes of the artefact that is generated by the program (system, product, process, service), such as total weight or technical performance attributes.

Parallel to the concrete engineering program outcomes, the needs of all stakeholders, *i.e.* their preferences, regarding all possible outcomes have to be captured. In our example, we use utility functions (Fishburn, 1970) to describe those preferences and their dependencies.

The overall objective of the engineering program is to maximise the program value, *i.e.* maximise the utility of the program across all stakeholders considering all program outcomes.

This also includes cost or other "negative" attributes (for example total weight), where the utility is inversely related to the realised outcome.

Fundamentally, the model of engineering program objectives is not sensitive towards the particular decomposition that is used to describe program outcomes, or the method used to capture stakeholder needs, as long as consistency is maintained between capturing stakeholder needs and the corresponding outcomes that are achieved by the program.

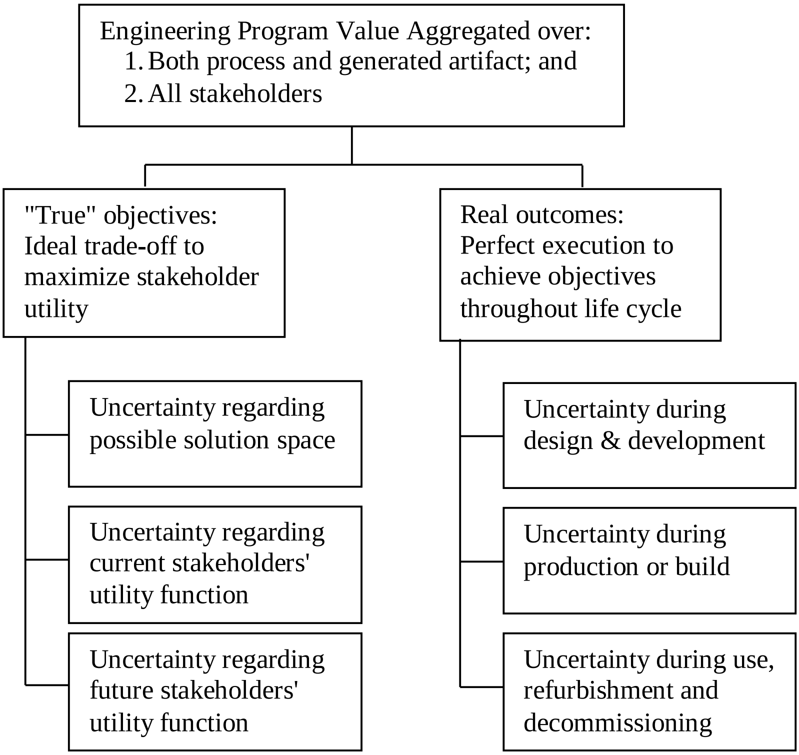

Figure 1.1. The achievement of engineering program value is defined by stakeholder needs and corresponding program outcomes

1.4.2 Uncertainties in Engineering Programs

Given the structure of engineering program objectives introduced above, uncertainties can affect the objectives through two fundamental pathways: By affecting stakeholder needs and/or by affecting the program outcomes. As discussed above, uncertainties (and depending on the definition of objectives, risks) are linked in complex causal networks. These possible interrelationships are not discussed here. Table 1.3 provides a preliminary list of uncertainties in PD programs, taken from the literature summarized in Table 1.2, as well as interactions with an industry focus group. It is broken down by the two pathways, as well as the top-level decomposition of engineering program outcomes (program execution attributes and artefact attributes).

Table 1.3. Examples of uncertainties

Categories of program outcomes objectives:	**Uncertainties affecting definition of stakeholder needs regarding…**	**Uncertainties affecting achievement of program outcome regarding…**
Engineering Program Execution Attributes **(*e.g.* process and organisation quality, execution cost and resource needs, execution lead time)**	• Completeness of program requirements • Stability of existing program requirements • Program execution performance of competition • Quality and frequency of customer interaction • Effectiveness of contracting practices • Quality and accuracy of plans and estimates (*e.g.* regarding cost and schedule)	• Stability of program execution • Organisational integration of the extended enterprise • Overall effectiveness of processes • Roles and responsibilities within the program • Alignment of competency and culture • Integration and effectiveness of process metrics and KPIs
Artefact Attributes **(*e.g.* technical performance, lifecycle cost, availability)**	• Completeness of artefact requirements • Stability of existing artefact requirements • Performance of competing artefacts (*e.g.* competitor product) • Market trends • Quality and accuracy of technical performance estimates (*e.g.* trade-off studies)	• Supplier engineering quality • Effective performance of technology • Effective performance of system after integration

1.4.3 Effects of Uncertainties on Objectives in Engineering Programs

Based on above discussion, uncertainties have a two-fold effect on objectives: First, they affect the quality of the objectives themselves (*i.e.* how well the objectives represent the true stakeholder needs). Second, they affect the quality with which an engineering program achieves those objectives.

In some sources, both "upside risks" (or opportunities) and "downside risks" (*i.e.* risks leading to a decreased overall value) are discussed. The implications for engineering programs are summarised in Table 1.4:

Table 1.4. Categories of uncertainty effects

	Uncertainties affecting definition of stakeholder needs	**Uncertainties affecting achievement of program outcome**
Uncertainty leading to "downside risk"	• System of objectives of program are below overall optimum trade-off value for all stakeholders over the lifecycle of the program	• Actual overall program outcomes fall short of objectives
Uncertainty leading to "upside risk"	• System of objectives of program are below overall optimum trade-off value for all stakeholders over the lifecycle of the program, but happen to align with unanticipated future configuration of stakeholder value	• Actual overall program outcomes exceed objectives

The "downside risks" are uncontroversial - not properly representing stakeholder needs or not achieving the set objectives diminish the actual value that is generated.

Regarding the concept of "upside risks", a "double negative" case is theoretically possible, but probably of mostly of academic interest: The stakeholder needs are not captured properly and subsequently the objectives do not represent the true stakeholder needs. Then the program fails to achieve these objectives, instead delivering results that are closer to the true stakeholder needs that were never properly understood, thus generating more value than initially anticipated. Whether or not the cases of exceeding stakeholder needs and objectives represent a true upside potential is debatable (although it certainly generates more value than falling short). If the objectives exceed the true stakeholder needs, then subsequent trade-off studies did not yield the optimum result. Similarly, if specifications or objectives are exceeded - assuming the objectives were correct - effort was wasted as the results of the program randomly exceeding the objectives, and not achieving the overall balanced optimum.

In some definitions of risk and uncertainty, value is defined as the absence of uncertainty (Browning *et al.*, 2002). In our definition of uncertainty, this would translate into one of the objectives regarding the program execution being a high level of certainty regarding the achievement of the set objectives - or a high level of certainty regarding accurately capturing stakeholder needs and properly translating them into objectives for that matter. In this case, every uncertainty is a "downside risk", as it diminishes the overall value of the program.

1.5 Examples of Prioritised Engineering Program Risks

The following section explores the relative importance of a number of risks in 8 categories, which are summarized in Table 1.5 according to the taxonomy shown in Table 1.3.

Through a survey instrument, data was collected regarding the frequency and impact of a number of example engineering program risks (see Table 1.5). A total of 49 underlying risk factors were explored in the survey, and the results aggregated to the 8 risk categories shown in Table 1.5 below (additional detail can be found in Bassler (2011). The respondents were asked to respond to the survey based on their experience in the last completed engineering program. Occurrence was indicated through a yes/no/no answer question, and the frequency computed based on the overall valid responses. The impact was indicated on a verbalised 1-5 Likert scale ranging from “very low impact (the risk occurred, but could be dealt with in the routine workflow)” to “very high impact (the risk significantly threatened the overall program success)”.

Table 1.5. Example risk categories along taxonomy

	Uncertainties affecting definition of stakeholder needs	**Uncertainties affecting achievement of program outcome**
Engineering program execution attributes		• Company-internal risks: Uncertainty regarding the efficiency and effectiveness of the program processes and their execution, including skill levels and productivity of the workforce. • Supply chain risks: Uncertainty regarding component development and delivery by lower-tier organisations. • Market risks: Macroeconomic uncertainty, such as political, social environmental or economic developments • Competition risks: Uncertainty regarding the actions of competitors.
Artefact attributes	• Customer requirements understanding related risks: Uncertainty regarding the quality of understanding of the requirements by the program organisation. • Customer requirements stability related risks: Uncertainty regarding the stability of customer requirements.	• New technology risks: Uncertainty of technology maturity and performance under field conditions • System integration risks: Uncertainty of system integration readiness under field conditions

The questions were developed based on a literature review of engineering program risks, as well as through discussions with an industry focus group consisting of representatives from the risk management functions of four US aerospace and defence companies, as well as one consultancy focused on risk management in aerospace programs. The collection of risks was refined over several iterations through telephone conference calls.

Respondents were invited from the risk management organisations of six US aerospace and defence companies as part of a risk management benchmarking study. The surveys were distributed through the risk management organisation to risk management and engineering program management professionals.

The results are summarised in Figures 1.2 and 1.3.

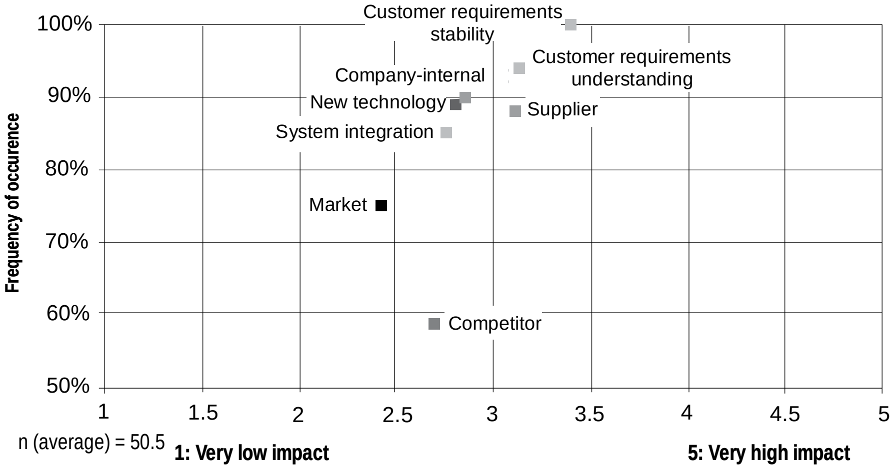

Figure 1.2. Distribution of engineering program risks regarding frequency of occurrence and severity of impact

The highest overall severity is carried by the two requirements-related risks (see also Stockstrom and Herstatt, 2008), followed by the supplier-related risks. All three risks are dominated by external factors that can only be indirectly addressed by the engineering organisations (for example through improved customer and supplier integration).

Technical risks (relating to technology and system integration) as well as risks relating to company-internal processes are in the middle of the severity range. The two lowest scoring risks are competition and market related risks, which might be specific to the aerospace and defence industry.

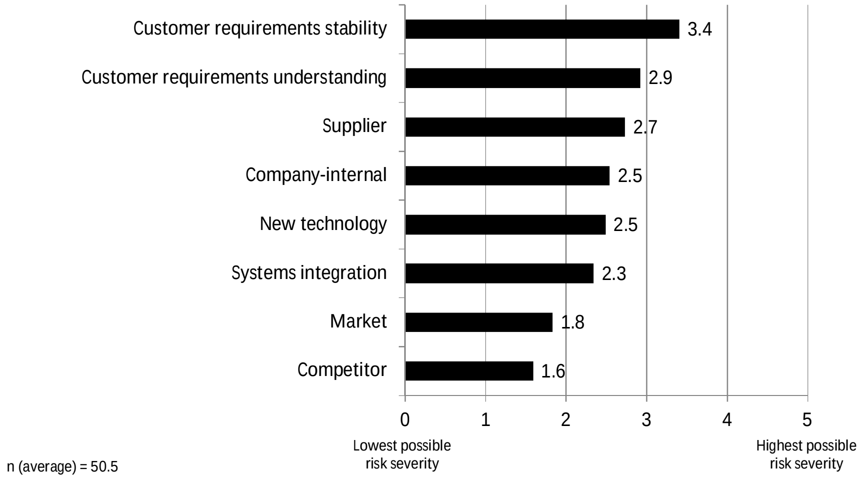

Figure 1.3. Overall severity of different engineering program risks, computed as the product of impact and frequency

1.6 Discussion and Conclusions

This paper contributes to the current state of knowledge by introducing a taxonomy for describing risks in engineering programs, covering the categories of uncertainties, effects and objectives that are necessary to describe those risks. It also contains examples of quantified engineering program risks, indicating that external risks with a root cause in customer and suppliers are most critical.

The paper makes a contribution to the academic discussion of risk management in product design and development by providing a structured framework in which to discuss risks, hopefully contributing to the clarity of the discussion.

It also makes a contribution to risk management in industrial practice by providing a structure for identifying, discussing and documenting engineering program risks.

There are several significant limitations to this paper, including: The framework has not yet been implemented in industrial practice, so feedback regarding its usability is missing. Also, the empirical data reported here is strongly biased towards engineering programs in the context of the Aerospace and Defence industry, as well as risk management professionals evaluating programs from an "ex-post" perspective. The quantified examples might therefore not be indicative of engineering risks in other industries or early phases of engineering programs.

1.7 Acknowledgements

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Chapter 2

Ambiguity, Risk and Change in Designing: A Micro-level Description for a Property-based Approach

S. Da Silva Vieira

2.1 Introduction

The purpose of this study is to know if risk takes place in designing and if so, to provide an understanding of risk underlying mechanisms and its influence in the design process. The study is a starting point to investigate the interplay and causal networks of ambiguity, risk and change (ARC) as properties of variables of design issues introduced in circumstances that ask for evaluation and decision, and that have the potential to increase or decrease uncertainty towards completion.

This paper presents the ARC hypotheses to explore the interplay between the three proposed properties of design issues variables. The investigation is based on the analysis of a set of meetings for the design of a robot developed at a Mechanical Engineering design consultancy. The approach has its application in the semantic analysis of the transcripts of thought sequences obtained from verbal reports. A closer look is given to critical design issues that emerged at the first meeting and how they evolved throughout the meetings.

A property-based approach underlines the investigation of ambiguity, risk and change as properties of variables and their influence towards the completion of design issues at design meetings. The study contributes with preliminary results that show interdependency between the properties. A domain-independent and property-based approach is proposed to assess risk in designing.

The leitmotif of the present study is the investigation of risk in designing. Design is, in this research, a cognitive process extensive to all the fields of human action that can be acquired and embedded through personal development and experience (Vieira, 2013). Risk in designing remains unspecified. Attempts to approach risk in design have recently established the basis for further research (Jerrard and Barnes 2006; Oehmen, 2010), though we still do not know what risk is and how it evolves in design. Besides not knowing what risk in design is, it is also not known where risk starts or where it ends. Risk perception is innate to thought with plausible influence in design as a cognitive process.

Although it is still not possible to fully assess how designers think and act while designing (Gero, 2010), the sharing of risk perception occurs when the important meaning and associated essential issues are communicated (Jerrard *et al.*, 2007). The implicit process of risk perception becomes explicit when the perceived risk is verbalized, shared with the design team and discussed in instances of evaluation that ask for decisions (Jerrard and Barnes, 2006). The study of the underlying mechanisms of risk in design is therefore dependent on the analysis of other underlying processes, such as valuation and decision-making towards the design completion.

This paper attempts to illustrate the understanding of how risk takes place in designing and is based on the analysis and mapping of selected moments from sequential meetings for the design of a robot, developed in a design consultancy specialising in mechanical engineering. Interdependent relations of risk with other properties of variables of design issues are hypothesized and investigated. The following section explains the theoretical background and illustrates the hypotheses.

2.2 Theoretical Foundations

Research in engineering design has placed more attention towards the investigation of risk in project management and product development. Structured methodologies for better planning and control of stable environments have been applied in order to transform the product development process into a more predictable activity, such as the stage-gate model (Cooper, 1995; 2008). Although with the focus on downside aspects the knowledge of risk in project management is well established.

The numerous technical methods for handling risk and uncertainty that are available to project managers, do not seem to fit designers' needs when it comes down to less instrumental design approaches and a more connected performance. Recent studies assert that in current practices risk management processes still tend to be treated as separate tasks of project management approaches (Oehmen and Rebentisch, 2010).

From the many definitions of risk that can be found in project management and product development literature, one particular definition is appropriate to the context of this study, 'Risks are defined within complex and dynamic causal networks' (Oehmen *et al.*, 2009). Studying risk in design requires the investigation of the causes, effects and underlying mechanisms of risk in order to provide awareness and strategic principles for risk management.

The integration of risk management as an intrinsic part of design processes is laid out in the Risk-driven Design framework (RdD) (Oehmen and Seering, 2011). This proposal emphasises that, when the design process is driven by the intention to manage risk, and known and unknown uncertainties and their effect on the objectives have been identified, then decision-making focuses on the most critical uncertainties. The RdD framework shows that if risk management is interpreted as the structured identification and reduction of uncertainty, all product development activities that aim at minimising uncertainty can be seen as risk treatment measures, such as quality management and review processes (Bassler, 2011).

The same reasoning can be extended to design, assuming that risk perception and the reduction of uncertainty are implicit processes always at the background of designers thought. Therefore, the understanding of risk in design requires the analysis of the verbalizations of perceived risk, its causes, antecedents, effects, consequences and influence in decision-making. The shared perception of risk has been hypothesised as a non-linear process and individual risk perception as value-laden (Jerrard and Barnes, 2006). A more complete understanding of risk in design may derive from the investigation of iteration processes (Cross and Roozenburg, 1992; Unger and Eppinger, 2011).

Designing relates to the search for variables that relate to what is not known (Gero, 1998) and designers are likely to take risks. The environments of greater uncertainty are those in which designers face a greater number of unknowns within the variables. Such environments seem to be appropriate to investigate the extension of risk effects in design, and provide a more complete understanding of risk in general.

From previous studies, results from the analysis of design meetings show interdependency between variables of design issues with influence in decision-making as one of the mechanisms of iteration in design (Vieira, 2013). When design issues are brought into discussion, some have an immediate resolution; others go through iteration processes of discussion and decision-making leading towards completion. On a macro-level, design *'fundamental issues are a topic or problem for debate and discussion, not particularly, nor uniquely related to any specific design task, design or design situation'* (Gero, 2010). On a micro-level, design issues are specifically related to the design subject context, and explicit verbalized in team.

Design issues are comprised of constants and variables and evolve through a process of the reduction of uncertainty towards completion. Variables are based on knowns and unknowns (Knight, 1921; Loch *et al.*, 2006) and evolve through evaluation processes and interdependency within other design issues. The underlying processes for completion of design issues are plausibly intertwined with risk perception and evaluation; consequently, the study of risk in design asks for the analysis of the processes of evaluation and decision-making towards the completion of risk-design issues variables. Such variables are context sensitive, can bring change and have variant meaning and intonation according to the design situation (Gero, 1998). These variables are the subject of a designers' evaluation that might change, not just their own values, but also situational relationships. Attempts for the understanding of change in engineering design processes unfold in complementary perspectives (Jarratt *et al.*, 2011). A call has been made to develop tools and knowledge to help understand and improve change processes.

From the literature, risk is recognized in two ways: a perceived risk that leads to the identification of an effect; or an identified effect with influence in the design outcome. Whether the effect is immediately or later identified, both influence decision-making and the design trajectory. The perceived risks are not clearly known. There is uncertainty underlying their perception. A risk effect clearly identified might have some space for uncertainty if its consequences are not fully considered.

This investigation explores the proposition that risk possibly derives from ambiguity. Identifying and solving ambiguity is to make the unknowns known, reducing uncertainty and setting the path for a decision. The definition of ambiguity is twofold: uncertainty or inexactness of meaning in language; or lack of decisiveness or commitment, resulting from a failure to chose between alternatives (New Oxford American Dictionary). Consequently, ambiguity is about unknown knowledge or unclear information and relates to knowledge assessment and decision-making. In other words, variables of design issues have, most likely, the property of ambiguity until they become known.

In this process of clarification, risk can emerge with a perceived effect on the design outcome and eventually lead to change, or change might be introduced and influence all that was done before, eventually bringing new risk and ambiguity. The term property is defined as an attribute, quality, or characteristic of something (New Oxford American Dictionary).

In the process of designing, attributes and qualities are specified to the formulation of ideas and solutions (Vieira, 2013). It is supposed that a set of temporary or permanent properties of design issues variables and constants influence the design trajectory towards its completion. From this set of properties, evidence from a causal network between risk, ambiguity and change emerged from the observation and analysis of designers' verbal reports.

The present study hypothesizes ARC as properties of design issues variables introduced in circumstances that ask for evaluation and decision, as a starting point to further investigation on the interplay between these properties.

2.2.1 The ARC Hypotheses

The study attempts to build on two hypotheses that can bring new insights and directions to research the causal networks of risk in design. The hypotheses are further explained and illustrated. The hypothesis H1 holds the following statement:

H1: Ambiguity, risk and change are properties of design issues variables.

The investigation of H1 aims to clarify if risk takes place when the design team discusses incomplete design issues and their causal networks, looking for a plausible explanation of when risks start and when it ends. The identification of variables of design issues under risk and ambiguity and what changes and effects can take place is proposed through the semantic analysis and coding of segments of designers' verbal intervention in meetings.

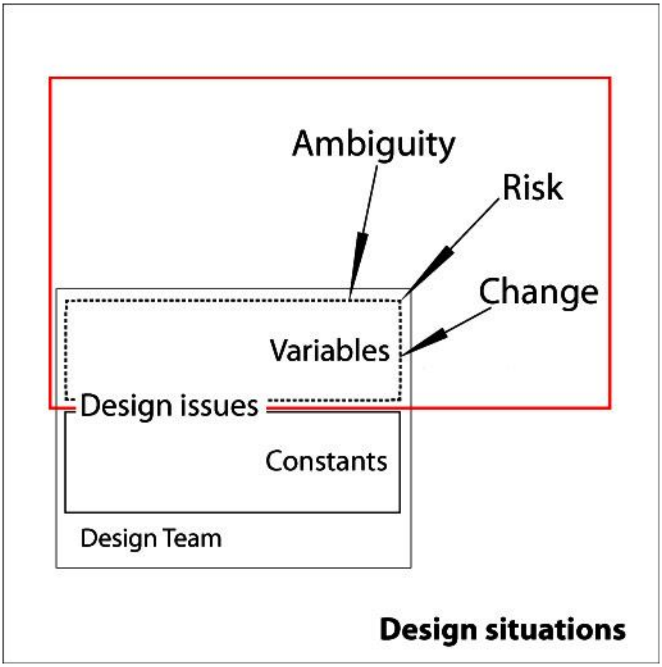

Figure 2.1. Illustration of the hypothesis 1: ambiguity, risk and change are properties of design issues variables

The hypothesis 2 sets out the following statement:

H2: Ambiguity, risk and change are properties of variables that influence design issues constants.

The investigation of H2 aims to explore how far the properties that influence the variables also influence design issues constants and have the potential to increase or decrease uncertainty towards the design completion.

Two perspectives of the interplay of ambiguity, risk and change as properties of variables are proposed:

- Ambiguity, risk and change have independent influence in the design issues variables with or without a resultant interdependency (H1).
- A direct interdependency between the three properties might emerge from ambiguity of the perception and identification of a risk, and therefore, to change (H2).

The present paper intends to present the ARC hypotheses and to investigate the phenomena based on the microanalysis of a piece of data, and further directions for researching risk in design and the hypotheses corroboration.

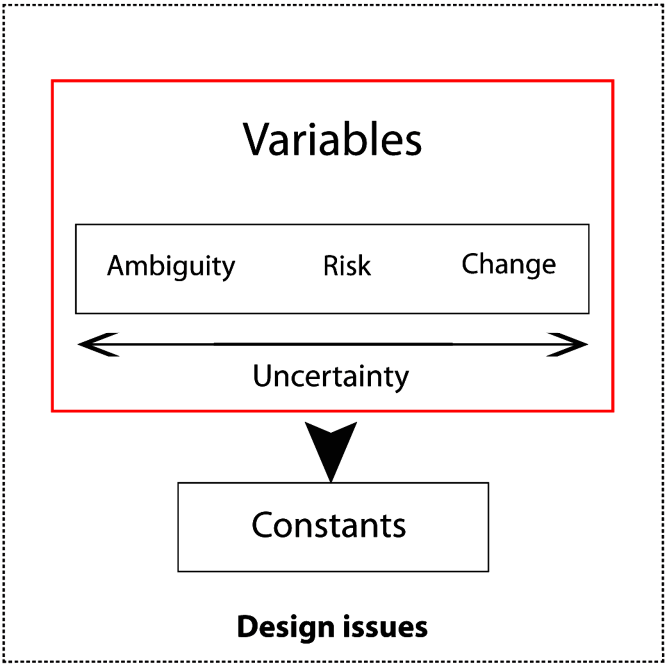

Figure 2.2. Illustration of the hypothesis 2: ambiguity, risk and change as properties of variables have influence in design issues constants

2.3 Research Methods

Studying risk in designing requires the analysis of designers' verbal reports in evaluation and decision-making processes in real life design environments, as the appropriate settings to assess designing activities with all the influences of the social and business context.

This research takes a different look at a piece of data previously analysed under the scope of prioritized design issues and their iteration, interdependency and decision-making processes at design meetings (Vieira, 2013) and under the scope of the Function Behavior Structure ontology (Gero *et al.*, 2013).

From these results, a closer look has been taken at the analysis of critical design issues, where the absence of essential aspects of the design process are identified and prioritised for discussion, thereby delaying decision-making. The study identified the sources of the absence of essentials in circumstances where risk and uncertainty are perceived on a base level.

Insights from these studies based on data gathered from several design disciplines brought into perspective that: change could be introduced in actions that relate to envisioning, rethinking direction and the focus of the design process; ambiguity could be introduced in circumstances that relate to information assessment and information transfer; ambiguity and change could bring consequent downside and upside risk effects. Critical design issues represent the basic level of influential situations in design where risk is perceived and therefore the first stage to investigate the ARC hypotheses. Studies of other types of design issues may bring further insight into other levels and mechanisms of risk causal networks and risk management in design.

For the purpose of this study, the analysis focus is the assessment of variables of critical design issues, and how far ambiguity, risk and change emerge and evolve as properties of the variables. The data consists of audio and video recordings of sequential design meetings referring to a design project, a robot developed in a mechanical engineering design consultancy. Previous results show that a higher incidence of critical situations occurs at the first meeting (Vieira, 2013). In these circumstances, the design team experiences opposition, at least from one of the collaborators awareness of the absence of essential issues. Table 2.1 illustrates the characteristics and details of the project and the first meeting.

Table 2.1. Overview of the design project and details of meeting one

Source of data	**Project**
Discipline	**Engineering design**
Design	Robot
Meetings	8
Observation	5 month
Meeting	1
Duration	01h 06 m
Topic	Detailed discussion of specifications and solutions
Team members	Leading Engineering researcher
	Electronics Engineer
	Software Engineer
	Technician

2.4 Data Analysis

The investigation of the hypotheses is based on the semantic analysis and coding segments of transcripts of verbal reports from moments of discussion of critical design issues that emerged in the first meeting of the design project. The analysis is based on verbalizations that relate to: risk perception or risk effect; risk interplay with ambiguity and change; variation of uncertainty underlying the three properties; and implications to decision-making. The paper reports a closer look at the analysis of four critical design issues, namely: a software, the space box for components, a demo experiment, and the Inertial Measurement Unit (IMU) specifications. Table 2.2 shows the design issues iteration across the meetings.

Table 2.2. Design issues frequency and iteration across the meetings

Design issues	Frequency per meeting								Total Frequency	Total Iteration
	1	2	3	4	5	6	7	8		
Software	1	1	-	-	-	-	-	-	2	1
Space box for components	1	2	-	3	-	-	-	-	6	5
Demo experiment	1	-	-	-	-	-	-	-	1	-
IMU specifications	1	2	3	1	-	-	3	-	10	9

The semantic analysis of the transcripts is based on the lines of each intervenient per segment of discussion. The segment lines were mapped out by the identification of verbalizations that relate to each one of the proposed properties – ambiguity (A), risk (R) and change (Ch) - underlying uncertainty (U), upside (↑) and downside (↓) effects of risk, decisions (D) on actions (∏) to take, solutions (3), conversion into design issues constants (¬C) or influence on variables (¬V). Table 2.3 illustrates the mapping across the segment lines of each of the four design issues. Due to the extension of the mapping two of the design issues are partially illustrated. The table shows the mapping of the initial segments where the absent feature is identified and the last segments where the problem is solved. Number one (1) represents the presence of the properties in the segment lines, while zero (0) means its resolution. A description of each of the four design issues based on the identification of ambiguity, risk, change, variables and constants is provided.

The software was malfunctioning due to a bug. A risk related to time lost emerged. The engineers knew that once the bug was known (ambiguity) an optimization procedure became necessary to overcome the problem. Meanwhile, other bugs could arise (perceived risk effect). It was found that the software had an untrustworthy compiler (variable), which was changed by an official package (change as replacement) that made the software function again (constant).

The design issue of the space box emerged when one of the collaborators had doubts about there not being sufficient space (perceived risk) to place the unknown (ambiguity) components and cables (variables) in a previously defined box (constant). This was a long-term issue that after some iteration was solved at meeting 4, but many times the need was raised to change for a box with more appropriate dimensions.

The demo experiment relates to the use of some robot components to demonstrate to the students an experiment that failed (risk). One of the connections failed because two pins were bent (involuntary change), presumably by the students (perceived risk). This accident triggered a mini capacitor from the bent pins (ambiguity), which was an unfilled need for a component that, in case it worked, would save time looking for another capacitor, and change the scheduled activities (risk upside effect).

The IMU specifications needed considerable iteration to be solved. It was a fairly interdependent issue that asked for clarification and many decisions to be arrived at. The space box and the IMU design issues have respectively 58 and 53 segment lines of evaluation at meetings. The discussion of these design issues evolved through the different intervenient speeds of perception, with many doubts to clarify, and information and knowledge to assess.

Table 2.3. Mapping of the moments of discussion per design issue according to the verbalized segment line (SL), Ambiguity (A), Risk (R), Change (Ch), Decision (D), Action (∏), solution (3), Risk upside effect (↑), Risk downside effect (↓), Uncertainty (U), conversion into design issues constants (¬C), influence of design issues variables (¬V)

	Software				Space box for components				Demo experiment				IMU specifications			
SL	A	R	Ch	D	A	R	Ch	D	A	R	Ch	D	A	R	Ch	D
1	1	-	-	-	1	1↓			1	-	-	-	1	1↓		
	U				U	U			U				U	U		
2	0	1↓	-	-	0			∏	0	1↓	1	-		1↓		
		U						U						U		
3	1	1↓	-	-	1				1	-	-	-	1			
	U	U			U				U				U			
4	1	1↓	1	∏	0			∏	0	1↓	1	-	0	0		
	U	U	U	U						U						
5	0	0	1	∏	1	1			0	-	-	-	1			
			U	U	U	U							U			
6	0	0	1	∏	0			∏	1	1↑	1	∏	0	1↑		
			U	U				U	U	U	U	U				
7	1	1↓	-	∏	1				1	¬V						∏
	U	U		U	U				U							3
8	0	0	1					∏	0	1↓		∏	1			
			¬C	3				U		U			U			
9					1	1↓			0	1↓		∏				∏
					U	U						3				U
48					1								1			∏
					U								U			
49								∏					0			∏
								U								
50					1								1	1↓		
					U								U	U		
51								∏					0			∏
								U								
52					1								1			
					U								U			
53					0											∏
																3
54					1											
					U											
55					0											
56					1	1↑										
					U	U										
57								∏								
								U								
58								∏								
								3								

2.5 Results

Results from the investigation of risk in designing derived from the semantic analysis and coding of a total of 128 segment lines. The paper reports four sets of results relating to: risk awareness and proposed definition of risk in design, ARC properties interplay, uncertainty underlying the properties, and convertibility of constants and variables, further explained.

2.5.1 Risk in Designing

Three stages of risk awareness were identified: perceived risk, risk effect, risk worth. Verbalizations on risk relate to: time lost, probability of downside and upside risk effects, awareness of inadequate characteristics (of objects, such as volume, space and a person's ability), suspension of expected connections (such as power or interfaces), unexpected opportunity, anticipation of preventive measures, synchronization issues and flow lost. n the three stages of risk awareness, whether risk is, perceived, an identified effect, or an opportunity, it can influence the initial variable under discussion, another variable within the same design issue, or a variable of another, but interdependent, design issue.

A preliminary conclusion can be stated: risk in designing is a property of a variable with a perceived or identified effect that can have situational relationships of expected or unexpected risk effects in other variables within a single design issue or interdependent design issues.

2.5.2 Risk, Ambiguity and Change: Properties Interplay

Perceived risk is preceded by the recognition of ambiguity. Ambiguity leads to several effects that are underlined by uncertainty, such as vagueness, abstruseness, doubt, formal dubiety, ambivalence, equivocation and double meaning, all having implications to the decision-making. Clearly identified risk effect is preceded by ambiguity clarification. The verbalization of risk worth can be preceded by a recognized ambiguity or ambiguity clarification. If the expected risk worth is successful it becomes an effective risk. Risk worth can be dependent on an expected change. Expected change depends on decisions of actions, reduction of ambiguity and identification of solutions. Whether change is voluntary or involuntary, four types of change were identified: change as replacement (a better alternative), change as modification (adjustment), change as transformation (conceptual change, process change) and change as regeneration (renewal). Clarification of ambiguity and accomplished change convert design issues variables into constants.

In circumstances where the influence and effect of risk reaches its utmost extent, a pattern of interplay settles ambiguity as the point where perceived risk starts and change becomes the ultimate risk effect. This corroborates hypothesis 2 and is illustrated in the examples from Table 2.3, namely in the segment lines: SL

4 of the software design issue; SL 6 of the Demo experience design issue. In both situations, uncertainty underlies the sequence, further confirmed or not in other segment lines.

From the analysis of this piece of data there was no evidence of independent influence regarding the properties of risk and change (H1), except for ambiguity. Other studies based on the analysis of various types of design issues across design disciplines might bring evidence of such circumstances.

2.5.3 Uncertainty Underlying Properties

Ambiguity is underlined by uncertainty. Ambiguity goes through a process of reduction until it is null and void, as knowledge is clarified and commitment to decisions is attained. Uncertainty has a dual state: you have it or you don't. Uncertainty is zero when ambiguity is zero, when risk is effective and when change is effective too. A perceived risk, an expected risk effect, expected risk worth or an expected change are always underlined by uncertainty and dependent on actions, reduction of ambiguity, decisions and solutions to know the extent of its influence.

2.5.4 Convertibility of Constants and Variables in Design

In the process of reduction of uncertainty, effective risks and changes can influence not only the variables, but also design issues constants and therefore the overall design trajectory. When the uncertainty underlying a design issue variable is reduced to zero the variable becomes a constant (see Table 2.3, Software, SL 8). However, risk and change of a variable can influence other variables (see Table 2.3, Demo experience, SL 7) and constants within a single design issue. A variable that became a constant can have as a consequence the conversion of a constant into a variable within the same or an interdependent design issue. The reduction of ambiguity evolves through the characteristic of convertibility between variables and constants (examples: Space box and IMU design issues where several stages of ambiguity reduction were mapped out).

2.6 Discussion

This study contributes to the investigation of causes, effects and underlying mechanisms of risk in design with consequences and influence to decision-making and attempts to provide awareness and strategic principles for risk management. Therefore, the present paper sets a proposal of a property-based approach for the analysis of risk causal networks with application in research and practice of design. The approach entails three layers of analysis, namely: analysis of design issues, constants and variables (knowns and unknowns), and assessment of ambiguity; types of design issues and assessment of perceived risk and its effects; assessment of the influence and types of change in the design process and decision-making. This proposal supports the notion that reduction of ambiguity and stages of uncertainty, risks worthiness, effects and consequential change are achieved through iteration processes of incremental learning in time.

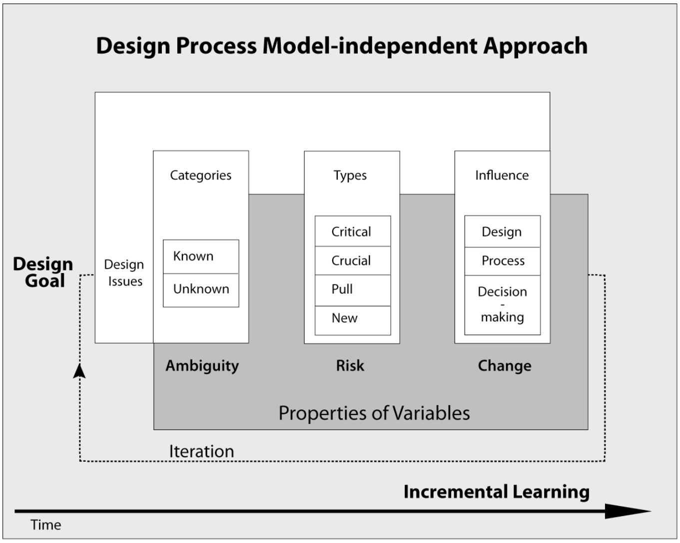

Figure 2.3. Illustration of the property-based approach

The approach is a property-based instrument that can fit different design and product development methodologies, as the traditional prescriptive models such as the Basic Design Cycle (Roozenburg and Eekels, 1995) but also newer approaches such as the VIP approach (Hekkert and van Dijk, 2001; 2011) among other design approaches, product development structured methods (Cooper, 2008; Ulrich and Eppinger 2011), and reflective models of the design practice (Schön, 1983; 1988), with application in research, industry, and practice of design. It has the utility to help in identifying what ambiguity, risk and change are, and how they evolve in design. This study aims to understand and proposes guidelines for researching risk in design, for example, how the joint use of this analysis can be useful in a stage gate process model (Cooper, 1995; 2008).

2.7 Conclusions and Research Implications

Evaluation and decision-making processes, as well as design issues variables and constants interdependency are relevant to the management of ambiguity, risk and change in design. The properties of variables influence the evolution of iteration processes towards the design completion within a time-related dimension suitable to each business context. The management of such processes influences the expected design outcome. The foreseen use of the present property-based approach is twofold:

- An instrumental approach for the analysis and understanding of risk causal networks in research in design across disciplines.
- A domain-independent approach to risk management for identification of causal networks of risk in the different practice design of design host disciplines.

Further studies can attain the consolidation of the approach with potential benefits at other development stages. More advanced studies might provide further knowledge on how to manage the three properties in highly complex and innovative design processes. Such achievements will be particularly relevant to improve awareness in the current economic context.

Further research might bring insights: on other influential properties of design trajectories; on variants and invariants of the causal networks of risk in design across its host disciplines (Love, 2002) through studies based on multidisciplinary and transdisciplinary design environments (Vieira, 2014); on implications to design management with improved methods to cope with ambiguity, risk and change; contribute to structuring the knowledge of design (Visser, 2009) as a discipline (Archer, 1979) with influential mechanisms of risk in design.

2.8 Acknowledgements

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Part II

Modelling Approaches and Virtual Tools

Chapter 3

Integrated Modelling of Information to Support Product Engineering Processes

A. Albers, A. Braun and T. Pinner

3.1 Introduction and Motivation

Product engineering processes are subject to increasing complexity. They comprise activities of product development, production and after sales such as service or decommission. Complexity arises from the large number of information elements and of their many interrelations (structural complexity - Maurer, 2007) in the context of product engineering. Information elements can be *e.g.* objectives with individual target values, activity description and their duration, decision criteria, resource capacities, *etc*. As a further challenge, uncertainty and dynamic behaviour of engineering processes lead to dynamic complexity (Diepold *et al*., 2010). In our research, we aim at handling the complexity of engineering processes through modelling information using the Integrated Product Engineering Model (iPeM - Albers and Braun, 2011). The iPeM provides a structure in which relevant information aspects can be clustered and interrelated. In this paper we present areas of potential support that can be realized with the iPeM modelling approach and present a prototypic implementation. We exemplify this concept by modelling selected aspects of a student project and use this test to evaluate our concept and to validate the software implementation. The paper is organised as follows: Section 3.1 outlines and motivates the research. In Section 3.2 we review the related state of the art and similar research approaches. From this, we substantiate why the iPeM is a suitable modelling framework for our research. Section 3.3 introduces the concept of our approach which is implemented as presented in Section 3.4. In Section 3.5 we describe an exemplary application which is critically discussed in order to evaluate our concept and to reflect upon the current software implementation. Section 3.6 concludes with a summary and an outlook on further work.

3.2 State of the Art

Table 3.1 gives an overview of selected approaches to modelling of product engineering processes. Exemplary aspects are compared to each other in this table which is in parts taken from Browning *et al.* (2006). The approaches can be classified by their respective focus on either design or project management or by their basis on either stages or activities (Wynn, 2007). Furthermore, the modelled elements and their typical variables and attributes can be distinguished. The different approaches contain diverse information contents depending on their modelling purpose.

Table 3.1. Overview of approaches to modelling of product engineering (PE) processes

Framework	Example References	Focus	Basis	Elements/ Contents	Variables/ Attributes
Activity Nets, PERT	(Elmaghraby, 1995)	Management	Activities	Tasks and their sequence	Activity duration elasticity
BPM	(Arkin, 2002)	Management	Activities	Activities objects	Myriad potential attributes
DSM	(Steward, 1981), (Eppinger, 2001)	Design or management	Activities	Activities and their relations	Dependency sequence
Integrated PD	(Andreasen and Hein, 1987), (Ehrlenspiel, 2007)	Design	Phases	Subsystems of PDP	Myriad potential attributes
IDEF, SADT	(NIST, 1993) (Ross, 1977)	Management	Activities	Function input, output	Control mechanisms
iPeM	(Albers and Braun, 2011)	Design and management	Activities and phases	Subsystems of PEP	Myriad potential attributes
Pahl/Beitz	(Pahl *et al*., 2007)	Design	Phases	Guidelines checklists	Product specification
Stage-Gate-Models	(Cooper, 2001)	Management	Phases	Stages, milestones	Stage duration decision critical
VDI 2206	(VDI 2206, 2004)	Design	Phases	Specification integration	Specification and validation criteria
VDI 2221	(VDI 2221, 1993)	Design	Phases	Stages, results for each state	Myriad potential attributes
ZOPH-Model	(Negele *et al*., 1997)	Design	Activities	Subsystems of PE processes	Myriad potential attributes

Most of these approaches are intended to serve distinct purposes, *e.g.* to establish transparency about activity relations or task sequences. Only ZOPH and iPeM have a holistic and systemic perspective on the system of product engineering. We apply the iPeM approach as a framework for our research since it aims at a holistic support of both designers and managers and considers the socio-technical nature of product engineering processes. The overall aim is to assist human beings in the centre of product engineering in terms of orientation, navigation, documentation, process- and knowledge work – with the help of transparent and integrated representation of information (Albers and Braun, 2011). Albers and Braun (2012) showed, that the iPeM allows modelling engineering processes at any necessary level of detail. It is based on system theory and can thus be regarded in a structural, hierarchical, and/or functional way (Ropohl, 1975). Hierarchic consideration allows clustering elements of related content and permits *e.g.* inheritance. Functional consideration helps representing the interconnectedness of the elements of the system through the exchange of deliverables (Albers and Braun, 2011). Changes on one single element exert influence on its interconnected elements and are propagated in the whole system of product engineering. For instance a change of “motor performance” may lead to changes on the “drive chain” (technical elements), but also to changes on organisational elements such as time schedules.

The iPeM meta model contains several subsystems and describes their interrelations. As also described by Ropohl (1975), a System of Objectives is transferred into a System of Objects by an Operation System. In the iPeM, the latter is further decomposed into a System of Resources and the activities matrix (Table 3.2). In this matrix, each activity of product engineering corresponds with a 7-step problem solving process (German acronym SPALTEN - Albers *et al.*, 2005). This forms a 10 x 7 matrix providing a structure for the assignment of information. The elements of the systems of objectives and objects as well as the system of resources’ elements may be interrelated with the activities in order to describe or prescribe functional dependencies; methods, but also knowledge and experience can be ascribed to the respective matrix field (Albers and Braun, 2011).

Table 3.2. Activities of the iPeM framework

Activities of Product Engineering	**Activities of Problem Solving**
Project planning and controlling	Situation analysis
Profile detection	Problem containment
Idea detection	Detection of alternative solutions
Modelling of principle solution and embodiment validation	Selection of solutions
Production system engineering	Analysis of consequences
Production	Deciding and implementing
Market launch	Recapitulation and learning
(Analysis of) utilisation	
(Analysis of) decommission	

In practice, several levels of product engineering processes can be distinguished *e.g.* planning or application. In the iPeM framework, activities can be arranged along a time bar in order to represent coherent phases or stages in a so-called phase model.

Here, a *reference model* depicts common invariant elements and their temporal dependencies describing past, similar engineering processes. It may represent best practice patterns that can be used to plan new projects. Such a plan results in an *implementation model.* An *application model* is the recording of a specific product engineering process showing the course of the real process. A set actual comparison can be used to readjust running projects or to learn from past processes in retrospect. The consideration of these model levels and the well-structured activities matrix separate the iPeM approach from other representations of the system of product engineering. We argue that this allows a wider range of support than a mere representation of activity or ZOPH-relations *e.g.* in a Multiple-Domain-Matrix (MDM) as presented by Hellenbrand and Lindemann (2011). Yet, it is still generic and could be applied more flexibly than approaches that focus on particular situations as for instance the pattern-based process navigator that has been developed by the research cooperation FORFLOW (Meerkamm *et al.*, 2009).

Albers and Braun (2012) showed in a test where a real project had been modelled descriptively, that the meta model of the iPeM is comprehensive enough to comprise any relevant information aspect in order to model engineering processes. However, the test also revealed limitations of the current (theoretical) state:

> *"The large amount of information leads to huge models fast, which requires additional means/possibilities for handling these representations by effective and efficient tools. A thorough investigation on the effort-value ratio has to be done before proceeding with any software implementation. For both modeling itself and for working with the models, usability needs to be enhanced."*
>
> (Albers and Braun, 2012)

In the next section we present a concept to enhance the iPeM's usability in practice with the aim of supporting product engineering.

3.3 Concept of the Integrated Modelling Approach

Our approach comprises the three model levels: reference, implementation and application level. Each of these levels may contain similar elements but represents different states of realisation. Where the application level represents the current AS-IS status, the implementation level contains the project-specific planning. The reference level contains planning elements that are project-unspecific and applicable for many different projects. In our consideration these levels are highly interconnected; every element may be included within one, two or three levels at the same time – which enhances the current understanding.

Every level contains five element classes according to the iPeM meta model: Objectives, Activities of Product Engineering, Activities of Problem Solving, Resources and Objects. All elements can be described in more detail by attributes such as durations in case of the activities. Elements can be combined with each other in order to describe particular dependencies within product engineering processes. In this paper, we focus on the prominent combination of the three elements Objective, Activity, Object, composing a so-called OAO-Triple.

According to the iPeM ontology, such triples describe how activities result from certain objectives and lead to related objects. In further considerations, also resources involved in this part of a process can be related. Not only objectives may be transformed into objects; also objects may lead to new objectives through activities such as analysis or validation. For instance, a strength calculation result of a shaft might lead to the awareness that a diameter or a steel grade needs to be changed.

3.3.1 Areas of Product Engineering Process Support

The following areas are adressed with our concept of integrated modelling.

Transparency of Dependencies is a concept to interpret and filter the holistic model in order to determine and to display relevant organisational and technical interdependencies for particular inquiries. This concept can be the means to cope with structural complexity. Due to multiple dependencies (often even across hierarchy levels), the effects of changes of elements cannot be foreseen directly. Calculating dependencies based on a holistic model can help to regain an overview for various purposes and omit mistakes due to oversight. A project manager might for instance be interested in interrelations of scheduled activities and resources. A designer might need transparency about the relation of technical product elements to elements of the system of objectives and so on.

Adaptive Project Control is a concept to support iterative planning and readjustment of processes by adapting to analysis results of the respective AS-IS status of projects or by adapting to changing boundary conditions. Thus, Adaptive Project Control can be a help to meet the challenge of dynamic complexity. Based on reference information that is assumed to be valid for a particular kind of project, specific implementation information can be established as a plan of the project. Monitoring application information (the project's AS-IS status), the planning state of the implementation level can be concretised or adjusted constantly. In this concept, there is a cycle of application and implementation that combines gradual planning with incremental realisation. Based on experience from transforming implementation into application level, successful planning information can again be stored as reference elements for other projects (Figure 3.1).

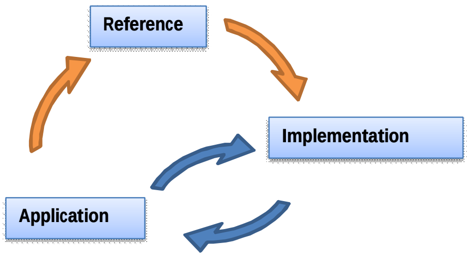

Figure 3.1. Circles of implementation and application within the three model levels

Best Practice Application is a concept of knowledge extraction and reuse. One example for a best practice pattern is the storage and provision of information about successful implementation to application transformations as described above. The information can be related to other elements in a distinct context. Our concept is to extract this knowledge from its carrier and to relate the information to generic iPeM elements (*e.g.* in form of OAO-Triples). With this, individual experiences can be modelled explicitly in a general framework. These representations may also contain individual boundary conditions of the respective situation; with this convenient retrieval and reuse of the knowledge in future projects becomes possible.

3.4 Software Implementation

We put our concept of supporting product engineering through a holistic modelling into practice with a software prototype. It is based on the CAM framework (Cambridge Advanced Modeller, see Wynn *et al.*, 2009). Information is put into the model manually at this stage of the prototype. We reflect on limitations of manual modelling later in the paper. Information is stored as an XML-file that comprises the model elements introduced in Section 3.3. The elements are visualised as follows in Figure 3.2.

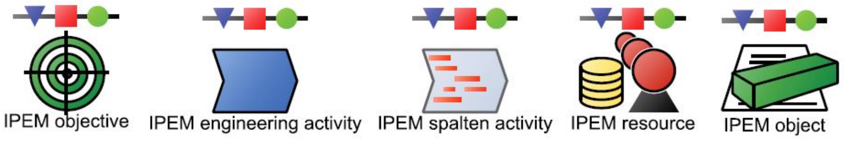

Figure 3.2. Visualisation of the elements in CAM

The connections on different model levels (reference, implementation, application) are visualised by different colours and connector shapes. Reference level connections are blue and shaped triangular; implementation level connections are red and indicated by square boxes; application level connections are green and feature a circle symbol. The following subsection introduces one particular view in which dependencies may be represented for different purposes.

3.4.1 DSM View

This view onto the holistic modelled data is based on a Design Structure Matrix (DSM, see Steward, 1981). Our DSM contains sub-systems, comprising the five model elements. The sub-systems are hierarchic, *i.e.* elements can be subordinate to other elements. With this, the level of detail of the representation may be adjusted to fit the respective purpose at hand. In the DSM, interconnections can be visualised across the sub-system boundaries. Figure 3.3 shows a screenshot of the DSM representation in

CAM where several model elements are connected in the three model levels as described in the paragraph above.

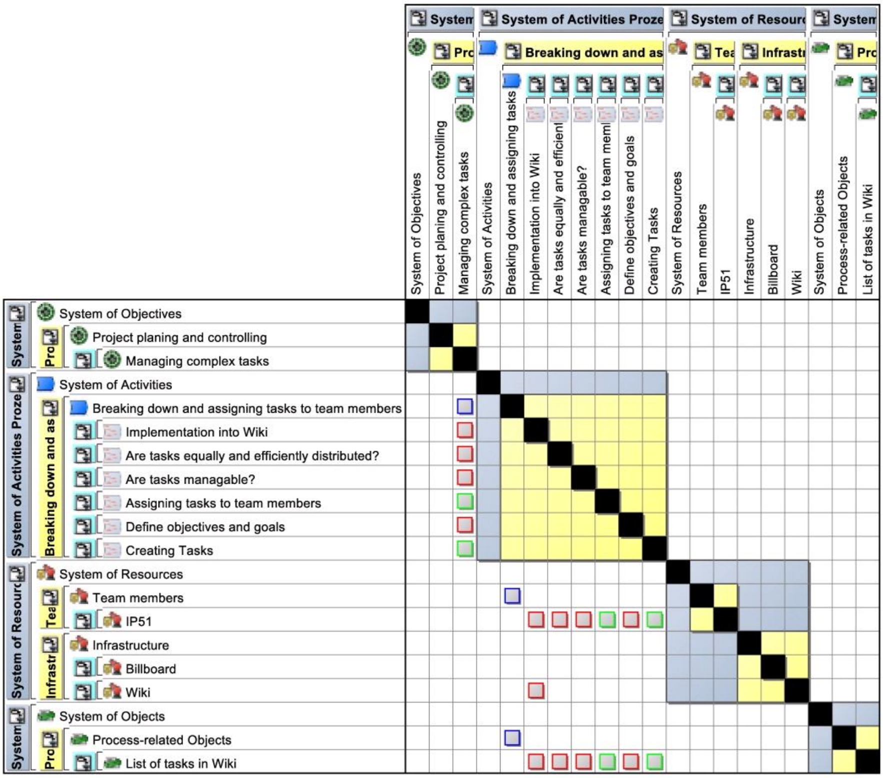

Figure 3.3. Screenshot of the DSM representation in CAM

3.4.2 Support through Transparent Dependencies

The DSM view is one tool aiming at transparency in the system of product engineering. In contrast to *e.g.* paper-based modelling, CAM offers several practical ways of further assistance. For instance, through a mouse-over user interaction, connected elements are directly highlighted which helps especially in navigation through large models.

Apart from that, several ideas for further assistance have been developed and implemented. Obvious but also hidden dependencies can be brought forward in specific perspectives called *explorer views* to achieve specific purposes. The objective explorer for instance (see Figure 3.4) uncovers dependencies between objectives, activities, resources and objects. Hereby, dependencies of technical aspects of the product can be represented in their interrelations; organisational aspects such as resource and activity planning are covered as well.

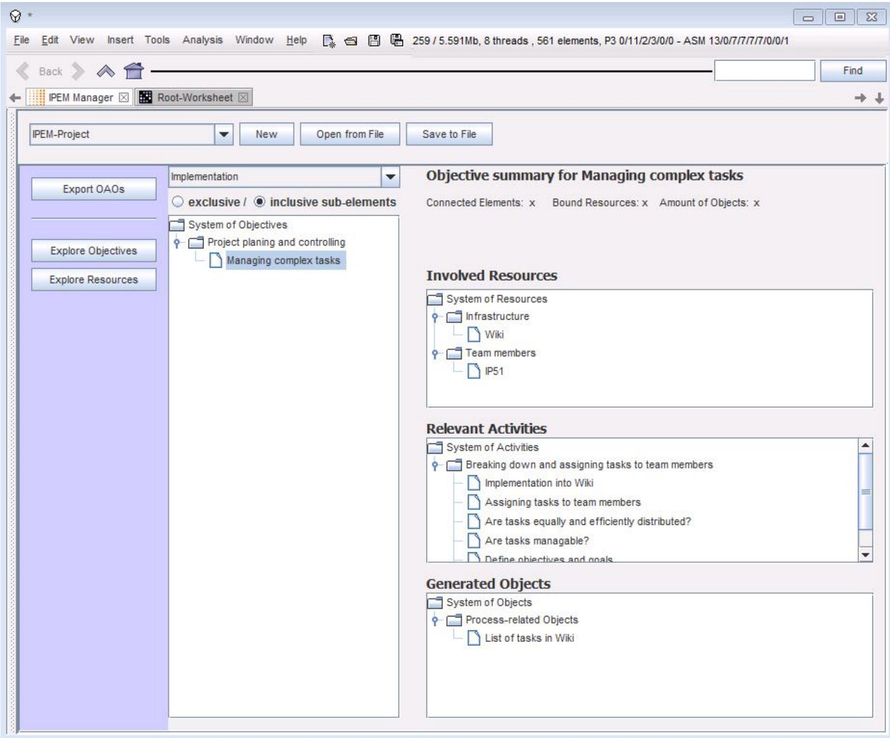

Figure 3.4. Explorer view with focus on objectives

Another representation that increases transparency - here with a focus on individual elements of the system of product engineering - is the *diagram view* where model elements are represented as boxes that are linked to each other via arrows. With the help of this, dependencies can be explored intuitively by selecting single elements of the diagram in order to optionally show their direct and/or indirect relations. A single click on any element focuses the view on this and shows all its connected elements. Double-clicking an element allows expanding or collapsing it in order to explore its hierarchic relations as well. In order to adjust the view to a given problem at hand, it is furthermore possible to select the element classes that shall be displayed in the diagram. Their hierarchy level may also be selected in order to further customise views.

Transparency established by integrated modelling also helps to develop projects in a managerial view. Through interrelating the three model levels of the iPeM (see Figure 3.1) it is possible to continuously validate a current process and to adapt it to changes; best practices can be stored and reused at all times. In a wider perspective, the core idea of this approach is to systematically reduce uncertainty that stems from the structural complexity and the dynamic nature of product engineering processes. For *Adaptive Project Control* purposes in the DSM view, the three model levels of the iPeM are indicated by colours and can be specified when adding new elements.

In our prototype, best practices can be exported by selecting existing combinations of objectives, activities and objects. With a particular user interface it is possible to make information available to other users. *Best practice OAO-Triples* can be selected from a list in order to export them as an XML-file. Every triple can be described through tags to facilitate the detection and reuse of suitable reference information in other projects. Users can select multiple reference elements and build individual reference patterns. As a result, the project's final reference level is geared towards the specific project and with regard to the combination of multiple reference elements. The idea of generally usable references but individualised support is realised in this way. Thus, the import and export of reference elements integrates seamlessly into the concept of adaptive project planning.

3.5 Exemplary Application in a Student Project

In this section we present a first application of our approach. The class 2011/2012 of the academic course "Integrated Product Development" has been chosen as a use case for the exemplary application. It is a four month product engineering project with a leading industrial partner and takes place in a realistic environment. It includes all stages of a (totally) new design - all the way from the definition of the market niche to the production of functional prototypes - as well as project management (time, budget, *etc.*). The project phase of one group of six students, where market demands have been detected and described, was modelled for our test. The project's initial task description in IP is very vague; hence uncertainty is particularly high. Therefore, it serves well for the purpose of an evaluation of our support approach. At the same time, the entire process is well observable as the supervisors have access to all intermediate files, sketches, documents, project plans, *etc.*

The project has been attended by a graduating student who is working on his thesis on product modelling. The model is comprehensive and includes over 800 elements with their attributes and connections to each other. For an application in industry, however, modelling by an external person can be a notable restraint, as described later in this chapter.

3.5.1 Evaluation of the Concept

The DSM view shown in Figure 3.3 contains excerpted elements of the four hierarchic subsystems according to the iPeM ontology. This provides a clear structure, in which the information elements can be modelled. The concept of interrelating reference, implementation and application level information is put into practice as follows in IP. For instance an exemplary objective - the need to manage complex tasks - arose during the project (see column 3 in Figure 3.3). A potential reference approach to deal with this objective is represented as a group of activities with the collective name *"Breaking down and assigning tasks to team members"* in our example. Reference information such as this can be provided by the project supervisors who assist the students in IP based on their own experience. In a first modelling step the (reference) activities lead to unspecified *"Process-related objects"* (see reference connections in column three/line five and in the fourth column of the DSM).

This reference model could be specified more precisely when knowledge about the project increased; *i.e.* a planning at a deeper level of detail was performed (modelled on implementation level). Sub-elements of the existing activity were defined and assigned to a more specific object (columns three and columns six to eleven). Nonetheless, these activities are still related to the same objective "Managing complex tasks". Consequently, this objective now belongs both to the reference and the implementation layer. In the further course of the project, performed activities were recorded in the application layer in which the real happenings and resulting objects are captured. By doing so, one could also store experiences as short text descriptions or hyperlinks to a product data management system, *etc*. The example shows this third type of connection between the objective "Managing complex tasks" and the activities "Create tasks" and "Assigning tasks to team members". Furthermore, the actual executor of the activities is visible (connection to resources). Successful combinations of real-life-proven procedures can be shared directly as reference which changes their signification from recorded data to guidelines for other projects.

This example shows that the transparent and adjustable views on the modelled information can be used successfully in a practical application. With this, the concepts of Adaptive Project Control and - in parts - also knowledge reuse could be exercised and evaluated. Feedback from the students whose project had been modelled, and a critical consideration of the insight from the field test by the modeller and the authors of this paper indicate that the concepts for support of product engineering processes presented in Section 3.3 work well.

However, there is also a critical reflection on the current software implementation: the software prototype in CAM is not meant to serve as a marketable computer programme. It was designed to support the concepts described above with the aim to allow a first evaluation. One big restraint is that a multi-user assistance has not been realised yet. Another problem is the effortive acquisition of information. Apart from the required time, also corruption of information due to the modelling by a third person hinders the benefit of the approach today. Further work should address ways to get large parts of model "on the fly" during running projects - *e.g.* with the help of tracking tools.

3.6 Conclusions and Outlook

In this final section we provide a summary of the approach and the findings of the case study. We close with an outlook on further research directions and work to be done considering software implementations of the iPeM.

3.6.1 Summary

In this paper, an approach for a methodological support of product engineering processes has been presented. After reflecting on the state of the art considering background and literature about available modelling approaches, own concepts for project support based on the iPeM have been presented. We illustrated a prototypic software implementation in CAM with the help of which these concepts have been put into practice. The application of this tool in a student project served as an exemplary use case and proved the approach's potential for a support of product engineering processes. Even with the limited scope of operation, the prototypic implementation helped well to model aspects of the student project in terms of the iPeM. Compared to pen and paper based approaches for instance, the software tool facilitates model creation and handling - especially for large models. However, there are several open questions (*e.g.* semi-automated modelling) and also weaknesses to be worked on in future efforts.

3.6.2 Outlook

The methodology for support presented in this paper is limited to Transparency, Adaptive Project Control and Best Practice Application for a first evaluation. Apart from that, a broad range of further support could be realised. Saak (2007), for instance, described a concept for a computer-aided tool for the efficient employment of the problem solving methodology "SPALTEN". It provides methodological support for each of the SPALTEN steps and would therefore benefit the iPeM application in practice. In a next step, consequently, this concept can be integrated in our software implementation.

DSM representations are based on graph theory. Here, comprehensive analysis methods can be applied to the selection of elements of interest. Prominent examples would be communication path analysis or critical path analysis for a schedule of activities. Dependencies between objectives or objects (*e.g.* contradictoriness of objectives or calculation results) might be analysed as well (see Browning, 2001 for DSM analysis methods).

The current software prototype also needs further effort in order to increase its usability for general use since it was only developed for our range of applications. Especially restrictions of the export or import functions have to be mentioned here. The intention to apply the tool *e.g.* in industry without experienced modellers or the application by students in a wider research study leads to open questions considering handling of information. We could show that our approach offers several beneficial functionalities; however the support can only be as good as the information it is based on. Therefore and most of all in order to reduce effort, ways to acquire data and to put it into the model efficiently should be developed.

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Chapter 4

The Functional Basis for Failure Mode Avoidance in Automotive Systems Engineering Design

I.F. Campean and E.J. Henshall

4.1 Introduction

The engineering challenge of automotive systems engineering design has been increasing rapidly over the past couple of decades with the accelerated pace of introduction of new technologies to address environmental concerns and the drive to enhance customer satisfaction. In spite of the development and use of enhanced CAE and virtual engineering tools, the effectiveness of automotive product development process has not increased as expected; this is clearly illustrated by the pattern and cost of engineering changes (Cash, 2003; Wasmer *et al.*, 2011). Related research (Webb, 2002) has also shown that the overwhelming majority of failures in the field are due to system interactions not being adequately managed during the design, which leads to failures due to lack of robustness to operational noise factors.

The failure mode avoidance (FMA) paradigm (Davis, 2006; 2007) has been embraced by the automotive industry as a strategy for enhancing the effectiveness of the product development (PD) process. Underpinned by Clausing's (2004) pragmatic definition "reliability is failure mode avoidance", FMA promotes a strategic focus on early identification of potential failure modes and development of robust countermeasures. The cornerstones of FMA are Davis' (2007) definition of a failure mode as "any condition (technical, planning, procedural) that will require a change to the plan", and the principles (i) that any failure mode should be identified in the same development phase in which it is created, and (ii) that failure modes should only be found and fixed once. The practical challenge with the FMA implementation is that early discovery of failure modes is technically difficult; this is not only due to the lack of hardware for testing early in the programme (which has been quite effectively addressed by CAE and virtual engineering developments), but also to the complexity of the automotive systems which require an integrated multi-disciplinary (mechanical, electrical, controls, software) approach to engineering design analysis and synthesis. It is therefore essential that the engineering tools employed early in the design process adequately support the complexity of the systems engineering design analysis, in particular to identify and cascade all functional requirements - including both main functions and interface functions required for system integration. On this basis the integrity of the design synthesis can be verified and validated early in the design process against critical function failure modes.

The engineering tools commonly employed within the automotive industry to support failure mode avoidance revolve around design FMEA (failure modes and effects analysis) and robust engineering design verification (Webb, 2002; Zhou, 2005). While both these tools have a functional basis, their practical deployment is often divorced from the systems engineering deployment achieved through functional requirements specification and cascade from system level down to subsystems and components. This gap between systems engineering design (SED) analysis and FMA analysis needs to be bridged in order to enable a step change in the effectiveness of product design and development.

The aim of this paper is to present an integrated framework for systems engineering design based on a Failure Mode Avoidance framework underpinned by a structured approach to function analysis of complex multi-disciplinary systems. The framework supports early deployment of function failure avoidance design strategies, within a coherent horizontal and vertical integration with the systems engineering framework. A case study on the development of an electric vehicle powertrain will be used to illustrate the framework, followed by a discussion on the authors' experience with process implementation within the automotive industry.

4.2 Failure Mode Avoidance Framework for Automotive Systems Engineering Design

An FMA framework has been developed by the Engineering Quality Improvement Centre at the University of Bradford, based on collaborative work with the global automotive industry over the last 15 years. The main considerations behind this development were:

- To set up an FMA *process* which is based on integrating existing practices and formal tools (such as FMEA, boundary diagram, function trees, interface matrix, P-diagram, design verification matrix, *etc.*) into a coherent information flow. It is important to base the process on existing tools in order to facilitate the take-up of the FMA process by engineers on a broad basis. The coherent information flow is necessary both to address disconnects between tools which are often used independently and on an ad-hoc basis, and to simplify the process by removing duplication;
- To strengthen the rigour of the analysis, by introducing new tools and enhancing existing tools to facilitate a more structured approach, in particular to support function decomposition, and to reduce the reliance on less structured tools based on brainstorming;

To set up a framework that facilitates the alignment and integration of the FMA analysis with (i) the systems engineering design approach used in the automotive industry, and (ii) the PD process, by enhancing the information content for design decisions at gateways and milestones.

The proposed FMA process, illustrated in Figure 4.1, is based on the following process steps:

1. *Function Analysis*: provides tools to support a structured and comprehensive analysis of functional requirements for the system engineering design, including function decomposition, mapping of functions on design solutions and evaluation of system interface functional requirements to support the flawless system integration.
2. *Function Failure Analysis*: management of early design risk assessment on the basis of function failure modes. The functional basis of failure modes analysis ensures a consistent focus on the customer required functionality (*e.g.* by supporting identification of failure modes due to lack of robustness – *i.e.* unacceptable variability in functional performance) as well as the functional safety considerations for the system.
3. *Robust Countermeasure Development*: provides a framework for robust design optimisation underpinned by a systematic consideration of noise factors (*i.e.* significant factors for functional variability), and based on engineering design strategies for managing the effect of noise factors and analytical methods for functional modelling under uncertainty.
4. *Robust Design Verification*: the aim of design verification is to demonstrate that functions are achieved robustly and reliably under real world customer usage conditions. Robust design verification tools support the development of efficient test methods and procedures to validate the functional robustness in the presence of noise factors at all levels of the system engineering design.

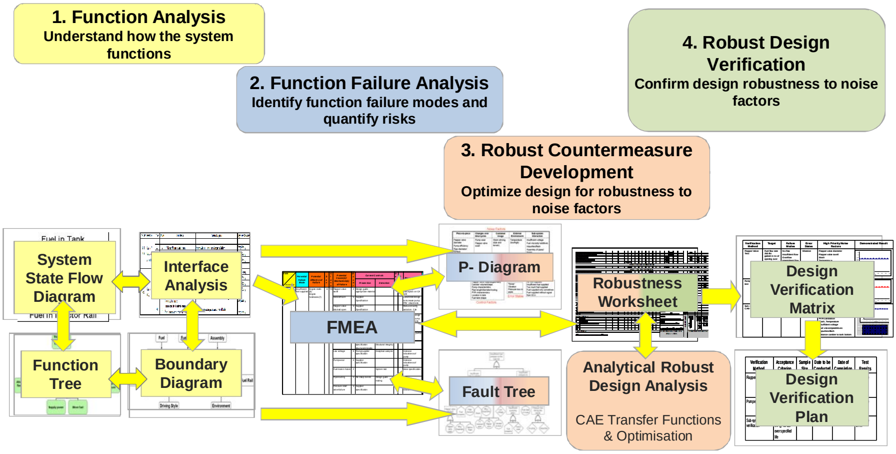

Figure 4.1. FMA framework, showing process steps and support tools

The FMA process as a whole, including the integration of the support tools illustrated in Figure 4.1, has been described elsewhere (Henshall and Campean, 2009; Campean *et al*., 2013); the main focus of this paper is the function analysis step which has been identified as a main weakness in the current automotive engineering design practice. The following sections of the paper provide an outline of the functional analysis framework and tools, illustrated with examples based on a case study of an electric vehicle powertrain (EVP) development. The alignment of the FMA process on the basis of the functional requirements information flow and the integration with the systems engineering design framework and the product development process will be subsequently discussed.

4.3 Function Analysis Framework

Within a consumer focused engineering approach, systems engineering design must focus on robust and reliable delivery of customer required functions. It is therefore essential that the functional focus is maintained throughout the systems engineering design process - from requirements analysis through to design verification and validation.

4.3.1 Function Analysis Challenge

The common theoretical basis for function decomposition analysis consists of the iterative mapping of functions and their solutions (sub-function structures) at increasing level of detail until a solution concept is reached (Chakrabarti and Blight, 2001). The axiomatic design paradigm (Suh, 1995) provides a useful conceptual framework in which engineering design is presented as an iterative (zigzagging) mapping between the functional domain and the design domain. This is illustrated in Figure 4.1, which shows the customer needs and requirements (C_i) in the customer domain which are mapped onto functions (F_i) in the functional domain; functions are mapped onto design solutions (S_i) in the design domain, which in turn are mapped onto part and process characteristics (P_i) in the process/hardware domain. Also illustrated in Figure 4.2 are the design verification loops; this shows that the design verification must be carried out against function at all levels of the design decomposition.

The separation between the functional and physical domains is essential, as it encourages engineers to focus on the functional requirements that need to be delivered by the system, rather that honing in on the design solution at hand. The systems engineering design cascade can be described as zigzagging iterations between the functional and design domains through the levels of the systems hierarchy, until a level of resolution is achieved where engineering design can be carried out (*i.e.* component level). It is essential that *all* functions are identified and mapped/cascaded, and not just the main functions; it is often the case that design engineers focus on main functions, and pay less attention to the functions that support system integration. Functional decomposition has further practical importance in that it helps to define the scope for responsibility of a design team (Eppinger, 1991).

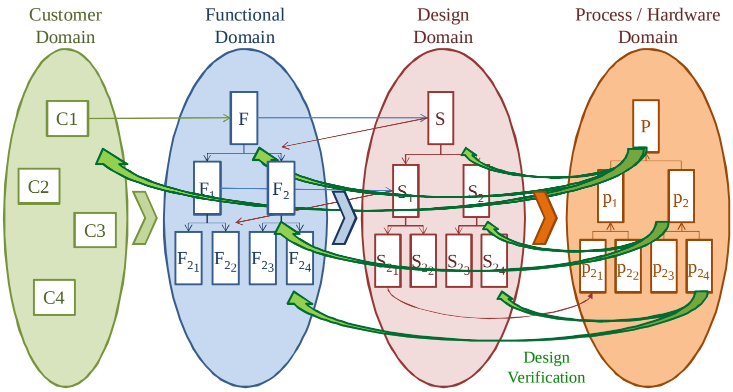

Figure 4.2. Functional decomposition by mapping and zigzagging between customer, function, design and process domains

The common practical approach to system decomposition is to use the "hardware" basis, *i.e.* decompose the system into elements. This is sometimes justified by the fact that automotive design is largely evolutionary, so the hardware structure is stable, in particular at high level (*e.g.* all car models will have a body structure, an engine or powertrain, transmission, driver interface, *etc.*). The function mapping is often done by attributing customer required functions (defined in the *customer* domain) to "hardware" clusters, or by setting up functional or "attribute" teams (*e.g.* driveability) with responsibility for the mapping and integration of a function across hardware groups. However, the increased complexity and multi-disciplinarity of the automotive systems, with a clear shift of focus towards mechatronic and control systems, have made this approach less effective and often impractical. This defines the need for a more structured process for function decomposition which satisfies the following criteria:

- Supports the upfront analysis of the system on a functional basis, leading to a decomposition based on functions, which are then mapped onto design solutions and hardware;
- Facilitates the analysis of interfaces between components and subsystems to identify all functions required for system integration to ensure a robust and reliable delivery of customer required functions;
- Is based on tools and methodology which can be applied across the engineering disciplines (mechanical, electrical, electronic, control and software systems);
- Is integrated with, or based upon, tools currently in use by automotive engineers, to encourage the take up of the process on a broad basis.

The following sections describe the function analysis framework and tools developed on the basis of the above considerations.

4.3.2 Function Decomposition Based on System State Flow Diagrams

The hierarchical functional decomposition is often difficult in practice (Ariyo *et al*., 2008) and can result in different function tree structures depending upon the team conducting the analysis. This can have severe consequences if support functions required for systems integration remain un-mapped.

Several function based analysis and decomposition frameworks have been discussed in literature (van Eck *et al*., 2007). The "functional basis" approach by Stone and Wood (2000) provides a consistent framework including a taxonomy for functions and a coherent representation of the overall function in terms of interconnected sub-functions, defined as operations on flows of *energy*, *material* and *signals* between identified inputs and outputs to the system. The Contact and Channel (Albers *et al*., 2009) framework provides a strong structure of support for functional decomposition. It is based on identifying working surface pairs (WSPs) at the system input and output, and the channel that connects the WSPs within the engineered system. A working surface is described in terms of a state characterised by measurable attributes, and the system function defined as "transfer between the states" (Albers *et al*., 2011). The functional decomposition is carried out by defining surface pairs with the channel, which correspond to design subsystems. While this framework is highly structured, it uses a taxonomy which is not conducive to the analysis of multi-disciplinary systems.

The system state flow diagram (SSFD) has been introduced (Campean and Henshall, 2008; Campean *et al*., 2011) as a diagrammatic approach to facilitate a more disciplined functional decomposition of the system. The fundamental idea behind the SSFD is the identification of discrete (stationary or pseudo-stationary) observable states of the flow of energy, material or information through a system, and then the identification of the functions that the system needs to provide in order to achieve the transition between successive states. The SSFD diagram convention is that the *states* are represented by boxes, which are joined by arrows which denote the *functions* that need to be achieved by the system to transition between states.

Figure 4.3 illustrates graphically a SSFD for an electric vehicle powertrain (EVP), based on a case study presented in Campean *et al* (2011). In an EVP there are three main flows, associated with the three main functions of the system, *i.e.*:

1) charge and store energy;
2) deliver controlled torque to the rear axle;
3) provide power for vehicle consumer units.

The SSFD analysis normally starts with the identification of the inputs (mains energy and driver demand) and outputs (controlled torque at rear axle and electric power to the fuse box) of the system. The SSFD in Figure 4.3 maps the flows through the system based on identification of states and functions that need to be provided to achieve the transitions between the states. For example, following the flow of electrical energy from the input (mains energy, alternative current AC), a next state of the energy flow is "electric energy/direct current (EE/DC)"; the function needed is to "*convert mains AC into DC*". On a diagrammatic representation such as the SSFD it is convenient to illustrate the mapping of functional requirements onto design solutions, established on the basis of design analysis and synthesis. At high level system analysis, as considered in the EVP example, design solutions are usually thought of in generic terms; *e.g.* a "*Charger*" is a generic design solution for the function to "*convert mains AC into DC*". This is illustrated in the SSFD in Figure 4.3, which includes the generic design elements in boxes alongside the functions they achieve.

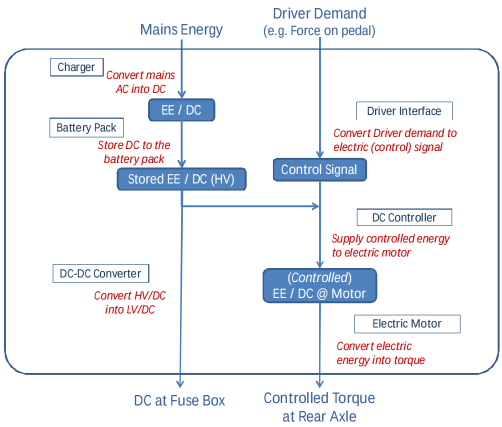

Figure 4.3. System state flow diagram for an electric vehicle powertrain (EVP) system

Thus, the SSFD is a composite graphical representation which combines an analysis in the function domain (mapping the main flows through the system in terms of states and functions), and also mapping the design elements in the design domain as systems that will deliver the function. From the SSFD we can extract a conventional function tree, illustrated in Figure 4.4. In common engineering practice the function tree would normally be derived through brainstorming. It is clear that mapping the states of the flow through the system provides a more objective way of deriving the function tree, addressing difficulties of multiple tree shapes for the same system discussed by Ariyo *et al.* (2008).

Given that the SSFD includes the design elements that deliver the functions, we can easily convert from the SSFD to a conventional system boundary diagram (SBD), illustrated in Figure 4.5, which is a representation of the system in the *design* domain, showing the system components as boxes, placed within the boundary of the system. The SBD also includes the mapping of the main energy flows through the system, represented as arrows connecting the boxes.

It is common practice to include in an SBD the external elements and systems with which the system interfaces (shown in Figure 4.5 outside the box which defines the system boundary). The double-headed arrows between the system boundary and the external interfacing system indicate that exchanges take place in both directions between the system and the external interfacing systems.

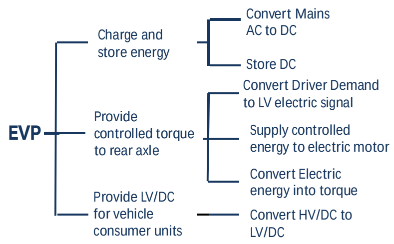

Figure 4.4. Function tree for the EVP system

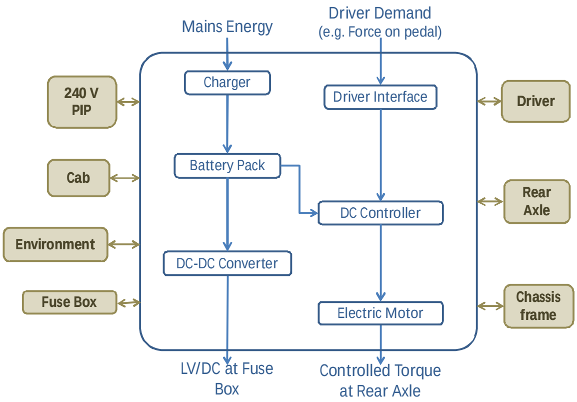

Figure 4.5. System boundary diagram for the EVP system

4.3.3 Interface Analysis

The SBD provides a concise graphical representation of the system, indicating the existence of interfaces between components. There can be multiple and complex exchanges at interfaces both within the system boundary and at external interfaces. The SSFD and the SBD are focused on the main energy flows through the system (associated with the main functions, and represented by arrows in the SBD) and, as such, do not provide a meaningful way of documenting multiple exchanges at interfaces. A matrix based tool, referred to as an *interface matrix* (IM), is commonly used in the automotive industry (Webb, 2002) to systematically analyse the interface exchanges. This type of analysis has been introduced in an automotive context by Pimmler and Eppinger (1994), referred to as *interaction matrix*. In broader literature this is commonly referred to as Design Structure Matrix (Browning, 2001).

Figure 4.6 illustrates an IM analysis for the EVP. The IM analysis includes both *internal* (*i.e.* within the system boundary) and *external* (*i.e.* between the system and external systems) interfaces. The analysis of the exchanges is carried out on a flow basis (Pimmler and Eppinger, 1994), *i.e.* identifying whether at any given interface there is a flow of *energy* (E), *material* (M) or *information* (I). It is also common practice to evaluate whether an interface involves *physical* (P) touch or contact; this information is primarily useful for capturing any geometrical compatibility requirements at the interface.

P Physical, **E** Energy, **I** Information, **M** Material

		INTERNAL INTERFACES						EXTERNAL INTERFACES						
		A	B	C	D	E	F	E1	E2	E3	E4	E5	E6	E7
		Charger	Battery Pack	Driver Interface	DC Controller	Motor	DC-DC Converter	*Driver*	*240V PiP*	*Cab*	*Environment*	*Chassis Frame*	*Rear Axle*	*Fuse Box*
1	Charger		E					P E	P E		E	P E		
			I	I				I			M			
2	Battery Pack	E			E		E	P			P E	P E		
		I						I			M			
3	Driver Interface							P E		P E	P E			
		I			I		I	I		I	M			
4	DC Controller		E			E					P E	P E		
				I		I					M			
5	Motor				E						P E	P E	P E	
					I						M		M	
6	DC-DC Converter		E								P E			P E
				I										

Figure 4.6. Interface matrix for electric vehicle powertrain

While the IM provides a compact analysis of exchanges at interfaces, both internal and external, it does not capture the detail of the actual exchange, normally discussed by the engineering team while analysing a particular interface. This is particularly important as there could be multiple exchanges of the same type at an interface. More significantly, if an exchange (*i.e.* a flow of E, M or I) is identified at an interface, then a functional requirement must be specified to manage this flow. Any exchange can be either detrimental to the main function of the system (potentially leading to a robustness failure), or beneficial, if not essential, for the system function. In both cases a function is required to manage the exchange. An interface analysis table (IAT) has been suggested (Campean *et al.*, 2011) as an enhancement to the IM. The IAT extract, illustrated in Figure 4.7 as an example shows two interfaces - one internal (*Charger* - *Battery Pack*) and one external (*Motor* - *Chassis*). The table includes a description of the exchange, a statement of the engineering function required to manage the exchange and an evaluation of the effect of the interface exchange on the main ("high level") function to which it relates with this main function also being documented in the table. Following Pimmler and Eppinger (1994), the rating of the effect on the main function uses a numeric scale from -2 to +2, the "-" sign indicating that the effect is detrimental to the main function and therefore the interface exchange must be minimised, whereas the "+" sign indicates a beneficial exchange which must be provided to support a main function of the system.

Cell Ref	Interface	Type	Effect	Description	Function Required	High Level Function
1-B 2-A	Charger / Battery Pack	E	2	HV/HC from Charger to Battery pack	Transmit Electrical Power from ***Charger*** to ***Battery***	Charge Battery
		I	2	Battery Temperature info to charger	Detect Battery state of charge (SoC)	Charge Battery
					Transmit Battery state of charge info to Charger	Charge Battery
5-E6	Motor / Chassis	P	2	Motor mounted on chassis	Mount motor securely	Propel Vehicle
		E	2	Electric exchange motor - chassis	Isolate motor electrically from chassis	Propel Vehicle
		E	2	Ground motor electrically	Maintain electrical contact to ground through chassis	Propel Vehicle
		E	2	Heat exchange from motor to chassis	Dissipate heat from MCU through chassis	Propel Vehicle

Figure 4.7. Interface analysis table (IAT) for EVP

It is good practice for the IAT to include the unit or method of measurement of the interface exchange and the associated function, as well as a range or target for the function. It is important that the interface functions are part of the functional requirements specification for the system, and thus part of the functional requirements cascade. For example, we can extract from the IAT all functions associated with the "*Charger*" which will form the basis for the functional requirement specification. While it is tempting to attribute an interface function requirement to one or other of the interfacing systems, this is not always beneficial early in the design process as it might unduly narrow the engineering design options. The recommendation is that interface functions should be cascaded to both interfacing elements with the decision as to which element(s) provides this function left until later in the design process.

4.4 Information Flow within the FMA Process

The IAT is a very comprehensive, information rich document which not only provides a sound basis for the functional requirements specification and cascade, but also feeds into the other tools in the FMA process. The flow of information from the IAT to the other tools in the FMA process is shown in Figure 4.1, with Figure 4.8 illustrating the flow of information from the IAT to the FMEA, which is the main tool for the FMA process step 2 function failure analysis. At each level of analysis (*i.e.* system, subsystem, component) the FMEA focuses on the main functions for the system under investigation. In taking a function failure mode approach to FMEA (Stamatis, 2003; McDermott *et al.*, 2008), the potential failure modes are (i) no function, (ii) partial function, (iii) intermittent function or (iv) function when not required (command failure). Figure 4.8 illustrates an example of partial function failure of the function "charge the battery", showing that the interface functions documented in the IAT provide the potential root causes of this function failure mode, recognising that failure to manage an interface function is likely to cause system failure. Thus completing the FMEA based on the IAT is a much more straightforward process compared to the conventional approach to FMEA (which starts with "brainstorm functions" and continues with the identification of causes in manner which often tends to be based more on the previous experience of failure than on a more fundamental engineering approach). The experience with the FMA process depicted in this paper is that the SSFD based functional decomposition facilitates better (more concise and precise) FMEAs than those developed in a more conventional manner.

Cell Ref	Interface	Type	Effect	Description	Function Required	High Level Function
1-B 2-A	Charger / Battery Pack	E	2	HV/HC from Charger to Battery pack	Transmit Electrical Power from ***Charger*** to ***Battery***	Charge Battery
		I	2	Battery Temperature info to charger	Detect Battery state of charge (SoC)	Charge Battery
					Transmit Battery state of charge info to Charger	Charge Battery

Number	Item / Function	Potential failure mode	Potential effects of failure	Sev	Potential causes / mechanisms of failure	Occ	Current design controls
1-B 2-A	**Charge Battery**	Battery overcharged	Damage to system	7	Battery SoC not detected / sensed	3	Battery temp sensor DVP, Ref. Battery temp sensor DFMEA
					Battery SoC not transmitted to Charger	3	Harness SDS & DVP; Ref Harness DFMEA

Figure 4.8. Illustration of flow of information from IAT to FMEA

There is a similarly straightforward flow of information from the IAT to other FMA tools (such as function fault tree analysis and P-diagram), supporting both FMA step 3 "countermeasure development" and the FMA step 4 "robust design verification". The fundamental conjecture is that a noise factor can only affect a system through an interface and so if the interface analysis is complete (*i.e.* all exchanges have been identified and characterised, and engineering functions specified), then all noise factors that can affect the functional performance of the system should have been captured (so there is no need to "brainstorm" noise factors in developing a P-diagram). Consequently, countermeasure development is in fact design optimisation based on all functional requirements and constraints (expressed in relation to the interface management functions) documented in the IAT. Similarly, the robust design verification process should demonstrate that the system achieves its function given the effect of the interface exchanges identified in the IAT, *i.e.* these interface exchanges need to be included in the design verification matrix.

4.5 Integration with the Automotive Systems Engineering Design

Systems engineering design in automotive industry is carried out at successive levels from high level system-of-systems (*e.g.* vehicle level) down to subsystems (*e.g.* powertrain), sub-subsystems (*e.g.* charger unit) and components (*e.g.* sensor), as illustrated by the Systems Engineering Vee model in Figure 4.9.

The FMA process should be applied at each level, starting with the highest level. Function analysis should always start at the highest level possible, where it can be directly linked to customer requirements, followed by iterative decomposition, setting the scope and resolution for analysis at each level. Within an FMA based SED framework, the functional requirement cascade should be underpinned by the IAT, which documents all functions needed, both for the main flow and the interface exchange management. Function failure modes must also be identified and prioritised early in the process, *i.e.* starting with the highest level system analysis, and cascaded down through to subsystems. As discussed earlier, ultimately, robust countermeasure development is based on robust design optimisation and as such can only take place at component level. Therefore countermeasure development cannot be completed at the higher levels system analysis (*e.g.* vehicle or powertrain), but functional requirements (including interface requirements) and critical function failure modes are cascaded down through the Systems Engineering Vee, to support subsequent robust countermeasure development. Design verification can be planned at each level of the system analysis, incorporating the effect of noise factors identified through the interface analysis. Verification tests can be planned at each system level to ensure that the reliability and robustness of the system is confirmed given the design countermeasures are in place.

The integration of the FMA process described in this paper with the SED Vee framework is illustrated in Figure 4.10. This shows the holistic two-dimensional integration of the FMA framework with the SED framework, based on:

- *Horizontal integration*: based on the iterative deployment of the FMA process at each system engineering level – from vehicle level down to powertrain, charger unit and sensor component;
- *Vertical integration*: based on the cascade of functional requirements, critical failure modes and design verification plans through the system levels, with iterative upward validation on the basis of the design verification results.

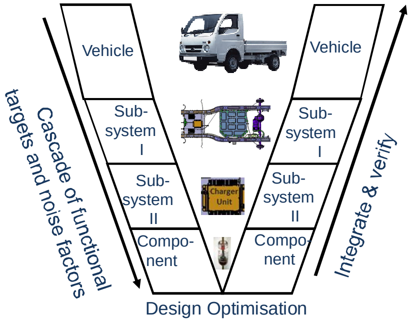

Figure 4.9. Systems Engineering Vee

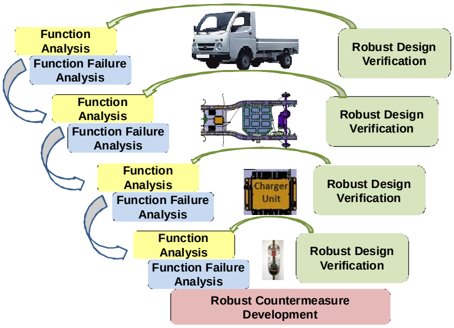

Figure 4.10. SED framework based on FMA

It is important to note that the IAT provides the basis of a strong information flow throughout the systems engineering cascade. For example, from the EVP IAT we can extract all the functional requirements associated with the *charger unit*, (including interface functions) and cascade these down from the powertrain level to the charger as a subsystem. The subsystem level analysis will be carried out by a different team, often at a different company (*e.g.* a supplier) if the component is outsourced. It is therefore very important that all interface functions are identified and cascaded, as well as the significant potential failure modes, because otherwise the supplier team are unlikely to have a vision and understanding of the exchanges between their system and other systems (both internal and external). The implication is that the subsystem FMA analysis should be carried out within the context of the system level analysis, rather than as a stand-alone separate analysis, which is often the engineering practice. For example in analysing the charger unit, we are in fact zooming in with the analysis to one of the subsystems within the EVP. Looking at this cascade in terms of the SBD, it is clear that the charger unit will have the same external interfaces as the EVP, shown in Figure 4.5 (although the charger will not interface with all EVP external elements **-** *e.g.* there should be no interface with the electric motor), and some of the EVP internal interfaces will become external interfaces for the charger (*e.g.* the battery pack is an external interface for the charger unit). Figure 4.11 illustrates the cascade of interfaces to the charger unit in graphical format, the detail of the interface exchanges being already documented in the EVP IAT.

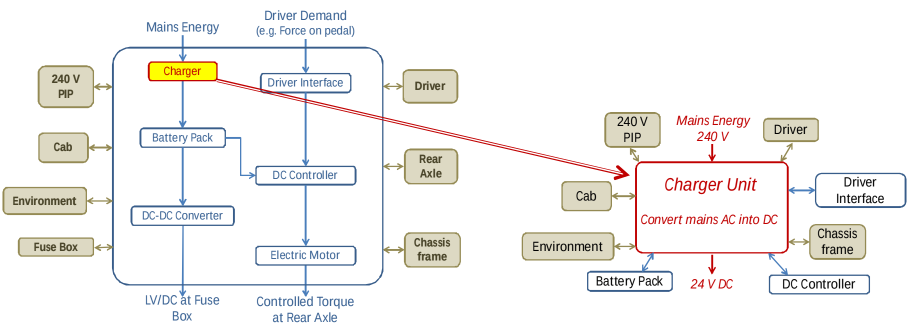

Figure 4.11. Illustration of the cascade of interfaces to subsystem level

Being integrated with the SED framework, the FMA process is also integrated with the Product Development framework. In this context the FMA process fulfils an important role in that it provides the information content for effective gateway review process, on the basis of functional requirements, critical functional failure modes and robust design verification outcomes (Campean *et al.*, 2013).

4.6 Discussion and Conclusions

The aim of this paper was to present an approach to systems engineering design which embeds the failure mode avoidance paradigm, framework and support tools. The FMA framework developed by the Engineering Quality Improvement Centre at the University of Bradford is based on a four step process, illustrated in Figure 4.1, which is iteratively applied at all levels within the systems engineering cascade, as illustrated in Figure 4.9. The FMA framework has a very strong functional basis, and it promotes the discipline of maintaining the domain separation throughout the systems engineering design process. This is seen as an effective way of avoiding the common pitfall of honing in on a known design or "hardware" solution, without considering the functional requirements in a holistic way (*i.e.* including the system integration requirements).

A main focus of the paper has been the discussion of a structured approach to function decomposition. This has great practical importance, not just in order to produce a representation of the team's understanding of how the system achieves its functions, but it also helps to define the scope for responsibility for the design teams on a functional basis. This is useful both in terms of aligning the PD organisation with the functional decomposition of the system, and also in communicating functional requirements for outsourced subsystems.

The function analysis and decomposition is based on three main tools: system state flow diagram, boundary diagram, interface matrix and interface analysis table. The function tree, which has long been regarded in industry as the main tool for function analysis, can be derived as a by-product from the more structured and fundamental SSFD tool. The iterative use of these tools, as discussed and illustrated in Section 4.2 of this chapter, provides a highly structured framework which maintains the separation of the domains throughout the analysis, leading to a complete and comprehensive functional decomposition and mapping, covering both the main functions and those required to manage interfaces. Information gained from this analysis is compactly documented in the IAT. Of the methods discussed in the literature, the contact and channel method (CCM) (Albers *et al.*, 2009) offers a similarly structured and comprehensive approach, which offers both a rigorous functional decomposition and potential for identifying interface exchanges as functional requirements. However, the CCM appears to be less portable across engineering disciplines in particular on modelling information flows, and it is less integrated with other tools commonly used in the automotive industry, which will likely inhibit a large scale take up by the engineering teams.

The IM tool widely used in the automotive industry is similar to the design structure matrix (DSM) (Browning, 2001; Clarkson *et al.*, 2004), except that it places a strong emphasis on the external interfaces (with external elements and systems) - which play an important role within the automotive industry. As argued by Davis (2007), the noise space that a vehicle is subject to even under "normal" driving conditions is much more complex than the noise space in industries such as nuclear or even aerospace. The framework used by the IM tool to identify interface exchanges is based on the generic classification of flow as energy/material/information and physical touch. An alternative framework discussed in literature is the so-called “linkage modelling method” (LMM) (Jarratt, 2004), which suggests a characterisation and classification of interface exchanges in more detail - which has some advantage from a mechanical engineering analysis point of view, as it provides a more accurate description of the linkage compared to the PEIM framework. However, the IM approach is much easier to apply to a multi-domain context - which is an important practical consideration.

The authors’ extensive experience of facilitating the implementation of this process in a real world automotive systems engineering design context has been very positive. Feedback from engineering teams working across different systems (representative of the multi-domain context of automotive systems engineering design) has highlighted (i) the structured approach to function decomposition which removes the reliance on brainstorming, delivering a more objective and comprehensive analysis; (ii) the portability of the approach across multiple domains - the same tools and process can be used to analyse predominantly mechanical components as well as software features; and (iii) the strong integration of the whole process through the information flow between the tools. While completing the function analysis tools, in particular the IAT, still require a significant effort/resource, this is seen as an integral part of the systems engineering design process (as the basis for functional requirement specification) and it greatly simplifies the completion of the FMA downstream tools - such as the FMEA. Most importantly, this analysis is carried out early in the product development process, providing strong facilitation for failure mode identification.

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Chapter 5

Innovative Conceptualisation through Sense Stimulation in Co-lab Development

J. Capjon and S. Hjelseth

5.1 Introduction

Should collaborative lab developments be based on technological or human preconditions? This paper initially suggests how complex human conceptualisation patterns can be described and modelled comprehensively in an innovation framing. A research-based metaphorical model, called the Plant of Collaborative Conceptualisation (PoCC), is summarily developed and visualised. The model is then used as a template for the following process development including evaluation and choice of new ICT tools that can stimulate basic human ideation patterns. The resulting *SimSam lab* is based on a 360 degree maritime simulator adapted to negotiating and elaborating several alternative propositions, and simultaneously displaying all relevant background data. Resulting 'perception map' formats secure easy comparability and integration of parts into new solutions. And 'participative drawing' and 'display organisation' are achieved through employment of multi-touch technology. The paper basically describes the principles and reflective design process behind its realisation.

5.2 New Contexts for Co-innovation

This project originally addressed cross-professional collaboration challenges in the Norwegian maritime sector and how industrial design thinking can influence this basically conservative environment towards enhancement of innovation level. Development processes for ships, bridges, machines and multiple crew are highly complex, involving several knowledge regimes. The R&D team had special competences which early brought the process out of the maritime sector as such and into a landscape of human capabilities. When generalised preconditions for all human actors were matched with knowledge and technology from the maritime and ICT sectors, new opportunities emerged.

How can human preconditions for collaborative conceptualisation be described - and how can updated tools be adapted to support basic human conceptualisation patterns? Innovation can be understood as idea generation, development of the idea into a product or service and marketing of the result. The definition suggests that ideation is an essential aspect in innovation. New conceptual ideas can be created individually by one or collectively by many actors. In collaborative ideation and development processes the actors are supposed to be different, which can involve differences in education, personality, values, priorities, action patterns and languages - or in short; dislike mentalities. Innovative interaction involves breaking mental barriers and seeing problems from new angles, and diverging approaches, backgrounds and views are accordingly highly needed. But for many reasons integrating human differences in shared scenarios invariably have a tendency to lead into problematic processes.

Many collaborative innovation and learning labs have been developed that are basing their process approaches on new technology support (www.lilan.org/; www.elearningeuropa.info/; www.creativelearningsystems.com/). The developments have, mainly through behaviour studies, reported numeral success stories. Behaviour studies or related design studies do not, to the knowledge of the authors, model the human preconditions for individual or collective creative processes understandably to an audience of design/innovation oriented professionals. This, of course, has to do with the complexities and professional controversies of studies involving human consciousness.

In Capjon (2004), which is reported and slightly revised to updated premises in Section 5.3, two main objectives were: (i) to describe individual and collective creative processes seen from perspectives of dislike human actors and (ii) to develop an easily understandable model of a cross-professional innovation process, which includes diverging mentalities of participating actors. Some human preconditions for interaction will be summarised as basis for the process modelling - through cognitive psychology, neurobiology and phenomenology triangulation.

5.3 Sense-stimulation of Central Human Capabilities

In design oriented fields there is general agreement that shared conceptual representations will support communication between innovation actors. Some examples are: Ehn (1989); hands-on-experience, Star (1991); boundary objects, Perry and Sanderson (1998); procedural artefacts, Brandt (2001); things-to-think-with, Boujut and Laureillard (2002); intermediary objects, Bucciarelli (2002); linguistic artefacts. The representations are supposed to represent mental ideas materially and thereby basically stimulate body-based senses. They can be drawings/graphs on paper, calculations, mock-ups, abstracted or detailed physical models or the like. But ‘conceptual representations’ will also in the following include ‘virtual’ visualisation on computer screens or projected onto display walls.

Cognitive psychology has outlined mental processing in conceptualisation as being based on *internal visual images*. Finke, Ward and Smith (1992) describe how much of everyday thinking is based on formation and transformation of visual images and how pathways of creative exploration are often opportunistic and unforeseeable. Kosslyn (1995) has specified four types of processing of mental imagery; *image generation, image inspection, image transformation* and *information retrieval* from long-term memory.

There are basic controversies, *e.g.* between neurobiology and philosophy, as to the nature of human consciousness and so-called Cartesian dualism. Velmans (2000) presents an outline of consciousness where updated proceedings of neurobiology are embraced if they are not misinterpreted as its ontology; “no discovery that reduces consciousness to brain has yet been made”. Consciousness, in his view, is restricted to situations where awareness or phenomenal content is present, and he specifies its three possible foci: space, body and ‘inside’. Engaged human experience then is where *conscious awareness* is focused at will, and not in the brain where its physical representation is. But these ‘locations’ are seen as *two fundamental aspects* of being in the world. They can together account for individual perception - which belongs to the encompassing world totality where all individual views are embedded. This *reflexive monism* framework reconciles phenomenology and neurobiology as two valid and inter-dependable approaches to human action - and is seen as highly relevant for development of design oriented theory.

Lakoff and Johnson (1999) describe the neurobiological view of embodiment of experiences through synaptic brain cell connections. But in creative conceptualisation *breaking down old* embodied patterns through *forming new* embodiments of new solutions’ advantages, become central objectives. Merleau-Ponty (1962; 2002) with his *intermonde* concept (between-world) describes a state of being between subject and object where wholeness can be immediately experienced. Ornstein (1986) describes between-world scenarios of *deautomatisation*, where movement, dance, play, rituals, music, aesthetics, contemplation *etc.* can break habits to achieve intuitive opening of the mind. Böhme (2002) likewise describes how *atmospheres* have high importance for communication through the connection they produce between actors, and how immediate perception of atmosphere and wholeness comes before separation of *I-pole* and *thing-pole*. Husserl (1900) basically describes how engaged experiences must converge repeatedly over time to achieve stable *understanding or meaning*. All these aspects contribute to the resulting description of a humanly foundation for a conceptualisation model.

5.3.1 Developing a Conceptualisation Model

Conscious attention can be focused at will between ‘internal’ and ‘external’ perspectives. Much used terms for these dialectic ‘positions’ are mind/world, subject/object, mentality/materiality, I-pole/thing-pole or spirit/matter. In a human ideation/conceptualisation process the consciously focused attention will be alternated between the poles, where each position is seen as a representation of the other. In innovative action a material model can be made to represent the internal perspective (idea) and a mental model, in turn, can represent sense-stimuli from the external model. A generated idea can be seen as a mental model resulting from dynamic interaction between internal and external foci. In emotional experiences the attention can be focused on wholeness instead of polarities.

Figure 5.1 depicts an (individual) ideation or conceptualisation process, where conscious attention (dotted spiral) originates in a between-world experience and gradually converges towards a matured relationship between internal and external representations through dynamic and interactive cycling between the two.

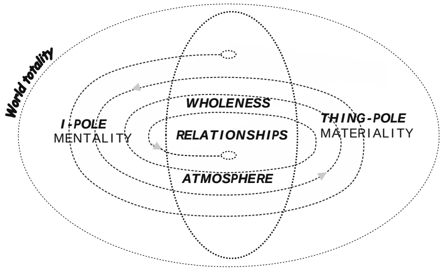

Figure 5.1. A basic conceptualisation pattern describing conscious awareness flow towards understanding

Figure 5.2 on the right side models the Process of Experiential Learning (Kolb, 1984), which alternates between the mental foci Concrete experience, Reflective observation, Abstract conceptualisation and Active experimentation, of which 1' and 4' are external and 2' and 3' are internal. On the left side is attached a model of a 'design cycle' agreed upon by four students (unfamiliar with Kolb or philosophy) reflecting on their own design work - which includes a material representation of their conceptual idea. Since Kolb focuses cognition (intellect) and the students focus aesthetics (emotion), the dislike aspects are seen as interdependent modes of design conceptualisation (called adaptive and formative respectively) - and connected through the material representation, representing both modes.

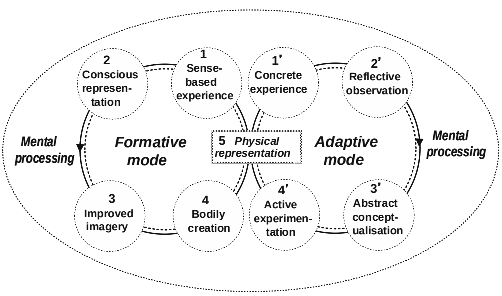

Figure 5.2. A cyclic design process showing interconnection between awareness on forming or adaptation aspects

Figure 5.3 expands the Figure 5.2 pattern by integrating the Figure 5.1 dynamics. Conceptual learning achieved through iterative mentality/materiality cycling converges towards an understanding (meaning) represented in the visual/physical model. The conceptual representation (model) in this scheme is supposed to represent (absorb) the actor's mentality - *e.g.* a vision of a conceptual solution.

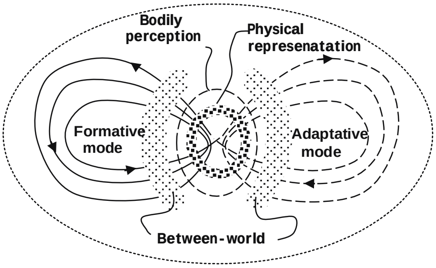

Figure 5.3. Model of an individual design conceptualisation process

Figure 5.4 further expands focus from an individual conceptualisation process to a collaborative process where several actors (three in figure, but many more possible) cooperate towards shared understanding or meaning. Dislike individual formative and adaptive capabilities give differently depicted patterns for each actor. Here the fact that the (physical) conceptual representation can be shared (whereas the mental representations are private) produces a unique opportunity for negotiations between diverging minds - if it is produced in such a way that it basically can represent all the individual mentalities.

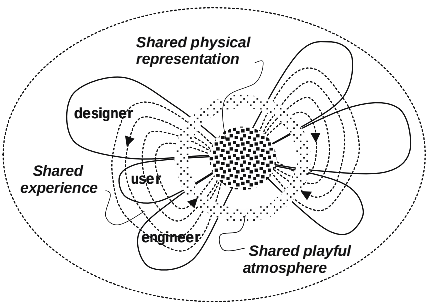

Figure 5.4. Model of a collaborative conceptualisation process with three collaborating actors

Figure 5.5 finally assembles the repeated efforts of a collaborative innovation team to reach shared understanding or meaning - or a conceptual solution where all individual actor views are represented and integrated. Individual mentalities are depicted as 'leaves' resulting in 'junctions' representing collaborative efforts, which can be evaluated (level) since they are modelled and shared by all actors through individual senses. Several efforts are made, evaluated, experimented with, negotiated and improved iteratively - some resulting in breakdowns and other bearing new ideas for improvements as basis for the next iteration. Ideation thereby becomes a process in dynamic focus flux between minds and world - and depicted as a (measurable) stem with leaves and a flower as the resulting solution (with seeds for next generation). The resulting metaphorical *Plant of Collaborative Conceptualisation (PoCC)* model suggests new terminology for central junctions: *Visiotypes* for early visions, *Negotiotypes* for collaborative draft models, *Prototypes* only for finished concept models and *Seriotypes* for market-test models. Like a plant, which adapts to the conditions where it grows, each PoCC model will have individual form. The five models are built from complex patterns of human consciousness. They are developed for professional innovation actors, basically uneducated in psychology, neurobiology and philosophy. The depictions can thereby serve as example of how vision sense stimulation can facilitate simplified understanding of complexity. The metaphorical PoCC model displays human preconditions for innovative conceptualisation - can it also prescribe principles for how a collaborative lab shall be organised and equipped?

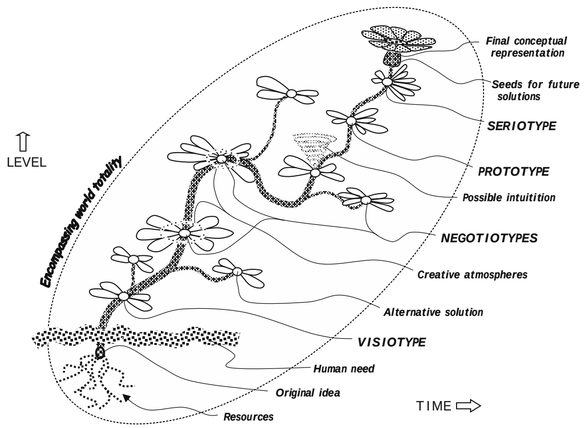

Figure 5.5. The Plant of Collaborative Conceptualisation (PoCC) model

5.4 A Lab for Perceiving Complex Conceptual Contexts

The PoCC model advocates: a) dynamically repeated external sense-stimulations of conceptual aspects as the basic principle for internal idea generation (mind/ world interactions), b) iterative idea representations based on shared learning from stimulated experiences, c) development of alternative concept suggestions which can be collaboratively experienced, d) the inclusion and elaboration of all the actors' different mentalities in the iterations and e) the importance of evaluating the alternative concept solutions in framings of wholeness. The model was originally developed from case studies based on material Rapid Prototyping. A new research question was now formulated: How can the above principles be further enhanced through implementation of new digital visualisation technology? In search of relevant answers some problematic characteristics of collaborative innovation processes were addressed - based upon many years of own experience in Norwegian industry:

a) *Complexity:* Updated co-innovation projects are based upon a multiplicity of data-file information formats,
b) *Anarchy:* As the amount of data tends to ‘explode’, typical projects have a tendency to achieve a chaotic structure, and
c) *Overview:* If the design aspect of alternative conceptual solutions is an issue of concern, detail implications have a tendency to demolish critical understanding of wholeness.

Therefore; in scenarios involving shared perception of actors with different backgrounds and schooling, the *visualisation principles* become highly relevant for a lab. The PoCC model prescribes alternative and iterative solution models. And the interaction between the co-actors will involve actions like evaluating different propositions, studying part-solutions, tentatively integrate part-suggestions, visually experiment with new combinations - and eventually trying to come up with radical concepts. *Comparability* then becomes a major challenge, including how data should be prepared and processed. This will involve aspects like the organisation and presentation of data aimed at:

1. Achieving and maintaining basic overview of complexity scenarios,
2. Developing visual comparability between different concepts,
3. Understanding the process stages behind each conceptual suggestion and
4. Organising and displaying data according to their basic nature.

Wodehouse and Ion (2010) have analysed the use of integrated groupware and digital libraries in collaborative design projects. They found that employment of such formalised procedures are basically considered as inconvenient in practical conceptual design work, not the least because they have emerged from librarianship rather than design - “and do not lend themselves to creating an explorative experience”. Instead they suggest a number of flexible approaches like fast browsing for information sources (Internet, *etc.*), emphasising the use of sketching, physical modelling and tagging of specific applications - “to allow the information to be used freely as stimuli in the generation of ideas”. The analysis supports many of our basic intentions. But their premises were found to be based on employment of small data screens for information displays, thereby limiting the possibility of functional overview and fast data access.

Our analysis ended up with a strategy at the opposite extreme, in accordance with the PoCC prescription of wholeness contexts. *Large screens* have a capacity to visually display large amounts of relevant background data. And it eventually emerged that displayed relevant data can be made *instantly available at a twist of the head*. The challenge then becomes how to organise data displays aimed at ‘intuitive’ perception - or so that it is instantly obvious for actors where to look for the support data of the problem in question.

To evaluate and compare between alternative conceptual propositions, each backed by much data, it appeared as essential to perceive the differentiated data as *ensembles* - in the sense that all data related to a particular solution should be presented as *one visual unit*. In evaluative discussions it would thereby be easy to distinguish between the conceptual alternatives.

Then came the problem of how to organise the display of each visual unit in an ‘intuitive’ way. It was found that the PoCC model can represent a relevant answer. It is built on an ‘archetypical’ concept for visual displays, at least in the western world, where the vertical axis represents *level* and the horizontal axis represents *time.* Gradually increasing conceptual level is thereby displayed visually along the diagonal. This invites to using this region for visual presentations of conceptual drafts - eventually leading to a negotiated concept proposition (*e.g.* 3D modelled) at the top right corner. But how should supportive data be displayed? Supportive data can be categorised in several ways, but hard-to-understand categorisations were seen as contra- productive. It was agreed that two simple categories will suffice: *abstracted* data and *concrete/visual* data. The lower right corner was assigned for abstract data (lower visual level) and upper left for visual data (higher visual level). Supportive data will then be perceived visually as supporting solution proposals which can be iteratively displayed along the conceptual diagonal. Figure 5.6 depicts an outline of one development story with relevant data and stages. It is intended as an easily understandable, or ‘intuitive’, visualisation of a basically complex conceptualisation process; a *perception map.*

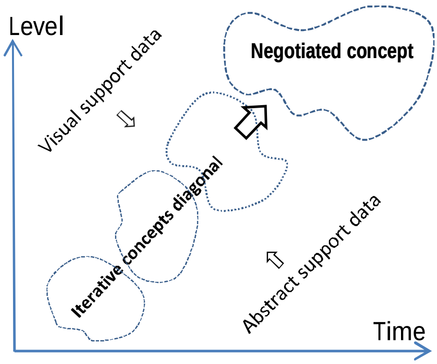

Figure 5.6. Easily understandable structure of one ensemble screen image, a *perception map*

How, then, should appropriate comparability between different perception maps be solved? It was agreed that a commonly shared experience from PowerPoint presentations should be avoided: the removal of slides after each display leads to ‘wasting’ focus on trying to remember data instead of using mental capacity for conceptual processing of the data. If perception maps of alternative solutions are placed *beside each other* instead, then instant comparisons between the central visualised aspects of each proposition could be easily facilitated - for all actors to see at a twist of the head. What aspect to focus could be achieved through equipping the actors with some pointing device. How could such a large-screen scenario be practically arranged?

Maritime simulators were eventually found to have potential attributes to comply with the specified functional characterisations. They consist of (split-up or coordinated) central projectors displaying visual projections on a large circular vertical screen - up to 360 degrees. Several conceptual perception maps (Figure 5.6) can be displayed consecutively, one at the time, beside each other. Each visual unit is then easily distinguishable from the alternative concepts represented on the neighbouring projections. And neighbour projectors can additionally be coordinated, *e.g.* for aspectual 3D modelling. A highly flexible arrangement thereby results.

For the realisation of a co-lab according to these specs, a 360 degrees barrel-shaped geometry of 11 metres diameter and 4 metres height and seven projectors was chosen (eventually called the *SimSam lab).* As a SimSam case example can serve a co-design process involving elaboration of three alternative concept propositions. One projection displays the design brief/framework, three separate projections display perception maps of each concept, one projection can display new concepts-in-the-making and two coordinated projectors display 3D simulations of selected details, one at the time. Coordinated projections are also appropriate for static/dynamic simulations of selected design issues.

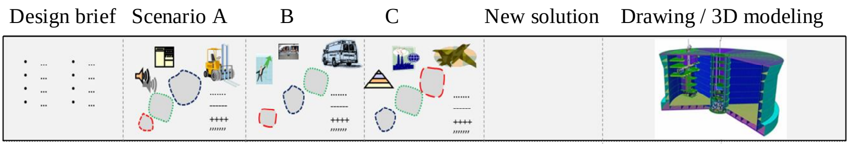

Figure 5.7. Outline example of unfolded 360 degree barrel screen with seven split-up or coordinated projections displaying perception maps. See Figure 5.6 of three conceptual propositions plus work spaces for co-creating new solutions.

The actors are placed on the floor near the screen centre. All screen images (Figure 5.6) are simultaneously comparable beside each other to optimise visual understanding. Simply in turning, standing or sitting on rotatable chairs, and pointing with laser pens all displayed scenarios are available, instantly and easily perceivable, for on-the-spot shared elaboration by all the actors, see Figure 5.8.

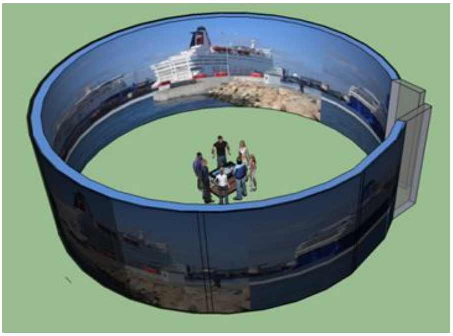

Figure 5.8. The resulting SimSam lab outline with coordinated or split-up projectors

Understanding from the PoCC model has thereby led the development to a physical arrangement where the need for large screens can be seen as a consequence of the need for rapid comparisons and integration between complex visual data of alternative concepts. Through further real-time 3D simulation experiments it was found that large screens can have additional perceptual advantages, particularly in early-phase developments. 3D CAD tools have eventually become crucial in product development of construction and animation industries. But the tools are not basically designed for creative cross-professional design processes, where “changing existing situations into preferred ones” (Simon, 1981) is at stake. Rhea (2003) describes how visualisations and models are created to simulate future scenarios that are often used in the final presentation of concepts – and *not as creative tools* in the conceptualisation phases when designing. As an improved strategy Turkle (2009) has suggested how employment of simulations can stimulate body/mind experiences of future conceptual scenarios in context, and visual *immersive systems*, like The CAVE (Cruz-Neira *et al.*, 1992), have been developed accordingly. By using a 360 degree panoramic view screen for both simulations and specificities, the team’s intention was to achieve a creative tool setup according to Rhea *and* immersive scenario displays according to Turkle. In an experimental collaborative workshop of future scenarios for Uddevalla harbour (Figure 5.9 left-hand side), it was efficiently demonstrated that perceptual limitations could be challenged through combination of large screens (3 coordinated projectors) and interactive simulation software (CryEngine was used). Figure 5.9 right-hand side shows a following health-care workshop based on ensemble projections of alternative concepts in accordance with Figures 5.6 and 5.7. Hopefully a powerful process can result from further development, with ability to simulate lifelike scenarios where ideas are visualized and animated to their use or action in realistic contexts – dynamically and instantly comparable with perception maps displaying basic conceptual aspects displayed in Figure 5.7.

Figure 5.9. 3D harbour simulation (left) and *healthcare co-development* (right)

A new challenge then becomes: How shall the scenarios be organised in terms of operational visualisation characteristics and tooling?

5.5 New Sense-stimulating Conceptualisation Technology

Support data will generally be of diverging visual expressions that are not appropriate for supporting a Figure 5.6 outline, whereby *reorganisation* becomes desirable. Central perceptual aspects with importance for choice and capacities of appropriate support-tools were specified accordingly:

a) *Organisation:* data-based statistics, graphs, quantifications and pictures, should be properly organised for comparable discussions,
b) *Categorisation:* data should be grouped according to their conceptual relevance, *e.g.* functional, quantitative, qualitative, detail and
c) *Scaling:* files should be easily scalable to comply with perceptual claims.

Supportive controls and drawing tools were evaluated for their visual conceptualisation support, including:

a) *Participation:* Capacity for new or add-on sketching contributions by all actors regardless of drawing competence,
b) *Speed:* Time compression because of a tendency to loose mental focus fast,
c) *Changeability:* Capacity for fast changes of visual representations,
d) *Inter-changeability:* Capacity of flexible altering between different software
e) *Simulation capacity:* Potential for static and dynamic 3D simulation.

Could technology be found which is adaptable to these perception-based operational characteristics? New touch- or multi-touch technology builds on perceptual stimulation as such, and it was early considered to be highly relevant. The technology employs scanning of touch impulses on a screen (*e.g.* fingers), where the registered signals are digitised and can be employed for sense-stimulating facilitation. See Figure 5.10.

Figure 5.10. Participative drawing on multi-touch table

In up-front testing and evaluations touch technology was found to comply with the above specified operational preconditions. It was found highly appropriate for rapid and effective organisation of data files, in particular for visualised files including graphs, figures, photographs, statistics *etc.*, but also for abstracted data. It was easy and fast for data manipulation, including categorisation, grouping for relevance and scaling. And it was found exceptionally well suited for arrangements and presentations of ensemble screen images, or display organisation, in accordance with Figures 5.6 and 5.7. So-called bi-directional (BiDi) technology has possibility of recognition of objects on the surface (‘tagging’), which involves that material objects, hand-operated upon the screen, can interact with data models through digital addressing. Physical models can be moved and played with (*e.g.* by role-playing actors) in sense-stimulating digital landscapes.

Multi-touch screens were also evaluated, with different software, for their ability to become a functional platform for digital drawing. The test showed that touch-screens employed for drawing exercises and combined with large-screen displays, appear to have a high potential for enhancing conceptual understanding according to the above specified claims. Screen employment can be time-efficient, rapid sketching can be easily facilitated, fast changes between wholeness and detail aspects can be easily achieved and changes between software packages can be done effortlessly - with high capacity for 3D design and simulation.

An important finding was that a touch table is appropriate for allowing several actors to participate in drawing actions towards shared understanding (Figure 5.10).

Actors can easily assemble round a table and contribute to *participative drawing* through finger-touching or with a touch-tool, to stimulate integrated contributions by all participants - regardless of drawing competence. This level of participation cannot be achieved in traditional drawing, which is basically dependent upon the skills of one drawing actor and her ability to interpret others actors’ mentalities.

The efficiency of the described visualisation scenarios is, of course, highly dependent upon the capabilities and competence of an operator. It was accordingly specified that SimSam lab activities should be led by a *facilitator*. A facilitator should have high competence in operating all the tools including several appropriate software packages. One important operational aspect will be, in advance of collaborative workshops, to prepare alternative conceptual ensembles in accordance with the pre-established outlines of Figures 5.6 and 5.7. Another important assignment will be to stimulate engagement between the actors through visualisation and integration of *their* mental images - in addition to her own.

Supportive materialisation tools were additionally found desirable for fast and functional facilitation. In accordance with Capjon (2004) 3D Rapid Prototyping tooling and 3D laser scanning were integrated for their ability of physical sense stimulation and features like speed, specificity and reversibility. Also workbench facilities for mock-up production were integrated, with materials like card-board, wire, clay, foam, *etc.*, for additional enhancement of sense stimuli. See Figure 5.11.

A project assignment was to establish a network for collaboration-at-a-distance between project partners in Sweden, Denmark and Norway. For this purpose so-called nodes were developed and used throughout the project. They were based on the same principles as the large lab, but equipped with two large flat screens and an internet-connected video/audio system – all at affordable costs.

Figure 5.11. Early full lab model equipped with large screens, touch-table interface, 3D printing, mock-up facilities and 3D scanning

5.6 Conclusions

Humans conceptualise ideas through active perceptual stimulation of their senses - as elaborated and displayed in the metaphorical PoCC model. The model was used as a template for an analytic design process of a new collaborative lab concept.

Perceptual complexity problems of current co-development processes were solved through PoCC-like *perception maps,* where easy comparability between alternative concepts is achieved through standardised graphics. Immediate access to diverse data for elaboration purposes and integration between alternative concepts were solved through *large screens* of a maritime simulator with side-by-side map arrangements and laser pointers for all the actors. Large screens were also found appropriate for *simulation* of future conceptual scenarios in context. Sense stimulation in collaborative conceptualisation was achieved through employment of a large *multi-touch table*, through which *participative drawing* and *display organisation* were facilitated by a facilitator with appropriate visualisation competence.

Table 5.1. Summarised features of a SimSam-supported co-innovation process

Developmental phase	Sense stimulation	Physical realisation
Organisation of premises	**Visual preparation** of data	**Laptops** before meeting
Arrangement data availability	**Immediate access** to data	**Large screens**, 360 degree simulator
Grouping in alternative conceptual ensembles	Simultaneous **comparability** between concept suggestions	**Side-by-side displays**
Intuitive arrangement of each alternative	**Conceptual diagonal** displays + supportive data from sides	Immediately comparable **perception maps**
Rearrangements of part solutions	Model developments + **Participative drawing**	**Mock-up facilities** + fast digital drawing with software
Elaboration of new concepts	**Simulation**, rapid 3D models + physical realisation	**Touch-table** with software + 3D printing (RP)
Verification of best concept	**Sense-based experimentation** with alternatives	**Facilities** for simulation and physical experiments

The authors thank the European Union for the project grant through the MARKIS program (Maritime Competence and Innovation Skagerrak Kattegat). Although maritime applications and cases have been focused during the development, the resulting principles, tooling and lab outline can be employed generally within any industrial or public sector where conceptual collaboration is at stake. Up-front design and development have been objectives of this paper, but explorative case studies of lab applications, experiences and extensions will now follow.

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Chapter 6

Determining the Degree of Parallelisation of Processes in a Tri-process-modelling-tool

N. Szélig, M. Schabacker and S. Vajna

6.1 Introduction

The current situation in product development is increasingly characterised by dynamic and complex tasks. The development of a product is not a linear process, which is continuously guided by well-defined steps to the target. Only few products are newly designed, most are adaptation, modification or variant designs. However, all cases have a common requirement when the processes have to be deposited for the first time in a process management tool: this must be done quickly and without great effort. There are various modelling techniques and languages such as network diagrams (*e.g.* flowchart representation as Business Process Model and Notation (BPMN)), Design Structure Matrix (DSM) and Container Modelling, the advantages and disadvantages and interaction of which are presented in this paper. Furthermore, a possibility is shown to optimise processes with the aid of simultaneous engineering.

For effective product development it is necessary to monitor and control all the processes and activities involved. In order to obtain a common understanding of some of the terms used in this paper, they are predefined as follows:

- A *process* consists of interrelated activities or sub-processes for performing a task. The amount of activities is not limited in its length and duration. The compounds of the activities or sub-processes are not rigid. Thereby a sub-process is the subset of a process and also a set of activities or other sub-processes (Freisleben, 2001; Schabacker, 2001).
- A *project* is a living process (or several connected ones), in which boundary conditions are defined and which is always unique (DIN 69901, 2009).
- A *process element* describes an activity, operation or one or more working steps respectively, and is initiated by one or more events and ends in one or more events. The individual process elements (activities) are closed in content and relate to each other in a logical context. The description is made on the basis of a defined structure, so that they are also suitable for use in computer-aided systems (Freisleben, 2001).

- A *process model* is a procedure model, based on the description and modelling in the form of processes, for efficient treatment of scopes of tasks, which are composed of a variety of interrelated or interactive single activities (Motzel, 2006).

One can distinguish between different types of processes. In Table 6.1 the main differences between processes in production and product development are shown. Insofar as processes in product development are neither predictable nor readily completely reproducible. Additionally, it is difficult to control objectives, durations, resources, and costs of a project in this environment. Thus, these processes are fundamentally different from those of manufacturing, sales, administration, and controlling (Table 6.1) (Vajna *et al.*, 2002).

Table 6.1. Differences of processes in companies (Vajna *et al.*, 2002)

Processes in manufacturing, controlling, administration	Processes in product development (engineering processes)
Processes are fix, rigid, to 100 % reproducible, and review able.	Processes are dynamic, creative, chaotic; many loops, and jumps.
Results must be predictable.	Results are not always predictable.
Material, technologies, and tools are physical available in manufacturing and described completely.	Defined objects, concepts, ideas, designs, approaches, trials (and errors) are virtual and often not precise.
Probability for disturbances is low, because objects and environments are described precise.	Probability for disturbances is high because of faulty definitions and change wishes (requirements).
Dynamic reaction ability is not necessary.	Dynamic reaction ability is necessary.
⇒ **Process control**	⇒ **Process navigation** ⇒ **Project navigation**

Figure 6.1 shows the dynamic project navigation with the help of three levels, which are implemented in different modules of the project navigation tool *proNavigator*:

- *Planning level*: The user captures and models processes with the module *proModeller* using predefined process elements. The module *proReviewer* simulates the affiliated processes with specified iteration number and alternative paths and provides information about the expected benefit-return, an estimation of the associated risks and an overview of the potential benefits together with their probability distribution. If necessary, the recorded processes are optimised and improved alternatives are generated.
- *Reference level*: The module *proManager* provides the integrated user interface that coordinates all the activities of the modules of the *proNavigator*.

- *Execution Level*: The simulated processes are carried out as projects in the respective project management software. If disturbances occur, the project will be stopped and a dynamic synchronisation will be performed, *i.e.* the project will be returned as a process to the planning level, simulated again and put back into the project management software. During a project the project participants have access to the belonging process documentation and description in the module *proBrowser*.

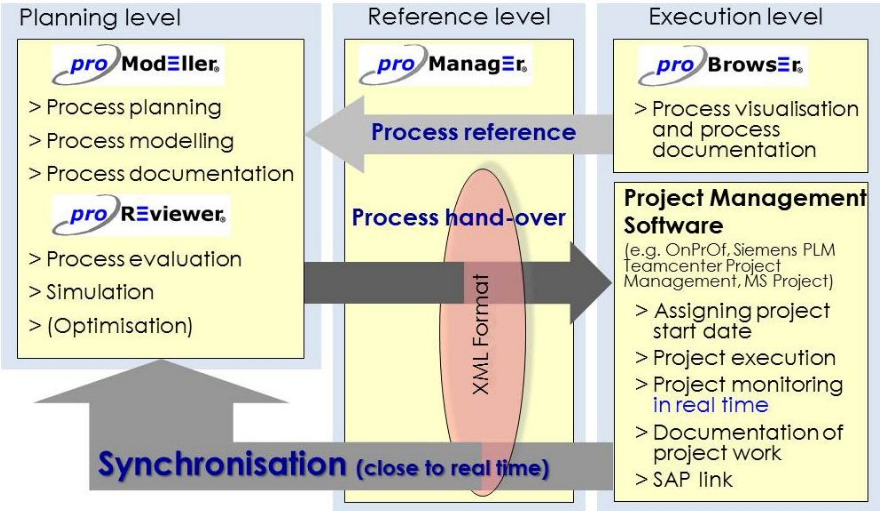

Figure 6.1. Dynamic project navigation

It must be noted that the creation and maintenance of process models require a non-negligible effort. For this reason a sense of proportion is advisable in process modelling instead of a highly detailed approach.

6.2 The Concept of the Tri-process-modelling-tool

While developing the modelling method it has to be kept in mind that the process modelling tool should meet all the requirements, allow different views for modelling and, at the same time, combine the advantages of the modelling method.

The result is a Tri-process-modelling-tool (Figure 6.2), in which a DSM (Design Structure Matrix), a diagram with BPMN symbols (Business Process Modelling and Notation) and a container model are merged into a Tri-Process-Modelling-Tool.

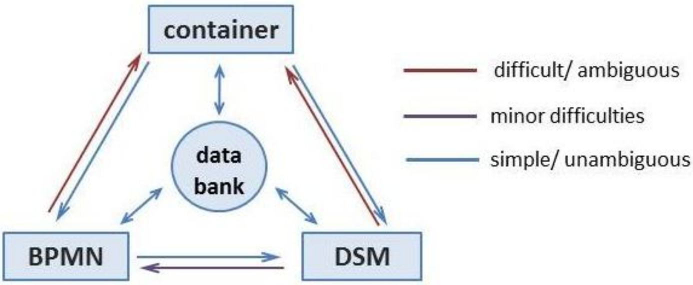

Figure 6.2. Interfaces between the three representations of the process model

The principle of Container Modelling according to the IDEF0 (International DEFinition Language 0) standard (*e.g.* in Marca and McGowan, 1988; Freisleben, 2001; Kim *et al.*, 2001) depicts that the sequential, parallel, iterative or alternative (sub-) processes may form a group, the so-called container. In these containers process activities are added, together with the corresponding process-relevant data and information. The containers can in turn contain other containers or be contained in other, larger, containers (Figure 6.2). Frequently used container constructs can be stored in a sub-process library and reused at any time, at any point in any process model.

From experience it has been found that container modelling on the one hand provides a very well-structured process representation, on the other hand it is difficult to be handled by the user during the process deposition step.

Therefore, the usage of the BPMN 2.0 standard (*e.g.* in Freund and Rücker, 2010; Palluch and Wentzel, 2012) seems beneficial. BPMN provides not only arrow-connected activity elements, but also sub-process icon elements that can be expanded from or reduced to higher level elements.

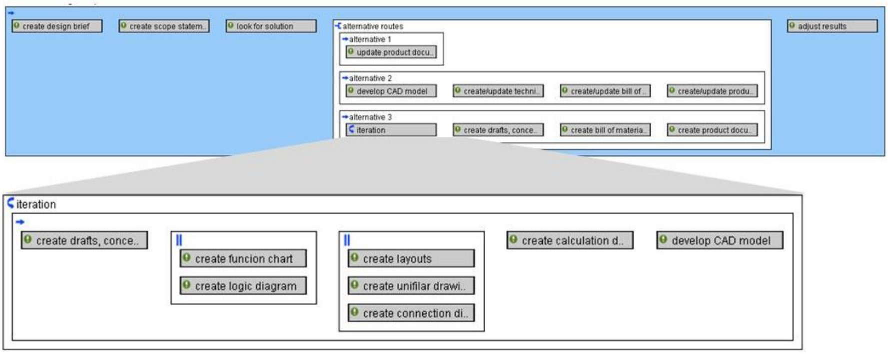

Figure 6.3. Container representation of sample process

The BPMN diagram (Figure 6.4) is a process node network with different gateways, allowing branches in parallel or alternative processes.

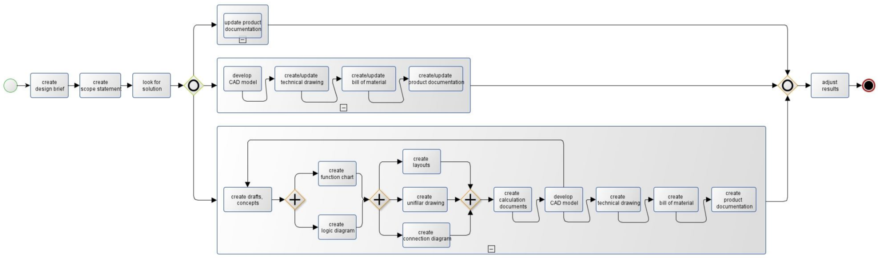

Figure 6.4. Diagram in BPMN representation

The notation uses standardised symbols of the BPMN. This graphic description scheme also allows the representation of stochastic procedures. For modelling the three gateways (data-based exclusive gateway (XOR), inclusive gateway (OR) and parallel gateway (AND) may be utilised, with the help of which the alternatives and parallel elements can be represented. In an exclusive gateway only one alternative can occur, which excludes the other. The gateway can be of a branching or composing type. The inclusive gateway can describe an and-or-situation in which either one, several or even all outgoing paths may be proceeded simultaneously. The combined effect will be reused where the paths converge again. Some actions do not necessarily need the completion of previous actions, but can be done simultaneously with one or more other actions. For this purpose the parallel gateway may be used, which operates both parallelising and synchronising. Parallelisation does not mean that the tasks must necessarily be performed simultaneously.

During the modelling process the number of possible iteration steps and the most likely path of process alternatives are not determined, neither in container modelling nor in BPMN modelling. This occurs at first in a process simulation, when the processing time and the costs of the process are to be determined. If the conclusion of a process simulation is that the process structure should be optimised, it is very difficult to break these structures in container and BPMN representation. Thus an intermediate step is required, which simplifies this breaking.

This is done using the DSM (Rick, 2007; Lindemann *et al.*, 2009), which defines and maps the relations of the single process elements with full precision (Figure 6.5). It treats the cycles and feedbacks clearly and simply. With an extension it is possible to model the alternatives in the process.

	create design brief	create scope statement	look for solution	update product documentation	develop CAD model	create/update technical drawing	create/update bill of material	create/update product documentation	create drafts, concepts	create logic diagram	create function chart	create layouts	create unifilar drawing	create connection diagram	create calculation documents	develop CAD model	create technical drawing	create bill of material	create product documentation	adjust results
create design brief		1																		
create scope statement			1																	
look for solution				1/3	1/3				1/3											
update product documentation																				1/3
develop CAD model						1														
create/update technical drawing							1													
create/update bill of material								1												
create/update product documentation																				1/3
create drafts, concepts										1	1									
create logic diagram												1	1	1						
create function chart												1	1	1						
create layouts															1					
create unifilar drawing															1					
create connection diagram															1					
create calculation documents																1				
develop CAD model									2								1			
create technical drawing																		1		
create bill of material																			1	
create product documentation																				1/3
adjust results																				

Figure 6.5. Extended DSM

In the DSM all alternatives are listed. These are represented as a fractional number. At three alternatives the value 1/3 may be possible. This value is not related to the likelihood of the alternatives. The active alternatives are treated later like the parallel elements.

The transition between the three representations is associative. It is possible to enter the process data in any representations, which is then converted to other representations. Each of the three representations has its advantages and disadvantages. It is not possible to create all process information in all the representations equally well. Therefore, the Tri-process-modelling-tool is used. So it is possible to treat all information in the currently best representation and to estimate and optimise the time and resource requirements of the process.

6.3 Process Optimisation of Product Development Projects

With graphical representation, such as BPMN, the process structure is modelled intuitively by using arrow connections. However, the sub-process structures are difficult to survey in this representation mode, especially for parallel structures. This drawback is countered by container modelling (a container includes a serial, parallel, iterative or alternative process structure), which provides a clear visibility with respect to process results present when leaving the container. However, this modelling technique has the weakness that, for iterative or alternative procedures, additional containers must be defined in order to know whether serial, parallel, iterative or alternative process structures are included. The representation of iterative processes in BPMN may be very confusing and ambiguous, because especially for nested, iterative processes the beginning of an iterative sub-process can hardly be seen. This disadvantage in turn is countered by DSM, as with DSM the relations between the elements are unambiguously specified and a clear process structure can be obtained. It is not expected that the elements are immediately written in the correct order (from the perspective of time, resources and costs). With DSM, the reorganisation of the process elements for compliance of time, resources and cost targets is possible.

After modelling a process, the following optimisations of the process may be initiated (Figure 6.6) (Schabacker and Vajna, 2003):

- *Qualification Balancing*: In the first step qualified personnel is assigned to the process elements based on the profile of necessary qualifications resulting from the individual process elements. In the second step, existing methods, approaches and tools are replaced by the most appropriate version with the BAPM method (Schabacker, 2001; Schabacker, 2002; Schabacker and Wohlbold, 2002; Schabacker, 2010).
- *Simultaneous Engineering*: The output data of process elements are compared to the input data of follow-up process elements with the aid of the degree of fulfilment (see Section 6.4). If the conditions of the degree of fulfilment are met, matching process elements are linked together, so that several different process elements can be (partially) processed in parallel. Additionally, waiting and idle periods of the individual process elements are minimised in this step. A control variable here is the provision of the minimum information necessary for the parallel or follow-up process element to begin (Vajna *et al.*, 2005a).
- *Concurrent Engineering*: A process element is distributed to several parallel processing commissioners, whereas a clear definition of skills and (chronological and physical) interfaces between these has to be made in advance to maintain the consistency of the process element (Vajna *et al.*, 2005a).

- *Time Concentration*: In the sense of a maximal shortened project processing duration, the entire process topology of the project is restructured (reconfiguration) with the aid of evolutionary methods (similar to the optimisation of products, such as in Vajna *et al*., 2005b; Vajna *et al*., 2011). Results may include, for instance, modified processing sequences and further parallelisation of the process elements.

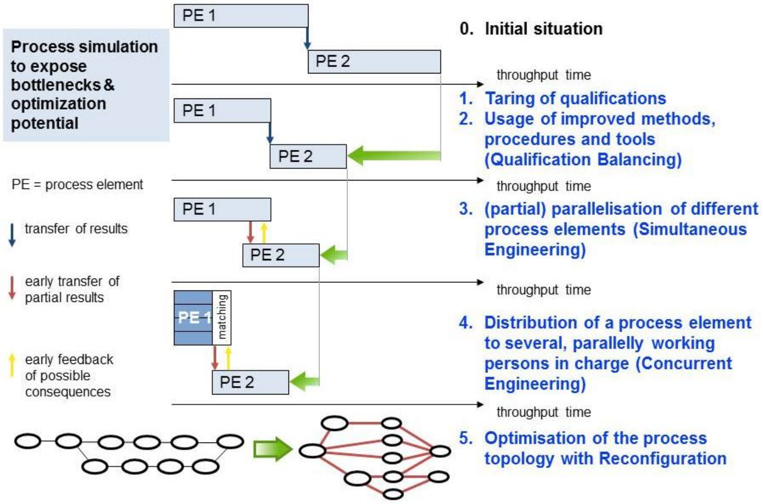

Figure 6.6. Stages of process optimisation (Schabacker and Vajna, 2003)

For the optimisation stages 'simultaneous engineering' and 'concurrent engineering' it has to be determined what percentage of a process element needs to be completed in order to start the next process elements. This can be done reasonably with the use of the documents to be created, such as CAD models, technical drawings, product documentation (Schabacker *et al*., 2002). The degree of fulfilment needed for parallelising process elements is thus measured by the partial completion of documents. Therefore, document types will be defined (Figure 6.7).

Depending on the process and the company, the extent of overlapping of process elements and thus the degree of fulfilment for parallelising process elements may vary. For simultaneous elements a lower limit for the time advance must be introduced, with which the earlier element completes before the later element (called minimum time advance), to ensure that the later element, which depends on the information of the earlier element, has enough time to run. Surveys can determine the percentage.

		product planning						product development													
		request for proposal	tender	quotation calculation	customer order	market study		design brief	scope statement	drafts, concepts	logic diagram	function chart	unifilar drawing	connection diagram	calculation documents	layouts	CAD model	technical drawing	bill of material	documentation	patent application
product planning	request for proposal			100		100		100													
	tender			100		100		100													
	quotation calculation					50-100		100													
	customer order					75-100		100													
	market study							100									80-100				
product development	design brief									70-100		100					50-100				
	scope statement									80-100	70-100	100					100				
	drafts, concepts										50-100	100			100		80-100				
	logic diagram											80-100					80-100				
	function chart																80-100				
	unifilar drawing																80-100				
	connection diagram																30-100				
	calculation documents																50-100				
	layouts																50-100				
	CAD model																	30-100	75-100		
	technical drawing																			25-100	80
	bill of material																			50-100	100
	documentation																				70-100
	patent application																				

Figure 6.7. Document types with possible degrees of fulfilment in percentages

If multiple documents are created in a single process element and a premature beginning of a document within a process element is possible, it is useful to divide the process element into sub-process elements (concurrent engineering), where each sub-process element contains exactly one document and therefore multiple commissioners can work on different documents and sub-process elements in parallel.

The lower limit of the degree of fulfilment provides the highest parallelisation, along with the highest risk. In this case, it may happen that the element needs to be divided into several parts, to ensure that the minimum termination condition is satisfied. If partial elements are undesirable, the degree of parallelisation is obtained by a comparison of the weighted difference between the degree of fulfilment and element length (100%) with the weighted difference between the minimum termination and the length of the next element. The smaller of these two differences is the degree of parallelisation of two elements. The degree of parallelisation of the overall process is the sum of the individual parallelisations. Standardisation is already taking place through the individual weightings, the sum of which is always exactly one.

Sample: In a process element, the three documents: a CAD model, the technical drawing and the product documentation are created. Of course, a CAD model doesn't need to be 100% completed in order to derive the technical drawing or begin with the product documentation. Perhaps the product documentation can be performed in parallel with the technical drawing. Furthermore, the project manager will be able to select the best possible qualification profile for all three documents separately. Instead of assigning a design engineer to work on all three documents, the project manager can leave the technical drawing to a draftsman, which under certain circumstances may lead to lower process costs, due to the lower hourly rate (Figure 6.8 and Equation 6.1).

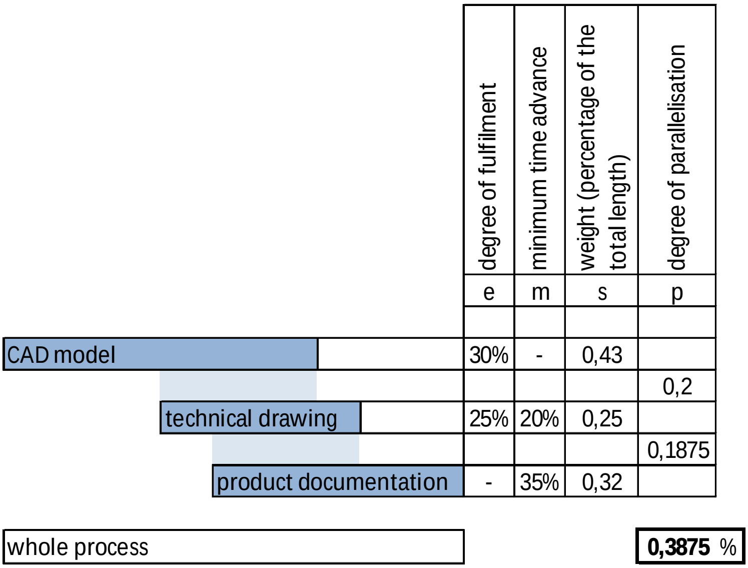

Figure 6.8. Sample data for the calculation of the degree of parallelisation

$$p_{process} = \sum_{i=1}^{n} \min\left[s_i(1-e_i); s_{i+1}(1-m_{i+1})\right] \tag{6.1}$$

6.4 Simultaneous Modelling in a Tri-process-modelling-tool

The time overlap of normally sequential workflows thus provides a bonus time and/or a shortened processing time, respectively. Once there has been sufficient information gathered in a workflow, the next workflow is started in parallel. This sometimes leads to more work, because it cannot always be operated with the final level of information, but the basis for work may change at any time.

For sequential process elements a time overlap is possible. A process element can be initiated before the previous item has been completed. The processing of the element can start with a certain amount of information delivered by the predecessor. The further data are supplied continuously. The predecessor must be ended earlier than the current element, so that all information can be adopted.

In the diagram representation the arrows that do not begin at the end of the element but at a certain point (with given percentage) indicate that at this degree of fulfilment overlapping is possible (Figure 6.9). These arrows lead to the beginning of the next element. Additional arrows from the end of a predecessor to a point in the current element indicate where no further proceeding is possible without the final data.

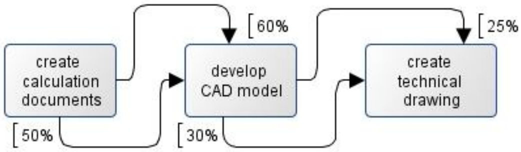

Figure 6.9. Representation of a simultaneous case

6.5 Summary and Outlook

With the modelling methods discussed above the Tri-process-modelling-tool combines the following benefits for a project manager:

- a flowchart representation for process planning, which is combined with BPMN;
- a container modelling tool is useful for checking the consistency of a process and;
- a DSM for time, cost, and risk forecasts especially for iterative and alternative processes.

Companies applying the optimisation approaches discussed above will be able to perform better and more efficient product development projects. The above mentioned assessment and optimisation approaches allow shortening the product development cycle times, therefore reducing the cost of product development and improving the utilisation of project participants in on-going product development projects.

The higher the degree of fulfilment to parallelise processes is, the smaller is the expected value for the total duration of the process. At the same time the risk that this expectation is exceeded grows, *i.e.* the distribution deforms toward larger total process duration.

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Chapter 7

Integrating Physical and Virtual Testing to Improve Confidence in Product Design

K. Tahera, C.F. Earl and C.M. Eckert

7.1 Introduction

Although testing is a value adding activity and improves confidence in design, lengthy physical testing in one phase can delay the product development process, because testing and design processes are closely intertwined. This study identifies that, due to long procurement times and lengthy physical tests, companies may have no choice but to redesign tasks before testing results are available in order to meet product delivery deadlines. This increases uncertainties therefore reduces confidence in design. This research proposes a model of integrated virtual and physical testing to support the testing and subsequent redesign phases of product development.

An engineered product must comply with its performance requirements; and in addition reliability, safety and durability must be ensured. A potential design may fail to meet requirements, have technical design faults, or raise issues about manufacturability and maintainability (Thomke and Bell, 2001; Qian *et al.*, 2010). Testing identifies these problems and is therefore central to product development (PD) (Thomke, 2003). Testing throughout the development process increases confidence because it corroborates the design. Testing is considered as a means to reduce uncertainty and thus risk. However, physical testing can take a long time, and delayed or negative results in one phase potentially jeopardize project schedules. Therefore, design for the next phase often starts before testing is complete. Redesigning without knowing test results might perpetuate faults or miss opportunities to respond to emerging problems. This paper argues that companies are forced into redesign activities with low confidence because testing results are not available, and therefore restructuring of the design and testing processes taken together could decrease risk in product development.

A case study was undertaken at a UK-based company that designs and manufactures diesel engines with whom we have worked for several years. Diesel engines are complex, highly regulated products with extensive testing to meet customer requirements, performance standards and statutory regulations. Thirteen interviews were carried out by the authors, recorded and transcribed, between March 2011 to August 2012 with six engineers: a senior engineer, a development engineer, a CAE engineer, a verification and validation manager and a validation team leader. We analysed the complex PD process structure with the objective of:

1. Speeding up the testing process without losing confidence in test results.
2. Managing testing and subsequent design activities with reduced uncertainties.

The paper introduces the case study in Section 7.2 and describes the product development process in Section 7.3. Section 7.4 analyses the issues in testing and redesigning, Section 7.5 proposes changes to the process structure for more effective testing and redesign measured through potential costs and benefits in Section 7.6. The case study indicates some general conclusions which are presented in Section 7.7.

7.2 Background to the Case Study

To be competitive and comply with legislation the company needs to introduce new technology. Even if a proven technology is deployed in a new context (for example, different use conditions and environment) it needs to be tested in these new scenarios. The "newness" in terms of new components or technology or reuse in different contexts introduces uncertainties to the system and proves to be challenging for the company. At each stage of the product development process engineers need to reduce these uncertainties and achieve a certain confidence level to proceed to the next stage (as shown in Figure 7.1). While uncertainty and confidence are closely related, the term confidence is used widely in the case study company and indicates how sure the company is that the design can eventually meet given requirements. Engineers can achieve confidence in design at a certain stage of PD process even though there are still a lot of uncertainties.

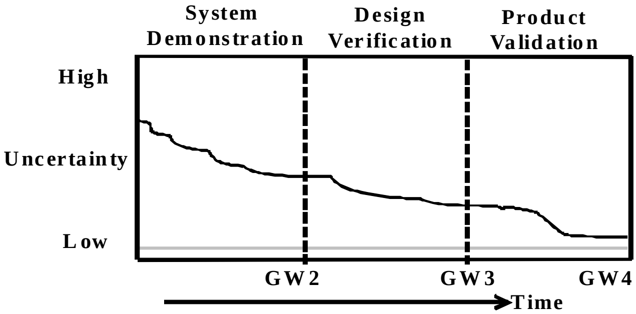

Figure 7.1. Company's uncertainty reduction curve during the product development process through its Gateways GW2, GW3 and GW4

Frequently, engineers in the case study company mention "*testing builds confidence*"or as the validation manger put it "*testing reveals the truth*". Even if testing produces many failures, it also increases understanding and learning especially in the case of uncertain situations. Small failures can create rapid learning and capture the attention of engineers, so that earlier failures can be mitigated in next iteration. Confidence in design reduced when redesigning happens without useful testing results to draw on. Hence, a significant amount of the development effort is spent on testing to acquire confidence in product design and decrease uncertainty and risk for the company. If the uncertainty of the information is low, the team has more confidence in the current information (Yassine *et al*., 2008). Different types of testing lead to different confidence level in the implementation. Physical testing reveals the true characteristics. Virtual testing using CAE and simulation predict the behaviour of the product. In this company, engineers are more confident in physical testing than virtual testing. However, in some component, like flywheel design, engineers have achieved enough confidence in the accuracy of virtual testing to require less testing physically in early stages of the process.

But physical testing can take a long time to produce any results which are useful for subsequent redesign. Therefore the company has to start redesigning with less confidence than they would like. Long running tests are hugely costly. The business manager in the case study company mentioned that,

> "…to develop the Tier4 engines can cost R&D alone in excess of £X million, I would break it down to design and engineering is probably 15%, material is probably around 30%, and actually testing around performance is the rest at around 55%. So most of the money in R&D goes into testing for performance and durability"

Therefore an effective way of reducing the testing cost without compromising the level of confidence is essential. In the next section we analyse the company's PD process structure and identify the close interdependence of design and testing.

7.3 PD Process Structure in the Company

The case study company has a structured gateway process for New Product Introduction (NPI) (Figure 7.2). It has eight stages starting from "Launch" to "Gateway 7". Most of the testing occurs between Gateway 2 (GW2) to Gateway 4 (GW4). This research focuses on these three main phases of the PD process.

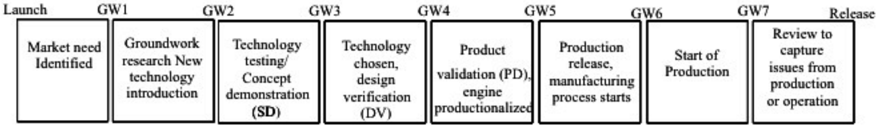

Figure 7.2. An outline of company's gateway process

Figure 7.3 presents four broad activity types: (Re/Design, Computer Aided Engineering (CAE) and Simulation, and Procurement (of test prototypes) and testing.) as time limited boxes, but in reality, a core team keeps working on design and CAE, and testing goes on almost continuously, in parallel to these activities. Design, CAE, procurement and testing undergo at least three iterations from GW2 to GW 4, and serve different purposes in each stage to improve confidence in design.

Initially, understanding of technology, historical expertise, confidence in previous designs are all used to evaluate a potential design. At the early stages (between launch and GW 2), the company uses tools such as quality function development (QFD) to translate the customer requirements into the technical characteristics of product design. Along with QFD, the previous product's health monitoring data and characteristics are used as input for the Design FMEA, which focuses on identifying potential risks so that actions indicating tests can be taken to prevent or minimize the risks. Designs only proceed to GW2 and further if the confidence lies above a level specified in product development plan. FMEAs are used in different phases of PD process to indicate the level of risk in a design.

Three phases of testing are distinguished: (i) Concept/System Demonstration (SD) shows that the technology can deliver the required performance; (ii) Design Verification (DV) aims to ensure that design outputs meet the given requirements under different use conditions, and (iii) Product Validation (PV) tests the product against customer requirements and specifications. Performance and Emission (P&E) and Mechanical Durability and Reliability are tested in each of the three phases. The mandatory tests required for acceptance usually occur during PV phases. The engine level testing blocks (in Figure 7.3) contain a large number of tests. Some tests are grouped and some are individual. Some test results can be obtained quickly whereas some require running the tests till very end of the testing phase.

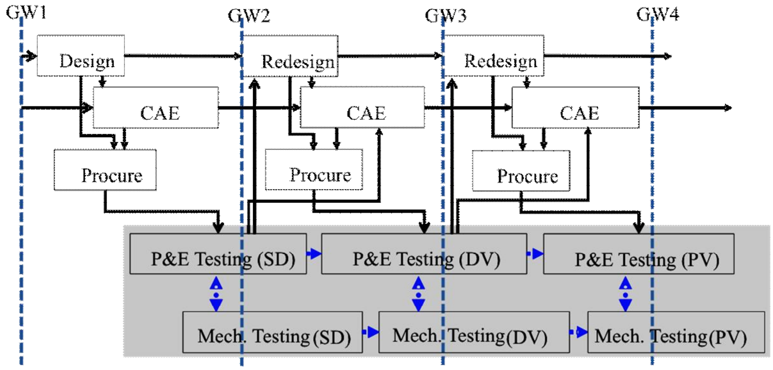

Figure 7.3. A schematic of the PD process from Gateway 2 to Gateway 4

Figure 7.3 also illustrates how engines are tested in sequence for SD, then DV and PV. However, in reality, several versions of the same engine are tested simultaneously in parallel test-beds. Some components are tested for concept demonstration whereas others are tested for design verification. Therefore, in each phase, different tests; some of which are long duration, are overlapped in a complex manner.

7.4 Testing in the Case Study Company

In analyzing the company's PD processes, two key issues concerning test emerge which affect how the whole process is managed. Firstly, long lead times for procurement of test component and secondly, the long duration physical tests.

Lead time for procurement of new engine components for testing is four to six months for the company. There are cases, for example during design verification (DV), when the company needs to start a certain test to meet the schedule of the next GW stage, but a core hardware component is not available from the supplier. The company cannot afford delay, and instead tests using alternative components. The validation managers need to identify suitable alternatives and calculate trade-offs. For example, an engine requires a piston to run a test, but the piston will not be delivered until a later date, so they will either continue physical tests with a prototype piston, or else simulate the ideal engine computationally and identify the associated risk. In this scenario the product cannot be signed off yet, and physical testing of the new piston in an engine is still necessary for verification or validation. This situation causes the DV or PV phases to extend over two GW stages instead of one.

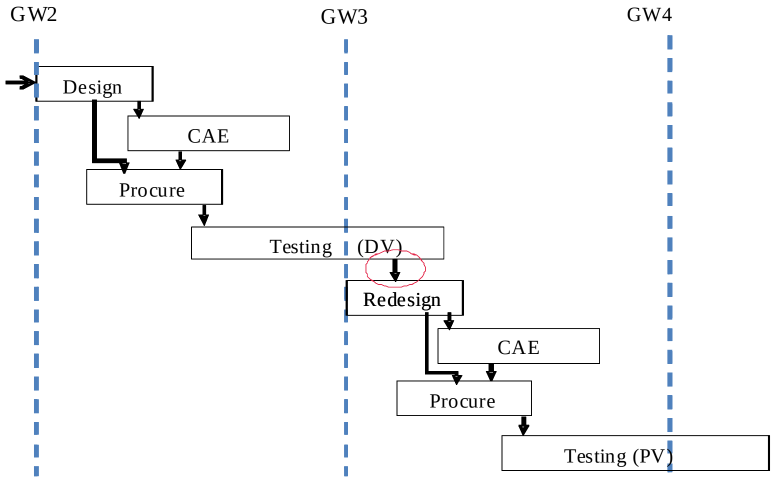

Figure 7.4. Overlapping between testing and redesign in two phases

Ideally, physical testing results from one phase should drive the (re)design and CAE of the next phase. However since testing takes a long time, it is often not viable to wait. For instance, the SD phase testing may still be on-going while the (re)design for the DV phase is started (and sometimes finished), and while procurement for the subsequent DV testing begins, as seen in Figure 7.4. Without the testing results being available, there will be uncertainties in redesigning and procuring for the next phase, resulting in significant number of iterations in subsequent phases to accrue the confidence. For instance, in cases where results from a physical test cannot be delivered before the end of the test, the durability testing of a new engine component may not produce any failure until very late in the testing process. This type of failure can prompt modifications with serious consequences (such as material changes) and may lead to an additional iteration in design and procurement. Knowing the associated risk of an extensive rework, the company has no choice but redesign because a design proposal is needed to commence another lengthy procurement process. However, running the testing is still useful and brings valuable insights of the product characteristics. Thus for this case, a way of accelerating the testing process was essential.

To overcome these issues, the company has developed two main approaches: an accurate level of specification to the supplier and reducing physical testing time through supporting CAE. To minimize long lead time procurement, initially a clear and appropriate level of specification of the product is required. The company also does CAE analysis and makes virtual prototypes with many iterations to enable the first physical prototype to be built closer to target. One engineer commented,

> "computer simulation is becoming increasingly important to the companies to minimize the effort and expense involved in product development".

The company uses CAE analysis and simulation, to identify improved boundary conditions for physical test, therefore physical testing becomes more focused. CAE analysis also can identify engine settings for test. For example in a performance test, simulation can predict when to measure a value or in which conditions, so less time is spent on the physical test.

7.5 Proposed PD Process Structure

We suggest that this case study company can respond to these issues through introducing virtual testing in parallel to the physical testing in each PD phase, as shown in the model in Figure 7.5. The proposed model separates virtual testing from the initial CAE analysis. Virtual testing can be regarded as distinct from CAE analysis proper. Initial CAE analyses may check interference and stress on components and assemblies using general purpose tools, such as FEA. A virtual test is designed specifically for a given situation and conditions and is representative of a physical test. Virtual testing of a piston should create a use scenario over the full range of parameters which might be encountered in a test bed. This virtual test for a piston would not be appropriate for another component like a connecting rod. Such virtual test models are founded on the technical understanding of product and the software development team in formulating mathematical models for the interacting engine components, writing appropriate numerical solution algorithms, and integrating the resultant programs into workable analysis. However, it is also noted that physical test results help to improve and validate virtual test models and this iteration is important. Initial CAE analysis should define the specification for procurement and virtual testing should assist the physical testing.

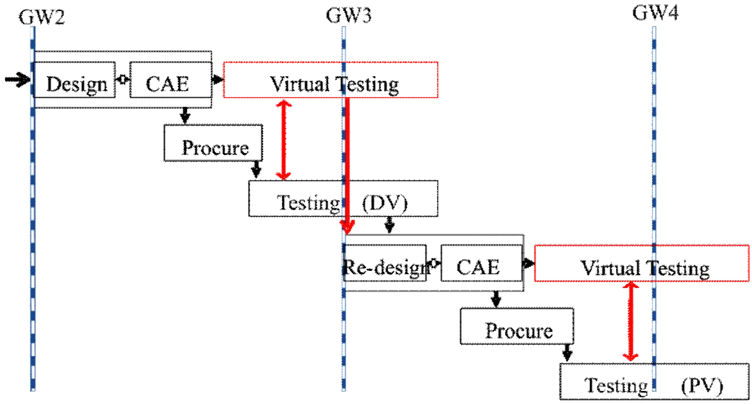

Figure 7.5. The proposed process structure with additional virtual testing actively

Initially, it is necessary to build a virtual test model before the actual physical testing starts. Engineering experience, prior understanding of the product, previous product testing and historical data should all contribute to the boundary conditions for the virtual test model. One engineer mentioned:

> "The baseline product definition is physically tested and that information is fairly adequate for simulation to run for multiple variables for longer time to find the optimum setup. Then a physical test is required to validate the simulated result".

The virtual test model is further validated and adjusted against the values gained from the physical tests. The limits of variation in the variables are adjusted in the virtual testing model through several iterations until the simulation model is representative of the physical tests and engineers can achieve enough confidence in the virtual testing model. Iteration in virtual testing supports fine tuning of selected parameters and rapidly produces new models of components or products. Effective communication between physical testing and the CAE team is a key success factor for this structure of parallel physical and virtual testing. Once a virtual testing model is matured, it will produce faster testing results than physical testing.

As discussed in Section 7.4, two improvements in the company's process are required. One is to produce fast and accurate specifications for procurement by frontloading of tasks and knowledge. Front loading a) increases the rate of problem solving cycles at early stages through enough CAE analysis (activity frontloading) or b) uses prior knowledge about tests on existing products to learn for the new product (knowledge frontloading) to reduce the necessary number of testing and redesign cycles at later stages (Clark and Fujimoto, 1991). Initial CAE analysis should drive design requirements. Optimization should take place earlier in the product development cycle (front loaded), to improve product specification to the supplier.

Another improvement required in the process is to make the physical testing process faster. Especially for the case, when a test needs to run for a significant amount of time to produce any useful information and subsequent redesign is highly dependent on that information, Krishnan *et al.* (1997) suggested that exchange of information should be disaggregated, to see if any information can evolve faster or can be practically transferred in a primary form. The virtual testing in the proposed model should evolve useful information faster than the actual physical testing and should provide required confidence in subsequent design tasks. The virtual testing is also aimed more at reducing the time and effort of physical testing however not all physical tests require virtual testing, or might be assisted by it.

7.6 Cost-benefit Analysis of the Model

Companies might be reluctant to accept the introduction of a virtual testing model if the costs are higher than the benefit. The cost will depend on two main factors: communication cost and the cost of establishing the virtual testing model.

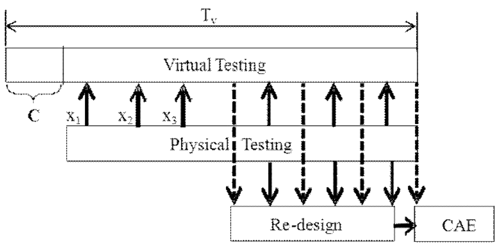

Figure 7.6. Information exchange between virtual testing, physical testing and design

Initially, the results from virtual (simulated) and physical testing may differ in several ways. These discrepancies may determine the number of meetings required which may increase with the level of uncertainty and potential dependencies between design and testing (Loch and Terwiesch, 1998). The cost of introducing the virtual testing block can be calculated as follows. Initially a fixed cost C is required to build the virtual model (as shown in Figure 7.6). This cost will depend on the company's capability in CAE modelling and simulation. With a well-established CAE department this cost might be lower than outsourcing. We are assuming that the cost for each meeting is X_i, for meetings i = 1, 2,..n. After the model is mature, the frequency of meetings is reduced. Each meeting results in modifications and further simulation in the virtual model, at cost Y_i. A regular maintenance and opportunity cost M is incurred per unit time, for the virtual test duration T_V. If a company has committed human resources for CAE analysis throughout the process, this maintenance might not add extra marginal costs. Thus the cost of additional virtual testing model is:

$$C_{VT} = C + \sum (X_i + Y_i) + M\, T_V \quad (7.1)$$

Savings denoted C_T will be accumulated in several ways. Learning from the parallel virtual testing will reduce the uncertainties in design and procurement. The gain is highly dependent on the amount of rework required for redesign. It is assumed that this virtual testing will make the physical tests shorter without any quality loss, given that the virtual test is assumed to be representative of the physical testing. A benefit in using parallel virtual testing will accrue when $C_T > C_{VT}$. However, the real benefit of using parallel virtual testing continues during iterations as this might avoid extending a testing into a subsequent gateway (GW). Even with another iteration (of DV for example), the cost of running the virtual testing phase will be approximately $\sum (X_i + Y_i) + MT_V$, as the model building cost C will be small as the virtual testing model is already mature, the number of meetings will also be relatively low. The duration of physical testing in this phase will be shorter, and uncertainty decreased. Thus larger savings in physical testing are possible.

The benefit of integrating virtual testing into the process structure can help to address the key objectives in Section 7.1. The first objective is to make testing faster. The proposed model of virtual testing can accelerate the physical testing process. Different tests benefit from integrating virtual testing with physical testing in different ways. Some benefit by focusing the tests, and identifying future values to minimize the number of iterations to yield a confidence in design, while others require running for shorter periods of time. For example, for constant speed and load, an engine has its intakes of fuel and air regulated, with the goal of achieving desired power ratings. An engine might require several iterations in design and test to achieve these desired power ratings. A virtual testing using a mature model can predict the likely consequences of certain values of fuel and air intake of the engine, thus suggesting appropriate values for next iteration.

Reliability and durability tests ensure performance without failure over an extended period of time. When a virtual test is able to accurately predict the behaviour of the engine, then the number of physical testing hours for durability can be minimized, saving time and reducing cost. The virtual testing might also indicate the points where the product might fail, making it possible to avoid unnecessary testing, or to replace a component before it fails and damages the whole engine.

The second objective is to produce effective information when testing evolves useful information very late and subsequent redesign is highly dependent on testing results. In such a case, we suggest using parallel virtual testing and starting the downstream design work once the virtual testing has produced results which are representative of the physical testing results that means virtual model is mature. Virtual test model simulation will predict parameter values faster than a physical test, and faster evolution or disaggregation of useful results will be possible. Early prediction or indication of failure can support an early design decision.

The third benefit from virtual testing is improved confidence in overall testing. Although a physical test will provide greater confidence in the test data; there are much inefficiency in physical testing especially where repetition is needed for reliable data, as mentioned during the interviews. A physical component test can deal with only limited variables and cannot always be comprehensive enough to include all the operating conditions. Furthermore, physical tests are conducted in a controlled environment and have limited capability to simulate the broad range of operating conditions, whereas virtual testing can handle a whole spectrum of variability across many interacting variables. Therefore, an integrated approach of physical and virtual testing might help to produce a focused and faster test, increase confidence and minimize iteration.

7.7 Discussion and Conclusions

The question remains as to whether such virtual testing models can be constructed. The case study company has partially done this, both to assist the physical testing and to apply when physical components are not ready. The performance, reliability and durability predictions of engine components using CAE is developing rapidly. For example, the material and structural analysis group's understanding of the principles of fatigue behaviour in complex materials, combined with historical data from high temperature applications, modelled in commercial (and internal) software, with a comprehensive materials database means that the durability of engine components can be reliably predicted and probability distributions applied to perform failure rate calculations. Whilst the company recognises there are still many technical challenges to overcome, on-going investigative work in virtual testing currently includes gas flows and combustion chemistry, cavitation in bearing oil films and metal fatigue under extreme temperatures. Moreover, to reduce the time and cost of physical testing by integrating virtual testing, procedures must be put in place to demonstrate that the virtual tests are able to replicate actual tests and to generate the necessary confidence within the design and certification communities (Maropoulos *et al.*, 2010).

This research suggests a process model to improve confidence in PD through integrating virtual testing in the process. This model is also useful to reduce the uncertainties associated with overlapping between testing and redesign. Overlapping has been studied in greater extend in several papers (Clark and Fujimoto, 1991; Krishnan *et al.*, 1997; Terwiesch and Loch 1999). This paper has considered the scenario where the information evolution of upstream testing is slow and the sensitivity on downstream design is high, a case which Krishnan *et al.* (1997) suggest does not provide favourable conditions for overlapping. However, companies often have no choice but to overlap activities. The proposed model suggests a possible strategy for overlapping providing several benefits: 1. reduced uncertainty in design and procurement, 2. improved confidence in physical testing, 3. faster physical tests and 4. reduced iteration and overall cost saving.

Further work will extend validation of this model in an industrial context, including the original case study company; in particular, considerations for the design and testing of products at different scale, complexity and maturity will be compared.

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Part III

Industry Case Studies

Chapter 8

Adapting a Design Approach: A Case Study in a Small Space Company

K. Gericke and H.A. Moser

8.1 Introduction

Many design problems often do not match the boundaries of a single discipline. As a consequence, designers from different disciplines have to collaborate. In contrast to that, it is observed that much of the developed support, such as design methodologies, is rather mono-disciplinary focussing for example on mechanical engineering, software development, or service design.

The development of design methodologies is accompanied by an on-going debate concerning their applicability in practice. While many authors highlight the usefulness of design methodologies for training of novices, it is recurrently reported that design methodologies are only seldom applied in design practice (Franke, 1985; Jorden *et al.*, 1985; Franke *et al.*, 2002; Jänsch, 2007). An argument usually produced concerns the abstract character of design methodologies (Eckert and Clarkson, 2005; Brook, 2010). As they are intended to be applicable in different branches within a specific domain, they propose only abstract process models, thus no exact representation of the design processes in each specific branch (Eckert and Clarkson, 2005; Wynn and Clarkson, 2005).

Currently there are two main axes for further development of design methodologies: the rising interdisciplinarity in design practice which is not sufficiently addressed in the rather mono-disciplinary design methodologies (Gericke and Blessing, 2011) and the adaptation of design methodologies to different contexts (*e.g.* to a specific branch, company, or product), which is recommended by many authors but lacks a systematic support (Maffin, 1998; Bender and Blessing, 2004; Meißner *et al.*, 2005).

This paper addresses the adaptation of a branch-specific design approach to different contexts. The term design approach is used in this paper in order to refer to a specific approach for the design of a system, for example described in design methodologies (Pahl *et al.*, 2007; Ulrich and Eppinger, 2007), standards (*e.g.* BSI, 2008; ECSS, 2008), guidelines (VDI, 2004), or company specific design processes.

The paper reports a case study in the space industry. The study is based on a document analysis and of expert interviews. This descriptive study compares the design processes of four projects, which show some major differences in context requiring a project-specific adaptation of a branch-specific design approach.

8.2 Adaptation of Design Methodologies

The claim of many design methodologies to provide a support which is applicable to a wide range of different contexts, resulted in a dilemma. In order to cover a wide range of different contexts the process models proposed in the methodologies, thus the whole design approach became rather abstract. The high level of abstraction resulted in the perception of being of limited use because abstract approaches usually provide less context-specific support. Providing a more detailed process model offering appropriate support for a specific context seems also to be no solution to that dilemma as this would limit the usefulness to a specific context, thus being in conflict with the goal to be widely applicable.

An approach suggested by different authors (Maffin, 1998; Meißner *et al.*, 2005) is to start with an abstract, context-independent approach and adapt it to a specific context. Lawson (1997) points out that the ability to manage this adaptation is one of the most important skills of designers. Obviously many designers do this regularly in a successful manner as they have to align their project plans with a mandatory design approach. Even though, no systematic support is offered to adapt design methodologies, thus the outcome of adaptation is dependent on interpretation of a design methodology and skills of the particular designer.

It is assumed that a systematic support for adaptation of design methodologies will contribute to an enhanced impact of design methodologies.

Meißner *et al.* (2005) highlight the influence of the context on the product development process. Based on a literature study they identified factors which are considered to describe the product development context such as market needs, company size, and design task complexity and grouped them into seven categories (see Figure 8.1).

Context factors are distinguished with regard to the level of abstraction of the design process. Meißner *et al.* (2005) postulate that abstract process descriptions (*e.g.* company specific reference processes), project plans, and specific situations within a project are all affected by their context. However, the context factors might not have to be the same for the long-, mid-, and short-term context (see Figure 8.2). Based on this distinction of the product development context Meißner *et al.* (2005) propose to adapt design approaches in multiple steps, beginning at a high level of abstraction considering the long-term context succeeded by further adaptation steps of more detailed process descriptions. Unfortunately no detailed recommendations or support for adaptation are provided.

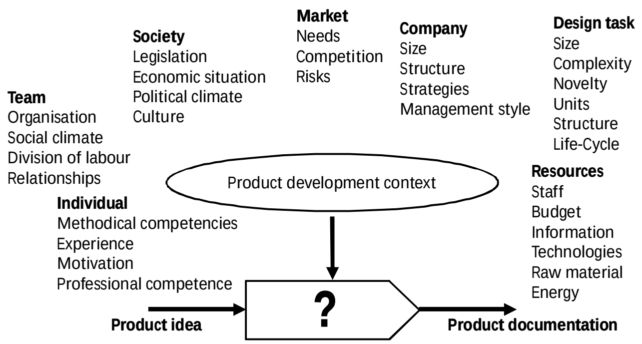

Figure 8.1. Product development context (Meißner *et al.*, 2005)

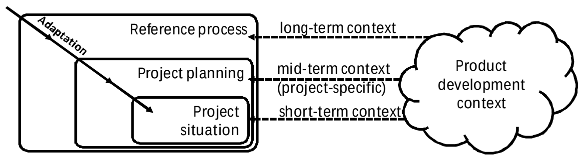

Figure 8.2. Different levels of context factors (Meißner *et al.*, 2005)

From the authors' perspective important issues which hinder currently the development of a support for adaptation of design approaches are: a comprehensive understanding of what context means, an empirically based selection of those context-factors which are relevant for adaptation, and an understanding of the rationale of process adaptation in practice. Therefore, this paper is guided by the following overall research questions:

- How do companies solve the challenge to adapt a generic design approach to a specific context?
- What are the main influencing factors for the adaptation?

8.3 The Case Study

The research presented in this paper is based on a case study of a small space company in Luxembourg (30 employees including 24 engineers). The company which is a subsidiary of a larger German group develops space applications (space related services), and space equipment (small satellites, subsystems of larger satellites). The analysed company has no defined departments and a flat hierarchy with the Managing Director on top. The projects are mastered by teams with members selected from a pool of different engineers specialised in certain disciplines. The position of the project manager introduces a project-specific hierarchy and is also performed by an engineer.

The study is based on a document analysis and expert interviews. The document analysis considered descriptions of the company's design approach and documentations of four completed projects. The expert interviews were used to verify the results of the document analysis and to analyse current practice of design approach adaptation and the identification of major influencing factors for the adaptation.

The interviewed experts have been involved in several projects prior to the interviews and acted as systems engineer, quality assurance and product assurance manager, and project manager. One of the authors was part of the engineering team of the four projects which provides a deep understanding of the internal processes, the developed systems, and validity and relevance of the gathered information.

8.3.1 Product Development Practice in the Studied Company

Current development practice in space equipment development is strongly determined by space agencies *e.g.* National Aeronautics and Space Administration (NASA) and European Space Agency (ESA). As this paper reports a case study of a space company in Luxembourg, standards provided by the European Cooperation for Space Standardization (ECSS) which define the design practices of ESA and their subcontractors are of major importance.

Design practices of the analysed company are documented in a company-specific handbook that covers all product life cycle phases in which the company is involved or responsible for and detailed process instructions for specific activities.

The company's handbook and the process instructions are based on the ECSS system. The company's handbook and the process instructions are written in German what limits their usefulness in a multi-lingual team, which uses English as working language. This leads to the situation that the team uses mainly the ECSS system (written in English) as guidance for their product development activities.

The ECSS system provides standards, handbooks and technical memoranda addressing project management, engineering, and product assurance (ECSS, 2008).

For each of these areas a set of disciplines are defined for which a considerable set of documents is provided. These documents offer process guidelines, descriptions of methods, a documentation guideline, factors and numbers for requirements definition, engineering and calculation.

8.3.2 Design Projects

The four projects which have been analysed as part of this case study: EAGLE1, EAGLE2, ORCA2, and COLIBRI (see Table 8.1) are part of a larger program of the company. All four projects were managed by a team of less than ten members. This multi-national team involves specialists from different engineering disciplines such as radio-frequency engineers, thermo-mechanical engineers, and software engineers.

EAGLE1 and 2 are company investments. EAGLE2 is an advanced version of the EAGLE1 spacecraft with the same operating baseline as an attached payload. Attached payload describes the fact that the spacecraft is mechanically connected to the last stage of a launcher but operating independently (Fleeter, 1999). The main drawback of an attached payload is the unpredictable attitude of the last launcher stage in orbit which imposes limits on power generation and thermal control. ORCA2 is a space project comprising two identical satellites which are leased to a commercial customer. EAGLE1 and 2 and ORCA2 are microspace missions (Fleeter, 1999). COLIBRI is an experimental payload operating in human spaceflight. Human spaceflight imposes the highest requirements on safety and risk. The payload is connected to another spacecraft, here the International Space Station (ISS).

Table 8.1. Characteristics of analysed projects

Characteristics	EAGLE 1	EAGLE 2	ORCA 2	COLIBRI
Type of mission	microspace	microspace	microspace	human spaceflight
Relation with other spacecraft	mechanically connected	mechanically connected	separate	electronically and mechanically connected
System complexity	low	low	moderate	high
Customer	company investment	company investment	commercial	institutional
Cost	lowest	lowest	low	moderate
Schedule pressure	moderate	high	highest	moderate
Allowed program risk	highest	highest	moderate	lowest

8.4 Findings

The case study focuses on the adaptation of a branch specific design approach. This differs slightly from adapting a generic branch independent design approach. The most important difference is: compared with a generic branch independent design approach (*e.g.* described by many design methodologies) a branch specific design approach (here the ECSS system) is already augmented by additional support for example standards, guidelines, methods, recommendations and modelling approaches. A further difference is that the underlying process model is more detailed and has already been adapted to the context of a specific branch (here space equipment). However, the claim of the ECSS system to be applicable to every type of space equipment makes the case study relevant for analysing adaptation approaches in general as it is expected (Meißner *et al.*, 2005) that adaptation of generic branch independent design approaches towards project specific design approaches should be done in multiple steps considering different subsets of context factors for each level.

This section reports two different approaches for adapting the ECSS system to the project specific contexts. The first approach is proposed by the ECSS and is applied when compliance with the ECSS system is mandatory. The second approach was developed by the company and is applied when compliance is not mandatory.

8.4.1 ECSS System Tailoring Process

> *"The ECSS system provides a comprehensive set of coherent standards covering the requirements for the procurement of a generic space product. This system can be adapted to a wide range of project types. The process of adapting the requirements to the project specificities is called tailoring."*
>
> (ECSS, 2008)

An advantage of the ECSS system is the consistency of the design approach and compatibility of interfaces. Compliance with the ECSS system is mandatory if the customer explicitly requires compliance, which is usually the case if the customer is a national or international space agency.

ECSS proposes a 7-step process for tailoring the ECSS system. The overall goal of this tailoring process is to establish the applicability of all relevant ECSS standards and their requirements. The process starts with an analysis of the projects characteristics. Main characteristics proposed by ECSS to be considered during the tailoring process are *e.g.* ECSS (2008): objective of the mission, product type, expected cost to completion, schedule drivers, maturity of design or technology, product complexity, organisational or contractual complexity, supplier maturity.

After an analysis of the project characteristics (step 1) and risks (step 2) which might be associated with them (for the product and the development project), the complete set of ECSS standards has to be screened for applicability (step 3). If a standard is identified as applicable all standards to which this standard refers become also applicable. During the next steps all requirements documented in the applicable standards have to be analysed regarding their applicability (step 4), completed by additional requirements if necessary (step 5), harmonised (step 6), and finally documented (step 7) (ECSS, 2008).

The tailoring (*i.e.* to let out selected activities) of the initial design approach goes along with augmenting (*i.e.* adding for example. specific activities, support, standards).

The ECSS tailoring process has some disadvantages if compliance with the ECSS system is not mandatory. The main limitation is that the overall goal of the ECSS system is to keep the risk at lowest possible level - at all cost. However, this is not always an appropriate design maxim, especially when the company has to operate in a highly competitive market sector and occurring risks have no consequences for other systems or human beings. Therefore, for such type of projects the company had to develop a new tailoring approach.

8.4.2 The Company's Own Approach

The new adaptation approach was developed in the company based on a project classification scheme which was introduced by the Quality Assurance and Product Assurance (QAPA) manager and supplemented by recommendations for adaptation based on experiences from the four projects EAGLE1 and 2, ORCA2 and COLIBRI.

8.4.2.1 Experiences from Past Projects

The COLIBRI project allowed no adaptation others than the tailoring process proposed by ECSS, but the EAGLE1 and 2 and ORCA2 projects required a further adaptation in order to make them feasible.

The EAGLE1 and 2 projects were affected by the risk of being mechanically connected to the last stage of a launcher. This connection imposes the risk that the satellite is oriented in an unfavourable attitude towards the sun which could cause thermal and power generation issues. This risk, which cannot be mitigated, leads to the premise to keep the cost as low as possible.

The ORCA2 project had an enormous schedule pressure which required a reduction of the systems complexity at constant cost and risk. In negotiation with the customer it was decided that the company applies a certain level of standards in order to show that customer's requirements are met, to secure team decisions, and to be able to sufficiently track decisions in case of anomalies once the spacecraft is in orbit.

While the customer of EAGLE1 and 2 is the company itself, COLIBRI's customer was a public institution and ORCA2's a commercial company. The two different customers of EAGLE1 and COLIBRI can be seen as origin of the three main contradictions which have been identified by the team members of the analysed projects and had to be considered in the adapted design approaches:

- QAPA approach especially configuration and documentation management,
- Team responsibilities,
- Coordination and communication.

Configuration and documentation management was seen as the major issue conflicting with time pressure and low resources. EAGLE1, being an own investment of the company had the strict goal of being a low cost project in a very short timeframe. Documentation was secondary priority after "getting the thing running up there". Contrary, COLIBRI was a project involving human spaceflight with a public institution as customer. Documentation of the process played a major role in the project. These two diametrical requirements on the documentation management caused the main contradiction.

The second contradiction identified by the team was unclear team responsibilities, *i.e.* defining and communicating who is responsible for what in the space project.

The third contradiction requested a better coordination and communication inside the team and with externals, *e.g.* keeping the team members up to date on the current status of the project, the system and the subsystems in order to identify and solve interface issues.

8.4.2.2 Project Classification Scheme

The QAPA manager of the company proposed a classification scheme which eases the whole adaptation process. The classification scheme is based on a project classification scheme described in a US Department of Defense (DoD) handbook (DoD, 1986). The DoD scheme describes four project classes: class A (high priority, minimum risk), class B (risk with cost compromises), class C (economically reflyable or repeatable), class D (minimum acquisition cost). For each project class specifications of selected characteristics like prestige, complexity, product life span, cost, and schedule pressure are given in order to provide guidance for categorisation.

The DoD classification scheme was adapted by the QAPA manager in order to improve the fit of the descriptions of each class with the types of projects usually executed in the company (due to confidentiality of the results the adapted scheme is not shown here). The project classification scheme allowed a retrospective classification of the analysed projects and a mapping of the lessons learned from these projects with the different project classes (COLIBRI - class A, ORCA2 - class B/C, EAGLE1 and 2 - class D). The project classification scheme in combination with the lessons learned data, which are now transferred into recommendations, offers guidance for adapting the product development approach for future projects.

8.4.2.3 Adaptation as a Collaborative Effort and Learning Process

During the execution of the projects the team reported continuously about issues with the design approach and the associated documentation process. The reported issues were discussed and reflected during a series of team sessions and by additional e-mail correspondence. The whole process was moderated by the QAPA manager and the lessons learned were documented.

Finally, the outcomes of this learning process resulted in the formulation of recommendations which could be related to the different project classes. The classification scheme and the recommendations build the support for the adaptation of future projects in order to provide some guidance and to avoid having the same issues again. More details on the analysis of the learning process itself can be found in Moser *et al.* (2011).

8.4.2.4 Consequences of Adaptation

For projects classified as class A, compliance with the ECSS system is mandatory, thus no adaptation other than the ECSS tailoring will be done. The design approach applied for projects of classes B, C, and D is still based on the ECSS system but will be adapted for each class based on the company internal recommendations together with the customer, thus simplified in different areas, for example: coordination principles, product simulation and test procedures, monitoring and reporting procedures, configuration and documentation management, and other.

Examples of possible consequences for Class B, C, and D projects are:

- emphasis on a trust-based sub-contractor relation rather than on formal reviews and assessments;
- different model and test philosophy;
- qualitative estimation of the risk because of the use of Commercial Off The Shelf (COTS) components and mitigation of the risk by de-rating and radiation protection according to ECSS system;
- documentation management (*e.g.* product description, test procedures, test reports) and reporting are simplified.

Projects of classes C and D show further differences. Change proposals are handled rather informal and in direct contact with customers. Projects of classes A and B will be executed as formal Stage-Gate processes, because payment by customers is dependent on gate-reviews. The gates and milestones are similar for projects belonging to the same class but differ for projects of different classes.

Even though, the coordination and documentation is simplified, the team agreed that regular internal progress meetings, regular progress reports and communication with customer and sub-contractors, and formal Gate-Reviews by the customer and the company's sub-contractors are necessary to ensure successful project completion.

8.4.2.5 Retrospective - A Reflection on the Developed Approach

After analysing the projects and the company's adaptation approach the main findings were presented to the QAPA manager. Subsequently he was interviewed in order to gather information about first experiences in applying the new adaptation approach on a project. The QAPA manager agreed with the statement that the DoD handbook 343 can be seen as a proper matching filter that includes the entire rationale parameters for having projects of different standards.

The ECSS system as a set of standards describing how to work in general but also in detail may be binding depending on the customer but also supports the design in providing agreed best practices to which one can refer in describing the way of working.

Further findings which are based on the conducted interviews and observations of one of the co-authors (acting as systems engineer in the company) are that the adaptation process is supported by the corporate management, contributing to the acceptance and utilisation of the approach. An important aspect which also contributed to the acceptance and usability of the approach is the development of the new approach as a collaborative learning process.

8.5 Discussion

8.5.1 Approaches for Adaptation

The company's design approach is based on the ECSS system which needs adaptation in order to be applicable for a specific project.

It was found that the company applies different adaptation approaches. One approach is proposed by ECSS and one was developed by the company. The main factor for the selection of the adaptation approach is compliance with the ECSS system. The ECSS approach for adaptation is used when compliance with the ECSS system is mandatory. The company's approach will be used when compliance is not mandatory.

Both approaches support a tailoring of the ECSS system, which means they focus mainly on a selection of those elements of the ECSS system which are relevant for a specific project. The criteria for assessing the relevance of elements of the design approach differ dependent on the class to which a project belongs.

In order to support and simplify adaptation the company developed a classification scheme representing typical projects. The development of an adaptation approach which is dependent on the classification of projects corresponds with findings from literature (*e.g.* Maffin, 1998; Meißner *et al.*, 2005) which highlight that adaptation needs to be context sensitive. The classification scheme is sort of a clustering of projects by using a selected set of relevant context factors.

As demonstrated in the case study, the development of a classification scheme and the formulation of recommendations and guidelines for the selection of suitable practices, methods for each project class can be done as a collaborative effort. This goes along with a learning process, which might enhance the acceptance and applicability of the developed support and guidelines.

8.5.2 Influencing Factors

Cost, allowed program risk, schedule pressure and product's complexity were observed to be the main factors that influence the degree of adaptation, respectively tailoring from a class A project "understand everything" to a class D project "go to the essentials". The different ratios, of which the cost/risk is the most prominent one, are negotiated with the customer.

In qualification, it should be stated that, the identified factors are derived from a case study in one company which operates in a specific context. Therefore, a generalisation is not possible, even though it can be expected that these factors are relevant for many companies operating in a competitive environment.

8.5.3 Adapting Design Approaches

Adaptation seems to be different for different levels of abstraction of a design approach. The adaptation of a generic design approach to a specific context requires different activities: augmenting and tailoring (see Figure 8.3).

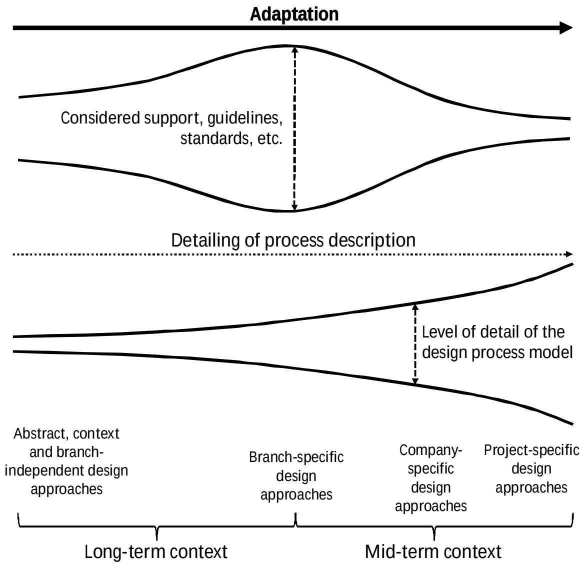

Figure 8.3. Adaptation of design approaches

The adaptation of generic and branch independent design approaches requires augmenting, *i.e.* the addition of process steps, design practices, guidelines, and other support. The adaptation of a branch specific or company specific approach to the context of a specific project can be seen as a tailoring. Tailoring means that only few additional elements will be considered and the adaptation is mainly a simplification of a comprehensive set of standards, guidelines and pre-selected support. Even though augmenting is more prominent for the adaptation on a high level of abstraction, and tailoring is more prominent when the design approach becomes context specific, both activities are conducted during the complete adaptation process.

Augmenting and tailoring of a design approach can be interpreted as divergence and convergence. Divergence and convergence during exploration and selection of suitable and necessary elements of a design approach seem also to differ with regard to the influencing factors which drive the process. Convergence seems to be mainly influenced by considerations of cost/effort, benefit, remaining risks, restrictions by standards, technical feasibility, and customer specifications. The rationale of divergence seems to be much more complex.

8.6 Conclusions

This paper contributes to design practice by describing an approach for tailoring of a branch specific design approach. The company's approach which is based on a classification of similar projects with regard to cost, allowed risks, schedule pressure and product's complexity eases the adaptation as established practices, suitable processes, and further recommendations are pre-selected, *i.e.* lessons learned are directly linked to project classes. This approach can be implemented by other companies after reformulation of the project classification scheme and collecting relevant experiences and lessons learned from their designers.

Furthermore, this paper contributes to the body of knowledge of design research by providing insights into adaptation of generic design approaches. The case study leads to a breakdown of adaptation into augmenting and tailoring.

Augmenting describes the activity to adapt a design approach to a specific context by adding *e.g.* specific support, standards, and design guidelines. Tailoring describes the activity to adapt a design approach to a specific context by selecting relevant elements. Adaptation can therefore be best described as the interaction between augmenting and tailoring of the provided support and an accompanying detailing of the design process description.

This more detailed representation of the adaptation of design approaches suggests that different types of support are required for different levels of abstraction of the design approach. The rationale for the divergent augmenting process seems to be a different one than for the rather convergent tailoring process.

The analysis of the categorisation scheme and the particular consequences for adaptation in the company allow drawing conclusions about the rationale of design process adaptation in practice, thus contributes to the debate on the applicability of design methodologies and generic design process models and provides some ideas for the support of a context dependent adaptation thereof. However, the identified factors (cost, risk, schedule pressure, product complexity) which guided the adaptation in the case study describe only the rationale of a tailoring process.

In order to understand the rationale of adaptation in general further studies are required, which also address the rationale of augmenting.

8.7 Acknowledgements

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Chapter 9

Formulation of a Questionnaire to Assess the Success of the Introductory Phase of Lean Development

K. Helten and U. Lindemann

9.1 Introduction

There are many companies who use the Lean philosophy - increasing customer value while eliminating waste - to make their processes more efficient. One field of application is product development. However, the implementation of Lean within a company, independent of a specific area, requires significant change, both in processes as well as behaviours. The introduction of Lean entails well-thought out management. The challenge is to sensitise employees to the need for Lean and to incorporate it in the long run.

While Lean as a philosophy is mostly described in literature by manifold definitions (*e.g.* of waste types), the specific introductory process with the aim of a long-term implementation is not discussed as often. The fact that improvements caused by Lean actions might become visible only after several months or even years is challenging. Therefore, it is of the utmost importance to assess the success of the introduction itself in order to foresee future implementation success. The application of economic key indicators is difficult and denies the holistic approach of Lean, *i.e.* changing employees' minds regarding customer orientation. It is more important to make people learn and experience Lean during the first application to allow future plans to sustain Lean in the company's processes.

The approach of this paper is to assess the preliminary success during the introductory phase of Lean Development. This is valuable for academic researchers and consultants or companies to assess what level of Lean a company has reached. During the specific Lean journey, it can help to derive further action plans.

9.2 Background

The underlying concept of this paper is based on the assumption that Lean Development is first introduced to a company, and that as time progresses the company's view will gradually shift from introduction to implementation (Figure 9.1). In order to embrace Lean, two sub-processes must be run through; a change process needs to inform and mobilise people, while at the same time employees need to increase their level of proficiency and learning.

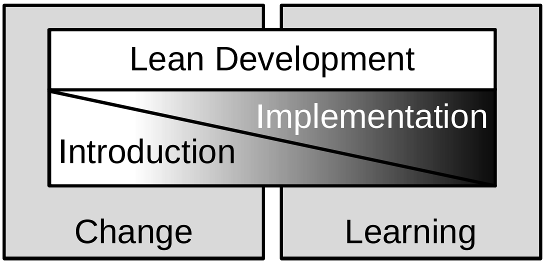

Figure 9.1. Underlying concept to assess the introduction of Lean Development

9.2.1 Lean Development and Frameworks for its Introduction

The basic idea of Lean is to focus on customer value and eliminate any wasteful task while creating this value. Generally, the literature refers to the success of the Toyota Production System for descriptions of Lean (*e.g.* Womack *et al.*, 1991). Womack and Jones (2003) defined the following five main principles of Lean: value, value stream, flow, pull and perfection.

However, the application of Lean in product development often leads to difficulties. Product development does not use tangible artefacts which can be counted and measured, but mostly uses ideas and information. Lean Development (LD), therefore focuses on the transformation of information and its improvement (Oehmen and Rebentisch, 2010; Siyam *et al.*, 2012). In order to make LD applicable, authors have defined waste types and derived specific frameworks of LD. Oehmen and Rebentisch (2010) reviewed the findings from several authors and their conclusions created a definition of eight types of waste in LD: "Over production of information", "Over processing of information", "Miscommunication of information", "Stockpiling of information", "Generating defective information", "Correcting information", "Waiting of people", and "Unnecessary movement of people".

Other authors have also investigated the necessary transformation with the use of roadmaps, *e.g.* Nightingale and Srinivasan (2011) described the "Enterprise transformation roadmap" of the Lean Advancement Initiative (LAI) at MIT. It consists of three cycles - "strategic" ("determine strategic imperative", "engage leadership in transformation"), "planning" (*e.g.* "understand current state" and "envision and design future enterprise"), and "execution" (*e.g.* "implement and coordinate transformation plan" and "nurture transformation and embed enterprise thinking").

Helten *et al.* (2011) suggest the use of a pilot project to introduce LD. Here the need to conduct a qualitative study to understand the mechanisms during the LD introduction is emphasised. A further paper proposes a pilot scheme that consists of four elements - "Analysis", "Synthesis", "Realisation", and "Implementation". For each element sub-tasks, such as the definition of actions, are defined. The scheme and its elements can be run iteratively (Helten and Lindemann, 2012). Nevertheless, none of the presented literature indicates a definitive point at which LD can be considered as implemented or how the level of implementation could be assessed.

9.2.2 Change Management and Implementation

Change can be considered as episodic or continuous. Whereas the first interpretation is based on the assumption of a certain failure or event that triggers the change process, the latter focuses on continuous modifications (Weick and Quinn, 1999). Based on an extensive literature review, By (2005) discussed change regarding three dimensions, such as rate of occurrence, how it came about and the scale. The author refers to Senior (2002) for this scheme. Depending on the two different perceptions of change, authors propose different models or definitions for managing it. Models in the context of episodic change are grounded more in the concept of several steps that need to be undertaken to reach an improved state. Others emphasise continuous efforts more, *e.g.* Moran and Brightman (2001) who defined change management as "the process of continually renewing an organisation's direction, structure, and capabilities to serve the ever-changing needs of external and internal customers".

Most literature on episodic change refers to the basic theory of Lewin who described the change process through three phases - "unfreezing", "moving", and "freezing" (Lewin, 1947). More detailed are models such as Kotter's (1995). He suggests eight steps to ensure a successful transformation. The model includes steps such as "establishing a sense of urgency", "creating a guiding coalition", "creating a vision", "communicating the vision" and "institutionalizing new approaches" (Kotter, 1995). General models like that of Lewin's are difficult to use for the intended assessment since it is very challenging to measure whether steps on such an abstract level have been fulfilled. Models like Kotter's are more specific and could support the assessment.

The term "implementation" is - like the term change - perceived differently in the literature, *e.g.* Daniel (2001) defined as implementation all activities which ensure that an object to implement is applied successfully. The author presented a "task based understanding of implementation" which consists of the elements "Planning", "Implementation", and "Result control", while having "Process control" the whole time (terms in Daniel (2001) were translated to English by the authors of this paper, see also the following paragraph). The model underlines that

a) the implementation starts rights from the beginning, and b) a continuous control is part of the final result control (Daniel, 2001).

Daniel (2001) depicted two aspects of implementation management. Besides functional management which integrates all activities for a successful implementation, institutional management refers to people (personal implementation management) including their organisational integration into the enterprise (structural implementation management). Goodman *et al.* (1980) differentiated by using the term “institutionalization” in two different phases. On the “individual level of analysis” individuals decide to behave in a new way, whereas on the “structural level” the whole organisation embraces the behaviour through three factors: “physical setting”, “social organization norms and goals” as well as “cohesiveness of the social organisation”.

Change happens in the light of an organisational culture. Schein (2004) described three different levels which manifest the organisational culture. On the first level are the “artefacts”, such as processes and structures. “Espoused beliefs and values” are assigned to the second level and on the third level the “underlying assumptions” like unconscious beliefs and perceptions are summarised. Whereas the third level elements can be considered as the underlying sources of values and actions within the organisation, the artefacts are the most visible but least decipherable from the outside.

Examples from industry related work in the field of product development were presented by Stetter (2000) and Viertlböck (2000). For the successful implementation of methods in integrated product development, Stetter (2000) proposed a five-layer model. As activities on the forth layer (“Implementation of methods”), the author suggests involvement of employees, anchoring of methods as well as the improvement and replacement of methods, among others. Viertlböck (2000) derived a model to enhance the introduction of tools and methods, and defines a set of 22 success factors. For example, the sensitisation, involvement and training of employees, the use of pilot projects and the assignment of enough time to allow for changes in mindset.

9.2.3 Learning Theory

Two types of learning can be differentiated - “single-loop learning” and “double-loop learning”. Single-loop in this context means that a person or an organisation behaves according to specified methods and strategies in case of problems. The underlying values and assumptions are not changed. In a double-loop environment, a person or an organisation can adapt both the existing methods and values if necessary (Argyris and Schön, 1999). LD mainly requires the double-loop learning. Employees need to understand challenges and potentials for improvements, *i.e.* they need to question the existing structure. On the way to a long-term implementation, some phases of single-loop learning might be necessary to allow employees to practice the results of LD actions.

9.2.4 Assessment of Lean Capabilities

The assessment of organisational capabilities is challenging. Maier *et al.* (2012) reviewed 24 maturity grids and derived a four-phase roadmap and related decision points for the development of such grids. The "planning" phase requirements include, among others, the identification of audience (*e.g.* change agent, CEO), and aim (raise awareness or best practice benchmark). During the "development" phase, maturity levels need to be defined. The authors identify the following as exemplary: "existence and adherence to a structured process, *e.g.* infrastructure; alteration of organisational structure, *e.g.* job roles; emphasis on people, *e.g.* training; emphasis on learning, *e.g.* awareness". Furthermore, the process of assessing by means of interviews and workshops needs to be named. The "evaluation" includes a validation and a verification. One requirement of the final phase ("maintenance") is to benchmark the organisation against others and to define a process of how to improve further.

In the context of the mentioned Lean transformation roadmap above, the LAI group at MIT has developed a "LAI Enterprise Self-Assessment Tool (LESAT)" which focuses on the transformation process to a high-performance company. Divided in three sub-categories ("enterprise transformation/leadership", "lifecycle processes", "enabling infrastructure") a total of 43 practices are presented and assessed. The assessment levels vary from 1 ("some awareness of this practice, sporadic improvement activities may be underway in a few areas") to 5 ("exceptional, well-defined, innovative approach is fully deployed across the extended enterprise (across internal and external value streams); recognised as best practice") (LAI, 2012).

In general, as stated by Reik *et al.* (2012), the measurement of LD itself already poses some difficulties. Specifically, in this context, time controlling shows limitations, *e.g.* because the durations of different projects are not comparable or development activities are hard to measure in detail and are seldom tracked to that level. Furthermore, management tends to ask for improvements on the level of waste symptoms, whereas actions address the causes. Key indicators, therefore, need to measure improvements on this level. On the whole, the authors propose the concept of a "Lean monitoring card". Taking the approach of the balanced scorecard of Kaplan and Norton (1992), it allows the assessment of the LD success by use of four perspectives - "user perspective" (developers as customers), "implementation perspective" (referring to measures), "learning perspective" (skills to continuously strive for improvements), and "corporate perspective" (*e.g.* financial key figures that have relevance beyond development).

9.3 Research Approach

The research team accompanied three small and medium-sized enterprises (SME) during their individual LD pilot projects. During the project, the researchers supported and monitored the companies at the same time. Support refers to the delivery of knowledge about LD, moderation and preparation of joint project meetings, leading important steps like the waste analysis as well as managing the overall research process. Due to the time limit of the research project, the single pilot phases ran for a period of between 12 and 18 months. The SME environment provided the opportunity to form a core team of almost all management levels, and to integrate a relatively high number of PD engineers during the introduction. The core team within a single company consisted of three or four people. In each company, a similar process was used, but adaptations were possible. For example, the companies tried at different points and to different extents to roll-out Lean to units other than the pilot's business unit.

The research method is characterised by the action research approach. The idea is that one learns the best about complex social systems by observing changes that have been introduced to the system. The researcher's work is characterised by both observing and participating (Baskerville, 1997). Action research can be described as a cyclical process which consists of five main phases: "diagnosing", "action planning", "action taking", "evaluating" and "specifying learning" (Susman and Evered, 1978). The approach supports the analysis of dynamic systems such as product development. Data is valuable since researchers get first-hand information and can rapidly clarify misunderstandings (Ottosson and Björk, 2004). According to Susman and Evered, action research follows the aim "to develop the self-help competencies of people facing problems" (Susman and Evered, 1978). The approach is therefore best suited to a research goal to enable the partner companies to establish LD within their organisation and enhance the idea in future.

One assessment interview was conducted in each of the companies. All members of the core team participated (in one company, a person had left the company and thus could not participate). The interviewees were all familiar with the pilot project from the beginning and were themselves aware of the current state of all taken and planned actions. The questionnaire was sent out before the interview to allow a prior assessment without the research team. Following the concept of a semi-structured interview, the questions are asked one by one by the researcher, allowing discussions and additional information at any time. The participants within the core team of a company are allowed to state different opinions to a question.

9.4 Questionnaire

Table 9.1 shows the structure and the questions of the questionnaire. The questionnaire integrates three main categories to assess the adoption of LD within the organisation.

First, the "understanding" of LD is addressed. Therefore, it is important to know whether the company has defined LD and its goals for the specific context. Furthermore, the questions in this category refer to the extent to which employees knew about the content of LD and its principles, as well as had understood the motivation behind the (planned) actions. With respect to the targets and the definition of LD, this first category could be considered as part of the "strategic cycle" according to Nightingale and Srinivasan (2011). The extent to which the targets of LD are formulated addresses Kotter's step to develop a vision and a strategy, whereas the extent to which the employees are familiar with the content, the motivation and the actions of LD refers more to aspects like "sense of urgency", "communicating the vision" and "empowering" (Kotter, 1995).

Second, ten questions are asked regarding the aspect of "implementing". Aside from the extent to which the company's goals are met, several questions refer to the defined waste types and actions - whether the waste was eliminated by the actions, whether the actions were realised completely, and what happened to both aspects at the end of the pilot project. Furthermore, the satisfaction of the employees and the rate of use were considered. Finally, the questionnaire asks whether success had been reached during the introduction as well as whether problems had occurred, in any form. This category mainly refers to the stage "realisation", but also considers "analysis" (of waste) and "synthesis" (of actions) (Helten and Lindemann, 2012). With respect to Kotter's model for transformation, the category "implementing" addresses the "empowering others to act on the vision", the "planning for and creating short-term wins" as well as "consolidating improvements and producing still more change" (Kotter, 1995).

The third category addresses the "institutionalising" of LD. Questions in this category ask whether LD is integrated in the processes, *e.g.* by working instructions or forms, and whether employees are assigned specifically to LD. Further mechanisms and media to either communicate or learn and train LD are of interest. In addition, it is relevant to see whether employees link the results of the actions to the LD introduction. Also addressed is whether other departments have conducted a LD pilot project or use any LD approaches. This category includes the main aspects of the "Implementation" phase of Helten and Lindemann (2012) to anchor Lean. It further refers to Kotter's eighth step - "institutionalizing new approaches" (Kotter, 1995). The third category also addresses the "institutional management" (Daniel, 2001). Both the second and the third category show similarities to the "planning cycle" and "execution cycle" according to Nightingale and Srinivasan (2011).

Most of the questions asked for activities and structures on a visible level, thus qualify as "Artifacts" in the concept of Schein. This is important to assess whether the company was able to realise and to anchor several activities of the pilot project. Nevertheless, several questions related to both "Understanding" (goals and principles) and "institutionalising" (training and communication) target Schein's second and third level ("espoused beliefs and values", "underlying assumptions") (Schein, 2004). If employees are integrated into the introduction as mentioned in those questions, the company is capable to ensure a double-loop learning environment (Argyris and Schön, 1999).

In general, the questionnaire follows the suggestion of Reik *et al.* (2012) to focus on the developer as customer, and to integrate perspectives on the implementation of measures as well as on learning.

In addition to the questions, the participants of the interviews are asked to rate the overall success, using a four-point Likert scale from "successful" to "not successful". All over, the questionnaire reflected the specific research project, *i.e.* important steps such as the waste analysis as well as the definition and realisation of actions were addressed.

Table 9.1. Questionnaire to assess the success of the introductory phase of Lean Development

GENERAL		The introduction of LD was…	Four-point Likert scale (*Successful, mostly successful, less successful, not successful*)
UNDERSTANDING	1.1	LD is defined within the organisation.	Four-point Likert scale (*Agree, mostly agree, mostly disagree, disagree*)
	1.2	The goals of LD are formulated.	
	1.3	All PD employees are familiar with contents and principles of LD.	
	1.4	All PD employees are familiar with the motivation and the contents of the (planned) LD actions.	
IMPLEMENTING	2.1	The company´s goals of the LD introduction were/are met.	
	2.2	The identified waste symptoms and causes were/are eliminated by actions.	
	2.3	The actions were/are completely realised.	
	2.4	Following the LD pilot project, further waste symptoms and causes were/are identified.	
	2.5	Following the LD pilot project, further actions were/are identified.	
	2.6	The affected employees are satisfied with the realised actions and perceive an improvement of their development activities.	
	2.7	All affected employees use the implemented actions.	
	2.8	All affected employees were/are involved in the implementation of the actions.	
	2.9	There have been/are successes during the LD introduction.	
	2.10	No problems occur(red) during the LD introduction	
INSTITUTIONALISING	3.1	LD was/is anchored permanently in the processes (e.g. working instructions or forms).	
	3.2	Employees were/are assigned who drive LD as a topic.	
	3.3	Mechanisms and media to communicate LD were/are established.	
	3.4	Mechanisms and media to learn and to train LD were/are established.	
	3.5	Employees can link the results of actions with the LD introduction.	
	3.6	In other departments a LD pilot project was/is run or approaches were/are adopted.	

9.5 Discussion

In all of the companies, there were different levels of agreement to different answers. As usual within a scale assessment, people had different levels of perception, *i.e.* some respondents answered a question with “agree”, others with “mostly agree” even if they had a quite positive perception and did not rate any question at all with “agree”. The discussion within the team showed in many cases that they were all referring to the same aspect or example. The interviewees therefore agreed often to a common answer in the end.

Several questions, especially the ones related to actions, were biased, because interviewees referred to different units of analysis. The most significant difference in the way questions were answered is that respondents only considered the actions realised whereas others considered all the actions, including those which caused problems. This does not cause problems for the qualitative analysis. Nevertheless, further questions about the extent of and reaction to failure should be included in the questionnaire. Specifically how the company intends to proceed with discontinued actions in order to bring them to an end or to keep a positive image of the Lean initiative is of interest.

Representatives from higher management levels generally compared the current state of LD with the vision of LD in each PD department of every business unit. Thus they rated the success lower than for example representatives from PD who were already able to perceive improvements in their everyday work. To improve the questionnaire, sub-questions could address different units. Still the authors think it is important to trigger a discussion on all levels to sensitise for both a strategic and operative perspective.

Some questions lead to misunderstandings since aspects were assessed differently while being asked in the same question. For example, the question whether “all” employees were “involved” was answered by one person with emphasis on “all”, by another person with emphasis on “involved”. It could be useful to differentiate in sub-questions between employees who are actively involved in the Lean initiative and those who are not. Examples of involvement should be given.

Furthermore, the interviews were conducted approximately nine months after the official end of the pilot projects. Hence the companies had already been required to find a way to manage LD by themselves without external support. This crucial phase of embracing and overtaking the full responsibility was therefore integrated into the assessment by the companies. This interval seems advisable to allow insights into the internal acceptance. Nevertheless, the questionnaire can be used during or shortly after the pilot project.

So far, the questionnaire does not mention specific financial key indicators as proposed by Reik *et al.* (2012) (“corporate perspective”). The related research project showed that after the short period of the pilot projects mainly figures were available which targeted the elimination of waste causes (*e.g.* access rate to a database in case of insufficient knowledge management) and learning effects. Companies could refer to individual key indicators when asked for their goals at the beginning of the questionnaire.

Overall, the answers to specific questions underlined the trend of the overall assessment by the company, *i.e.* considering the majority of the mentioned scale levels. Thus the questions, even though no mean values are calculated, seem to be in coherence with the aim to holistically assess the current state on the Lean journey.

To use the questionnaire to qualitatively analyse change processes in academia, the impressions of the researcher also need to be included, especially when comparing different companies.

9.6 Conclusions and Outlook

The paper generates a scheme to assess the success of the introductory phase of LD. Lean in product development is challenging due to less tangible artefacts and the creative character which incorporates hardly any repetition. Since results of Lean may only be measurable after a long period, a qualitative, early assessment is required. Important areas to integrate are frameworks on Lean, change management and learning theories. A questionnaire is derived as a basis for semi-structured interviews with the core team of industry based pilot projects. Three main categories structure the questionnaire, addressing different levels of awareness and behaviour. Firstly, it is the "understanding" of LD, its goals and principles. In a second step, the knowledge is used to act in a Lean way and to implement actions ("implementing"). Finally, the experiences from the realisation help to anchor LD within the organisation ("institutionalising").

The interviews show that the assessment of the introductory success strongly depends on the unit of analysis and the perception of the team members. The main issues reflect the differences between the success in one development department or business unit versus the whole enterprise. Further, the success is related in some cases to specific (realised) actions, whereas other companies refer to all (including not fully realised) actions. Finally, terms such as "involved", "use", and "established" are difficult to assess. In order to improve the questionnaire, additional questions should address the handling of failures (*e.g.* discontinued actions) and ask more differentiated questions for the various units of analysis.

Overall, the qualitative approach allowed controversial discussions which were valuable to assess to what extent the company has embraced Lean. In a further step, engineers and employees outside of the core team could be asked about their perception of the introductory success. The scheme is of utmost help for both external resources supporting the introducing companies (*i.e.* academia and consultants) as well as internal assessments.

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Chapter 10

The Dilemma of Managing Iterations in Time-to-market Development Processes

M. Meboldt, S. Matthiesen and Q. Lohmeyer

10.1 Introduction

This paper considers the authors' experience in industrial practice and reviews it from the point of view of scientific discussion. From scientific point of view there are three major Research questions: Why are iterations conceived differently? What makes an iteration valuable or harmful? What are appropriate strategies to deal with iterations under time pressure? The Papers give answers on this major research question by showing different aspects of time-to-market development processes and the challenge of effectively handling iterations within them. One of the authors was development head of a business unit responsible for various development and innovation projects. The other, in his position as global process manager for research and development, was responsible for the design and improvement of development processes in the same company. Thus both views represent the conflicting aspect of process modelling and iteration, which is a key topic in scientific discussion (Table 10.1).

10.1.1 Delimitation of Product and Process Area

Most publications and research in this area are concerned with huge development projects, *e.g.* in aircraft or automotive companies. These development projects are characterised by large development teams and stringent external safety regulations. In general there are only a few publications reflecting iterations in practice. For example Wynn *et al.* (2007) remark that there are only rare examples of the correlations between specific design reworks and project delays. One of the cited time-to-market projects is from the Airbus A380.

The authors' experience is based on design practice in small design and projects teams (3 to 15 development engineers, and project teams with up to 30 people). In addition to this, the external safety regulations for product approval are at a lower level. The major difference is that the decisions about product quality and maturity are made within the company itself. It has to be investigated in further research how these experiences can be compared to development projects with large teams and stringent external regulations.

Table 10.1. Different views of process modelling and iterations

	Process	**Iterations**
Development point of view	Every development process is unique and defined by the challenges resulting from the occurring problems, which are always different.	Iterations are day-to-day business. They are essential learning cycles in development that allow a continuous gain of knowledge and thus a mitigation of uncertainty and ambiguity.
Management point of view	The process model is a company standard and mandatory framework for risk mitigation. It is essential to effectively steer communication, resources and investments in the company.	Iterations are expensive exceptions. They cost time and money. Iterations have to be eliminated: The goal is a zero-iteration process as defined by "Do it right first time".

10.1.2 Iteration in the Context of this Paper

A time-to-market development process is about designing, producing and launching successful products in order to make money. During this process, a lot of decisions are made on vague assumptions and estimations. Later in the process these decisions are verified or found to have been false (falsification). A successful verification approves former assumptions, whereas a falsification always leads to minor or major iterations. On one hand these iterations are time and money consuming, on the other hand they are important to gain knowledge about the specific issues in a project. Thus, a falsification leads to learning cycles and in consequence decisions made are overruled and changes have to be implemented.

This paper focuses on development iterations in the product life cycle caused by the following areas: 1. technology and production issues, 2. market issues including competitor situation and patents, 3. changing company situation and strategy, 4. changing applications and external regulations made by customers or suppliers. Here, the following types of iterations can occur:

- worst case iterations: iterations triggered by issues occurring after the market launch - the consequences are product recall and loss of reputation;
- serious iterations: issues requiring the change of a decision from a previous development stage - for example a patent situation requires a conceptual change after the design freeze;

- targeted iterations: iterations within a development stage, which do not impact on previous gate decisions and do not jump back to a previous stage - these iterations lead to product maturity (Krehmer *et al.*, 2009).

Based on a research overview the paper shows how process modelling is adapted to a company process model. It describes the different aspects of iterations and escalations in regard to the project objectives. As a conclusion at the end of the paper, the authors give recommendations based on a good practice approach.

10.2 Models of Iterations

In the literature there are several definitions and classification proposals for iteration. According to Costa and Sobek (2003) a common approach is to consider iteration as repeating design activity. Most definitions in research state that iterations describe a cycle of gathering information, processing that information, identifying possible design revisions and executing those revisions in pursuit of a goal.

Wynn *et al.* (2007) differentiate between six non-orthogonal perspectives of iteration: exploration, convergence, refinement, rework, negotiation and repetition. These implicate differences in the understanding of iteration between the technical and management contexts. Le *et al.* (2010) summarise that authors focusing on the negative effects of iterations refer to unproductive rework, which can be caused by factors such as flawed design and inadequate quality assurance. Authors reporting the positive effects focus on iteration as being necessary to systematically explore and understand the complexity of design problems and their potential solutions, thus leading to a more efficient solution finding process.

10.2.1 Basic Models of Iteration

One of the basic models of iteration is the TOTE unit according to Miller *et al.* (1960). TOTE stands for Test-Operate-Test-Exit (see Figure 10.1). It is a model from cognitive science that represents an iteration as a continuous evaluation-action process that proceeds until a test sequence yields a positive result. The TOTE unit is applied in psychology, cybernetics and artificial intelligence to represent problem-solving processes.

Another basic model is the PDCA cycle according to Deming (1986). The model describes iteration as a cycle of the four generic activities ‘Plan’ (design the product), ‘Do’ (manufacture the product), ‘Check’ (test it in service, through market research) and ‘Act’ (put it on the market). Nowadays the model is applied to the improvement of processes, products, and services in several organisations, as well as to improve aspects of one's personal endeavours (Langley *et al.*, 2009).

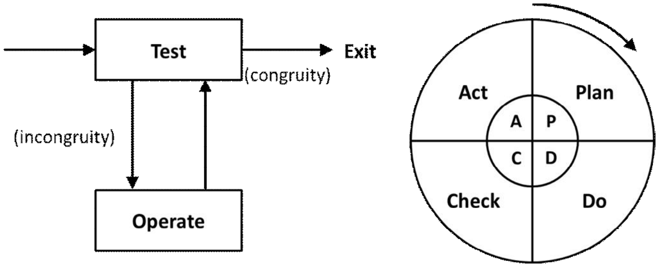

Figure 10.1. Basic models of iteration: TOTE unit (left) and PDCA cycle (right)

10.2.2 Advanced Models of Iteration

The Unified Innovation Process Model for engineering designers and managers according to Skogstad and Leifer (2011) depicts the design process and explains how its participants' actions affect it. The model considers three central activities: 'Plan', 'Execute', and 'Synthesise' that occur repetitively during every phase of the design process (see Figure 10.2). The model also includes three feedback paths: 1. Re-planning signifies the action taken by designers when the results gained during synthesis are so different from what was expected that they must return to planning and change their approach. 2. Revision occurs when the results of synthesis are not sufficient to qualify as a solution, but are not so far off that the overall approach has to be changed. 3. Reworking is the process of re-executing until the output is satisfactory enough to advance to synthesis.

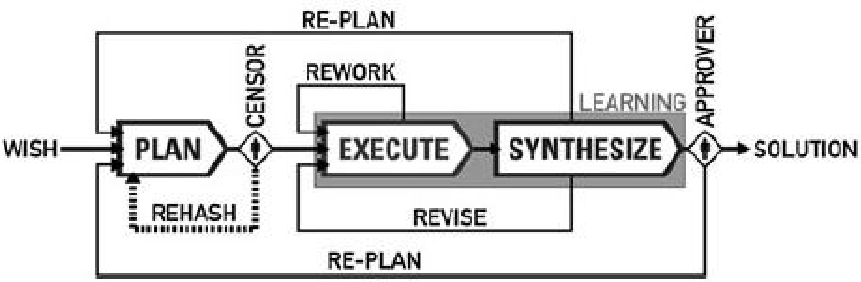

Figure 10.2. Unified Innovation Process Model according to Skogstad and Leifer (2011)

The Advanced System Triple according to Albers *et al.* (2011) describes product development as an iterative process of synthesis and analysis of both the system of objectives and the system of objects (see Figure 10.3). The model represents the designers as the operation system.

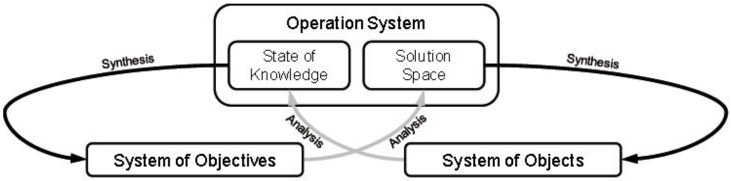

Figure 10.3. Advanced System Triple according to Albers *et al.* (2011)

Based on their knowledge and additional information gained from relevant objects, they make their first decisions about product-specific objectives. So they build up an initial system of objectives that frames a vague solution space. The solution space is a designer's mental model and therefore an element of the operating system. In the next step the designers have to find different solutions, where every solution embodies certain decisions. Solutions are described by virtual or physical objects that in turn lead to new information, which the designers use to refine the system of objectives. By repeating this refinement cycle, uncertainty is progressively mitigated.

10.3 Management of Time-to-market Processes

Development processes in companies are not static, they are subject to continuous improvement. Processes are adapted to changing internal and external needs and requirements. And the optimisation target is always to keep the non-value-adding activities to a minimum. The challenge is to reduce losses within development projects, by eliminating non-value-adding activities - inevitably this sometimes applies to iterations. A development model is always company-specific and adapted to the company's development philosophy and culture.

In industry, stage-gate models are the leading standard. In the nineties these "deliverables-oriented" management approaches replaced the "activity-oriented" methodological engineering design approaches as the leading standard in development processes. The key idea of these approaches is that between every stage of the process there is a gate which includes a management review. These validation points review the results and approve entry to the next stage (Cooper, 1990). The key purpose of these approaches is to steer investment and communications with other departments and partners. With the stage-gate approach the paradigm for process models changed from "the model tells the teams what they have to do" to "the model only describes, what the teams have to deliver at the gates".

Early stage-gate approaches included a large number of gates. These development process models had two major issues:

- many non-value-adding iterations: these detailed process models caused a lot of cycles. The key insight was that development activities cannot be separated into small units without increasing iterations which revise decisions from previous gates;

- decisions were shifted to management: The degree of freedom of the project team was limited and highly steered by the management. As a result teams worked to fulfil tasks not to set and achieve objectives.

After major reworks most processes were reduced to models with five or six stage-gates. Process design is always on a thin red line between loss of productivity due to non-value-adding bureaucratic process work, and loss of productivity caused by insufficient communication and rework.

10.3.1 Time-to-market Process Model

The time-to-market (TTM) process model used in the company the authors worked for describes a six stage-gate development process (see Figure 10.4). TTM processes are about bringing a product to market and ensuring return on investment. These processes start on the basis of a technologically mature product concept. By Gate 2 (G2), at the latest, the product prototype has to achieve 80% of the performance at 120% of the cost of the final product. Thus, at a very early stage in the process 95% of the detail design is already done, including tolerances, testing and manufacturing. From this point on iterations start to become critical.

At every stage of the process pre-defined key deliverables have to be fulfilled. For example, one of the key questions in Gate 3 (G3) is: Has the value proposition been confirmed by a customer acceptance test? Usually most iterations occur just before a gate, because all critical information and test results converge in gate decisions. This can be described as a “bow wave effect”. Critical topics and open questions are pushed towards the next gate decision. This effect masks the issues at the beginning of the next stage. In order to make robust decisions, it is highly important that the iterations occur early in the stage, right after the gate. If they occur early, there is still time to solve issues and optimise the design within the stage. In consequence it is important not to prevent iterations but to provoke them very early in a stage.

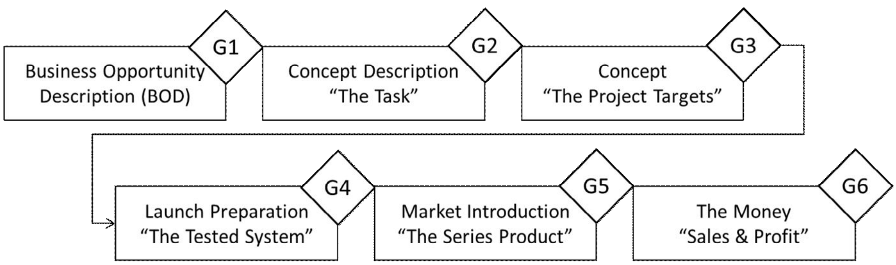

Figure 10.4. Time-to-market process model according to Esquius Serra (2010)

10.3.2 The Dilemma of Managing Iterations

The dilemma of iterations is whether an iteration can be predicted or not, and if an iteration should be included in the project plan or not. The central management assumptions are that, if an iteration is predictable, then it is preventable, and if an iteration is not predictable, then it is not projectable. From the management point of view planned iterations, without specific content are regarded as buffers. Buffers are "squeezed out" of the project plan for the very good reason that they inevitably extend the project duration.

The following dialogue gives an insight into this dilemma between a development engineer and the management steering board of a project. The development engineer, who is the technical project manager, is asked to present the project plan for the development of a new product. He planned three iterations in stage 2 until G2 (concept freeze) and in stage 3 until G3 (design freeze). Management asks him to report on the specific reasons and contents of the iterations and what he is proposing to avoid them in order to reduce development time: "The planning of these iterations is based on my experience. We need them to solve unexpected technical problems, we do not know yet, what they are about, but they will occur." The management replies: "We need to shorten the development time, in order to be first on the market. An early market launch is directly linked to the return on investment that we can achieve with this product. You will get all the resources you need. Please specify these unknown problems and the additional competences you will need in your team so as to solve them before they occur."

10.4 Two Fundamental Types of Iterations

In early development stages the issues of iterations are not critical, because there is still time to react flexibly. At that point, when the market entry communication (at G3) or the investments for series production tools (at G4) are made, the situation changes completely. After this point every iteration is critical. Based on our experience most of the iterations occur after this point (between G3 and G5). In this context we differentiate between two fundamental types of iteration. 1. In-stage iterations (these are iterations within a stage which do not impact on previous gate decisions); and 2. cross-gate iterations (iterations which affect decisions from previous gates and have an impact on investments and market launch).

10.4.1 In-stage and Cross-gate Iterations

In-stage iterations are learning cycles. Because of this it is important to provoke them very early in a process stage. Here, the most effective strategies are validation and system integration under realistic boundary conditions. Iterations must not be understood as doing the same twice, it rather is about having clear hypotheses of the iterations' outcome in order to verify them or declare them false. Provocation of iterations is an objective-oriented step to improve the overall system. These iterations are essential to find the best solution.

Cross-gate iterations are learning cycles as well, but they are expensive in cost and time, so they have to be prevented. If functional issues occur early in the process the probability of an impact on other stages is small. It is important that the process and deliverables encourage the team to look at critical issues and test them as early as possible.

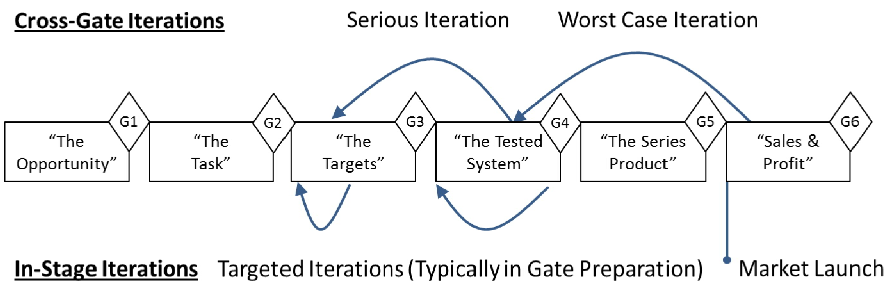

Figure 10.5. In-stage and cross-gate iterations

An experienced engineering designer is able to build up powerful mental models of the product, its application and boundary conditions. In several mental iterations he or she synthesises a design proposal, which can be validated later in the process. The designer is able to pre-think, how the design will behave for the customer in a real application under realistic boundary conditions (Matthiesen, 2011). Now it has to be validated to see if the mental model covers all relevant elements of the real application and environment. This is done, for example, by prototyping, testing and system integration under realistic boundary conditions.

One of the key deliverables at G2 is definition of the product's value proposition (VP). At G3 the value proposition has to be confirmed by customer experience with a physical prototype under application conditions (Customer Acceptance Test). Here, there are three possible outcomes:

- the VP and the design match the needs of customer (no iteration);
- the VP is verified, but the customer identifies weaknesses in the design of the product, *e.g.* the power tool is not well balanced. These are quantitative issues, which lead to a redesign (in-stage iteration);
- the VP is found to have been false and does not meet customer expectations. Thus, the VP, a key decision at G2, has to be redefined, *i.e.* the concept has to be changed. In consequence the development progress for stage 3 is obsolete and the process has to restart in stage 2 (cross-gate iteration).

10.4.2 Practical Examples of Iterations

The first example considers self-drilling screws that are used in steel construction to fasten metal sheets to metal structures. The performance of the drilling process is severely limited by the temperature of the screw's drilling tip, which increases quickly during the drilling process. A promising concept is to cool the cutting edge while drilling to increase performance. In the field of self-drilling screws this was a novel idea. Thus, there was knowledge about increasing performance by cooling cutting edges, but no specific knowledge about increasing performance by cooling the tips of self-drilling screws.

The idea was firstly realised in a power tool that pumps cooling liquid through a hole in the screw right to the drilling tip. The development team faced several problems and iterations while developing this power tool. Every iteration led to new knowledge about power tools that are able to cool self-drilling screw tips. When the power tool finally worked, it failed to achieve the predicted performance increase. Qualitatively, the function was not fulfilled. Thus, the result was a cross-gate iteration that threw development back from stage 3 to stage 1 of the TTM process model. Validation was concentrated on the power tool not on the general idea itself.

The second example concerns a fibre reinforced belt that was the most important part of a new power tool concept. This belt passed around some metal pulleys in order to transfer high dynamic forces. It was especially developed for exactly this application. The first prototype of the belt was produced and tested in a prototype power tool. After some hundred test cycles the power tool broke down. Due to the fact that the power tool was a functional prototype and thus not meant to meet lifetime requirements, the breakdown had been foreseen. The belt itself performed very well and all known requirements were fulfilled. The wear of the belt was low and projected to meet lifetime requirements. No further problems were expected.

Based on the test results gate G2 was successfully passed and management approval was given for investment in the production tool. In the following stage the team's knowledge was sufficient to design and produce the first power tool for lifetime tests. This time the belt broke after half of the estimated and required lifetime. The reason was found to be abrasion by the metal pulleys, which changed the stiffness of the belt and its pliability.

The development team did not foresee this problem, because it did not know about it and was not able to learn about it, before a lifetime test of the power tool had been carried out. Thus, the function was qualitatively fulfilled (*i.e.* the belt generally worked) but the quantitative requirements of the function were not achieved (*i.e.* the belt did not work as long as required). The failed lifetime test led to new knowledge and thus to the definition of new requirements and the redefinition of existing requirements.

In both examples knowledge was gained. The first example led to a cross-gate iteration, because qualitative fulfilment was not achieved, whereas the second example illustrates an in-stage iteration caused by failing to meet a quantitative target. Cross-gate iteration should generally be avoided. Here, one strategy is to set up validation tests very early in the development process to ensure qualitative fulfilment of a function. In the first example a substitution test might have worked in the following way: apply cooling to the metal base material and validate with regular self-drilling screws, to see if the requirements can be met.

10.5 Escalation Strategies in TTM Processes

The most critical iterations in TTM processes are iterations that affect the launch date. Several studies have shown that in the development of series products a delayed market launch is more expensive than an increase of the development costs (see Figure 10.6). Thus, in TTM processes the primary objective is to ensure the launch date. For a development team this means enormous pressure. If unexpected problems appear, they usually react by applying different escalation strategies. These strategies are not explicitly documented and they are not considered in a company's process models.

Escalation strategies contain different levels of escalation, which depend on the current problem situation and the company's prioritisation of objectives. Each level of escalation requires a "sacrifice" of cost, quality or functional objectives. Due to this the escalation strategies are also called "sacrificial strategies". In most cases the market launch will only be postponed when all levels of escalation have been exhausted. In escalation fixed project objectives are changed or even removed completely.

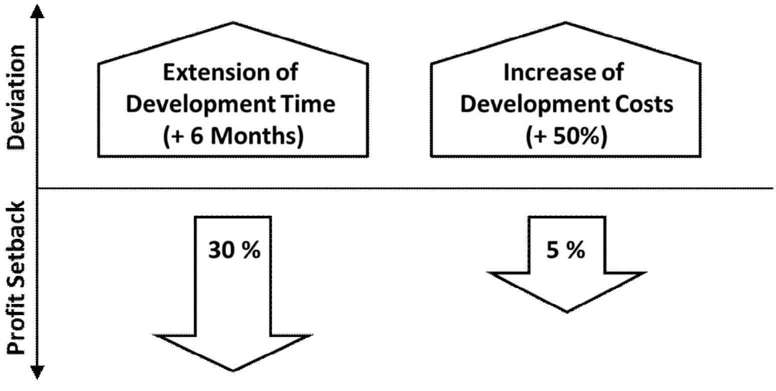

Figure 10.6. Profit setback caused by an extension of development time and an increase of development cost (product life time: 5 years) according to Hall and Jackson (1992)

On the basis of the authors' experience, levels of escalation can be described as follows:

- Escalation Level 0: Initialisation of Escalation - a critical problem occurs that might lead to an unexpected iteration affecting the market launch date. Higher management's attention is attracted and the pressure on the project team is increased in order to prioritise the critical issues;

- Escalation Level 1: Sacrificing Project Resource Efforts - at this level the work load is increased by overtime work. Task forces are established that have a daily briefing at 7am and a wrap-up meeting at 8pm;
- Escalation Level 2: Sacrificing Cost of Development - at this level the project budget is increased and additional personnel resources are assigned to the project. These can be external personnel or people from other projects within the company, which are then stopped. In consequence the project plans of the other project become obsolete;
- Escalation Level 3: Sacrificing Cost of Production - here the product's cost objectives are changed. In order to maintain the product's quality as well as its launch date expensive improvements, *e.g.* coating, are approved;
- Escalation Level 4: Sacrificing Development Quality - in this case the functionality of the product is consciously reduced so as to maintain the market launch date. Here, quantitative fulfilment (*e.g.* ventilation slots in a previously closed housing) and qualitative fulfilment (*e.g.* entire functional features) are sacrificed;
- Escalation Level 5: Sacrificing the market launch date.

The application of escalation strategies is recognisable in different industries. The first generation of a novel product often has quality or functionality issues that are known. The first generation always has the target to bring the product to market, followed quickly by a successor with issues from the first generation fixed. For example in automotive industry, with a longer product life cycle, they handle these issues by recalls disguised as general service inspections.

10.6 Conclusions

The question of whether tight project plans and time are the most critical factors in the development process is a question for the management philosophy of the company. But it is clear that a company only earns money when the product is on the market. The strategy of ambitious project plans ensures focus and helps to set the right priorities. The competitor situation in the market is hard, and you need to take calculated risks to win the game. The guiding philosophy in a lot of companies is the quote from the Formula 1 driver Stirling Moss: "If everything is under control, you are just not driving fast enough".

It is a fact that every product development project lasts exactly until the market launch date can no longer be postponed. The launch date is defined by the willingness to postpone the launch date - and if there is a buffer the time is always filled and at the launch date the product is ready although there are still a lot of aspects to improve. Development is not about bringing the best product to the market, it is about bringing a product to the market that is good enough. Good enough is the guiding principle. If the technical departments could decide, when a product was ready for market launch, the company would be bankrupt before the launch happened. This situation shows the daily conflict between technical development and market-oriented management. The technical view is that they want to bring the best product to the market; the management view is to bring a product to the market that is good enough.

In conclusion, the quintessence of the authors' experience in practice is that:

- iterations cannot be prevented; they are valuable and essential to gain insights and knowledge;
- cross-gate iterations should be avoided at almost any cost. One strategy to avoid them is to set up validation testing very early in the development process to validate the quantitative fulfilment of critical functions;
- in-stage iterations should be provoked to enable informed decisions by verifying qualitative function fulfilment at minimum cost;
- iterations should be provoked in the early stages of a project by validation with prototypes, system integration testing, and testing under realistic boundary conditions;
- iterations that affect previous gate decisions should be prevented by focusing on qualitative issues;
- the combination of mental pre-thinking and prototyping should be employed to minimise iterations.

In order to steer iterations effectively, a deep and detailed knowledge of the functions and dependencies of a system is an essential precondition. In further research it will be important to link process models and iterations to functional product models. Iterations have to be balanced; management's antidotes are the different escalation levels.

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Chapter 11

A New Brief Creation Process to Improve Design Innovations in Home Healthcare

F. Yang, Y. Benjamin and C. Roberts

11.1 Introduction

This paper presents research findings and conclusions which investigated the strengths and weaknesses of innovation management strategies of small and medium sized enterprises (SMEs) in the home healthcare (HHC) field. It explores how to improve opportunities for innovation by better understanding the needs of all stakeholders, particularly users and carers, in the design and development process.

The demand for well-designed home healthcare products (HHCPs) and services (HHCSs) grows whilst product and service development strategies adopted by many suppliers have not matured to realise innovative solutions which adequately address the real needs and requirements of end users. Working collaboratively with companies in the sector, this research identifies that the shortcomings are most prominent in the front end phases of the development cycle. It suggests an improved brief creation process model which addresses the factors which have significant influence on innovation success but are generally missed. This new model focuses on addressing end users' real needs, adapting to changing environments, fostering greater stakeholder engagement, and managing information processing in a formal and structured manner.

Health systems worldwide have been actively exploring ways to improve the quality of care so that it is cost-effective, often with a focus on people with long term health conditions and the aim of providing people with care in their own homes (Steventon and Bardsley, 2012). HHC is viewed as one of the potential solutions, and is a fast developing sector. In England, the 3Million Lives Project launched recently in January 2012, aims to support three million people with long term health conditions.

With the increasing demand for HHC, the market in HHCPs and HHCSs is expanding, particularly in areas where healthcare resources for hospitals and society are barely enough. HHCPs include a wide range of equipment and systems, from the simple weight scale and thermometers to complex equipment such as oxygen generators and home dialysis machines. They are widely used for home diagnostics, patient care, daily living aids and mobility aids. Recent advances in technology and medical equipment design have greatly simplified the operation of equipment. This has enabled people without advanced medical training to operate the equipment, eliminating the need for a full time care giver.

The satisfactory performance of HHCPs and HHCSs is the premise to bring about the benefits above. However, as pointed out by the Design Council (2007), many HHCPs on the market are poorly designed and have poor functionality. This is unsurprising as HHCP and HHCS innovation is more complex and relatively new compared with many other industries. This complexity is present in many aspects, for example, the diversity, unpredictability and fluctuation in users' profiles and abilities. Such situations are further complicated as a large percentage of users suffer long term health conditions and disabilities, which may impair their ability to operate the equipment. Consequently, the design of HHCPs is expected to accommodate the dynamic, uncertain and complex profile of the widest range of users and environments. However, the sector is dominated by SMEs who have minimal resources to carry out user centred design studies and design research, which in turn limits their abilities to innovate. All these factors lead to the conclusion that there is a need to support suppliers in developing HHCPs and HHCSs to improve their HCCP and HHCS offers to the benefit of users.

11.2 Business Strategies and Development Direction

Responding to the pressure from competitors and powerful customers, one common strategy adopted by SMEs in the sector is to improve their operational efficiency. Techniques such as the Stage-Gate Innovation Process, the Product Development Funnel and Six-Sigma are widely employed for this purpose. However, the focus on operational efficiencies offers limited space for improvements related to the actual product-service offer to end users.

11.2.1 Types of Innovation

Our literature review and study on twenty home healthcare product and service suppliers suggests that innovations carried out by SMEs in this sector are generally incremental. They rarely offer new products or services which are significantly improved compared with the existing ones, or create new product categories or industries. This applies not only to new entrants to the market but also to those SMEs who have already established a strong foothold and even to leaders in specific areas. For example, in one company where they had a total of more than 1,000 "projects" of various sizes in the last ten years, they had developed only three main categories of product throughout this period.

The question then is should SMEs radically innovate or incrementally improve their market offer? Radical innovation is generally defined as an out-of-the-blue solution which creates new industries, avenues and markets. However, there is no absolute distinction between radical innovation and incremental innovation as innovation is wholly contextual to the individual SME. That is to say, completely new knowledge, skills and resources for one company, which is required for them to radically innovate, can be familiar to another. Therefore, it is essential for individual SMEs to define the constraints and challenges from the outset of a new project, and to review its managed development against the levels of innovation that the SME can achieve. An adjustment on the innovation management technique must not be neglected as the development processes suited to managing incremental innovations often fail to manage the complex and uncertain environment of radical innovation projects (Williams, 2005).

11.2.2 The Business Driver and Lack of Appropriate Data

The driver of innovations in the HHC field varies in different scenarios. In terms of business drivers, there are generally two main types of innovations: user driven and customer driven. End users are not always consumers. For example, the main customer of the e-health and telemedicine are public sectors, such as the local authorities and housing associations in the UK. These public sectors usually provide the equipment to the residents for free. They may charge the end users to maintain monitoring services. In this case, customers and users are diverse groups.

Business success is based mainly on factors such as the relationship with stakeholders in the sale, the delivery of service, added value and business flexibility. However, suppliers, especially SMEs rarely engage in user research with the purpose of exploring users' real needs in the outset of innovations (Figure 11.1 left). In user-driven projects, consumers are end users.

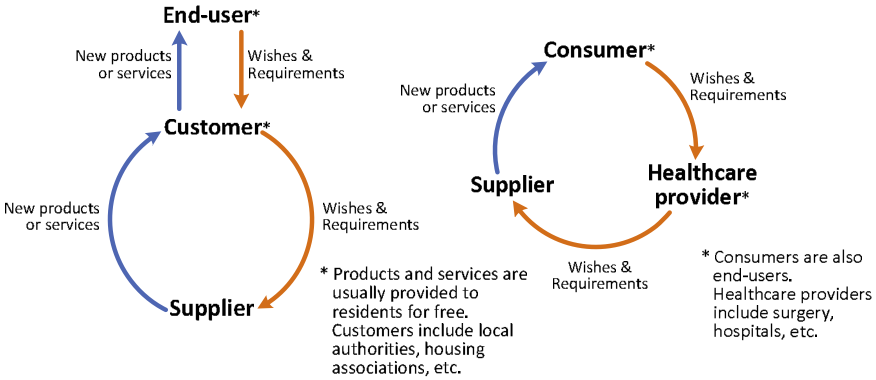

Figure 11.1. Customer-driven innovation (left) and user-driven innovation (right)

The user performance of products weighs heavily on determining their commercial success. Even in this situation, suppliers do no always approach the users. Instead, users' demands for new solutions are often collected by the medical institutions and distributors (Figure 11.1 right). This lack of early user input into the design process can explain why the design and the user performance of many home healthcare products and services are unsatisfactory.

Engaging users prior to the generation of solutions assists in minimising the overall development risks, discovering new business opportunities, and gathering rich user information to feed into generating design solutions. Although all five SMEs interviewed in this project claimed that they applied users' insights in developing new products and services, they conducted user research solely during the later phases of the development process- to evaluate prototypes amongst the target groups. These activities generally focused on moving established prototypes forward into production or delivering ready products onto the market, rather than providing a thorough understanding of people's life and behaviour in its broader social context.

The 'user' insights that HHCP 'suppliers' use in forging strategies and generating solutions are often based on "second hand" information from public organisations, medical institutions and distributors (Figure 11.2).

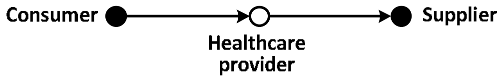

Figure 11.2. The knowledge transfer relationship

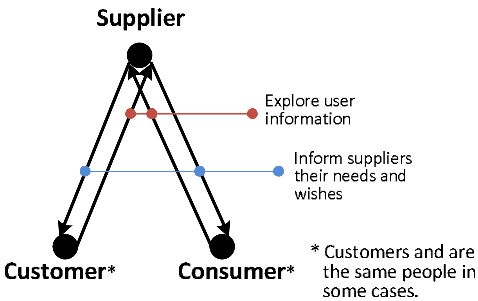

Figure 11.3. The gap between the real user data and the knowledge received by suppliers

There is no guarantee that users' essential needs and requirements have been collected. Using second hand data can lead to false information being used, whilst, valuable information is missed during the information translation and transfer, since neither the healthcare providers nor public organisations involved are specialised in research and design (Figure 11.3).

To improve the user experience of innovative HHC products and services, the development team must perform primary and formal user research, for discovery, planning and reviewing (Figure 11.4). Although the extra work requires time and money investment, it will pay off through benefiting the overall development of suppliers.

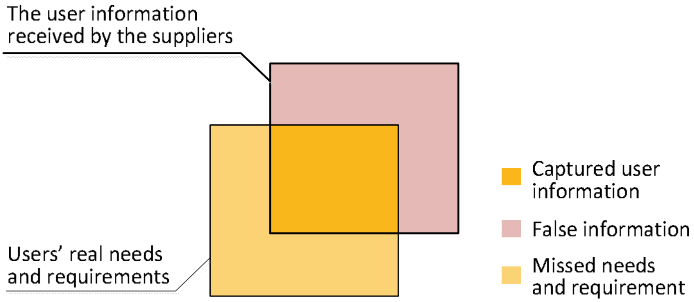

Figure 11.4. The ideal situation

11.2.3 Business Focus: Product Based, Service Based or a Hybrid?

HHC suppliers can be categorised as product based, service based and product-service hybrids. Most SMEs in the sector are based on delivering products. Service-based SMEs are more frequently seen in the telemedicine area. In home healthcare, product and service are frequently present as two essential and interrelated components of realising the intended functions. Furthermore, unlike cars or computers, many HHCPs are required to be operated by end users and other stakeholders including the medical institutions and public sectors in different stages of operations, which creates opportunities of service development.

SMEs usually take the first step by supplementing their products with services to address users and customers' wishes and requirements that cannot be incorporated by products alone. These services include product maintenance, user support, training, product customisation for specific customers' needs, *etc*. Product-service hybrid SMEs with experience and resources may take a step further, to take over customer operations that are related to the use of products. With service's increasing share in the overall business, the time comes for SMEs to choose a business focus but should that focus be on product or on service? It is wise for most SMEs to do so as the two modes of innovation are actually pulling against each other, and running the two modes in parallel may create unbearable challenges. Before shifting the business focus, SMEs need to assess both the internal and external challenges carefully. If a company decides to make a choice, new or revised development processes and approaches are required which usually leads to changes in the driving force behind the business, its culture and organisational structure.

11.2.4 The Impact of Changing Business Strategy on Innovation Management

Management challenges are more evident in those companies of the product and service hybrid type. The more rigid and disciplined stage-gate processes generally suit new product development, especially projects with the aim of providing variations on existing products (incremental improvement). In contrast, developing new services requires a process which embraces a more flexible, inclusive and relational context, in which service innovation flourishes (Susman *et al*., 2007). In addition, the implementation of new innovation management techniques may demand adjustments in company operations, culture, organisation structure, techniques and skills.

Some of the differences in innovation management considerations between running product-focused, service-focused and product-service hybrid project are described in the table below:

Table 11.1. Differences in innovation management considerations

Business mode / Considerations	**Product based**	**Product-service hybrid**		**Service based**
		Product focused	**Service focused**	
Customer satisfaction	Customer satisfaction is based on the product.	Customer satisfaction is based on both the product and the service-correlated considerations. The weight of the product in determining customer satisfaction depends on specific market and business.	Customer satisfaction is based on both the product and the service-correlated considerations. Those factors determine the success of service development tend to have more significant influence.	Customer satisfaction is based on service delivery, added value, relationship and reputation, flexibility, customisation, *etc*.
Modes of operation	The more rigid and disciplined stage-gate approaches.	A formal and adaptive overall process which is designed with full considerations of different innovation types.	A formal and adaptive overall process which is designed with full considerations of different innovation types.	A more flexible, inclusive and relational approach.
Driving force and culture	Show a high priority on new product development and time-to-market; Emphasise the end user experience and performance.	Show a high priority on product customisation and providing product variations; Values time-to-market and relationship with customers.	Values customer relationship, flexibility and customisation; Eager to improve the product design to mitigate the cost of related services.	Values customer relationship and satisfaction, flexibility, variety, responsiveness, speed and customisation.

11.3 Can We Improve SME Innovation Strategies?

11.3.1 Developing a Formal and Adaptive Development Process

In business and engineering, new product development (NPD) and new service development (NSD) are the terms used to describe the complete process of bringing a new product or service to the market. Both product innovation and service innovation can be viewed as a process. Like other processes, they can be managed in a formalised and structured way within the overall framework of the NPD cycle. Adopting a well-forged development management process is the key to leveraging companies' innovation capacity and operational efficiency and it enhances SMEs' strength in competition with larger companies.

As described previously, an adjustment of an SME's innovation process is essential when carrying out different types of innovations. The use of linear and rigid processes may restrict the creativity and flexibility required for radical innovation and new service development. In contrast, a very flexible structure may decrease the operational efficiency of incremental projects. Hybrid companies therefore need techniques adapted for different types of innovation.

11.3.2 Forging Better Project Briefs and Design Briefs

Project and design briefs should set the course for the entire SME project development process. Forging briefs of high quality is critical. The creation of briefs is at the front end stages of the development process, which is full of uncertainties and activities often involving iterative feedback loops between marketing, design, manufacturing and other functions. These iterations may not be amenable to project management techniques. However, a level of structure and control is necessary to ensure success and to avoid unexpected risks.

11.3.3 The Brief, Establishing Early Requirements

Project requirements and constraints from diverse aspects must be explored from the start of a project, and be updated continuously. The purpose of doing this is not limited to evaluating project proposals or design ideas. It sets boundaries which aids the 'project developers' in determining a more correct direction which is fit for purpose. It also reminds the developers to consider the practical measures of commercialisation from the start of the design work. Further, it helps to address diverse considerations throughout design and engineering. Also, it helps to achieve the consistency of work between development phases and between the development team, which frequently presents as a challenge in collaborative projects, especially if a third party is involved. Most of the initial requirements and constraints will be set to be flexible and fuzzy, commonly known as the 'Fuzzy

Front End' (of the product development process) and must evolve with the progress of a project to become more transparent and rigid as the project matures.

It is essential to ensure that all key players understand the requirements and constraints which have connections with their own functions in time, and any revision made during the development cycle. It is also necessary to provide all players equal and easy access to all identified requirements and constraints. As observed and concluded in this project, several approaches can help to achieve this goal:

- Transparency: Centralised information management that has open access to all involved in the project development.
- Consensus and understanding: Giving thorough consideration to diverse factors, for example, the economic feasibility of an idea, and achieving a consensus between all involved when writing the project design briefs.
- Presentation and access: Providing rich information instead of that which supports 'abstract' written briefs using techniques *e.g.* image, video and collage.

At this early stage of exploration, it is believed that these three complementary areas can provide the framework for underlying tools and methods to create briefs that are written with common data, built upon a consensus and are presented in ways that are engaging and informative.

11.3.4 Fostering Greater Engagement in the Brief Creation

Fostering greater engagement in the brief creation process between all developers, increases the opportunities for generating new solutions, importantly, with a consensus in place. It also ensures that essential tasks have been considered and addressed early in the development, which helps to avoid unpleasant surprises in the later phases of projects and reduce risks.

Involvement of all the stakeholders ensures that innovations are not led by a single business, design or manufacturing objective, and helps design teams consider and capture every essential aspect of the design problem.

In highly innovative projects, it is more frequent to find design features and requirements which are difficult to foresee in the early phases of project. This makes it even more important that all stakeholders are engaged. The risks produced by the uncertainties in projects can be dramatically reduced by fostering greater stakeholder engagement and consistent communications. All need to be aware of diverse aspects, including market segment and positioning, functionality, aesthetics, technical feasibility, manufacturability and sales - in the front end phase of projects. Each stakeholder should be kept updated with the latest findings and conclusions equally. When making major decisions on specific functions, stakeholders of other functions should participate and provide their feedback. To make design modifications in the late stage of projects less costly, designers and engineers should address those uncertainties in their daily work, such as leaving space for modifications when designing a product's structure and inner space or saving 3D models in an easy to edit format. Compared with most other arenas, taking HHC products into markets requires suppliers to be compliant with complex and strict regulations and policies, that can be complicated by regional differences.

11.3.5 Addressing the Operational Requirements at the Outset

There is practical value in carrying out extensive research on market segmentation and positioning, and on clarifying and understanding potential customers from both strategic and design levels in the early phases of development processes. Addressing the requirements of the sales plans and strategies carefully in the creation of briefs aids in making projects less uncertain. When potential customers and markets are identified during the development cycle, consideration must be given immediately to whether new design requirements or revisions to preset requirements will be necessary. In case major changes in design are required, teams in options, service and installations need to be notified quickly to address the changes in downstream applications such as plans for tooling, manufacturing, installation and maintenance. The earlier the changes at strategic level are absorbed into designs, the less negative influence they will have on the whole project.

11.4 An Improved Brief Creation Process Model

The brief creation process model proposed in this paper focuses on addressing end users' real needs, adapting to changing environments, fostering greater stakeholder engagement, and managing information processing in a formal and structured manner. This model suggests intimate collaboration across functions from the outset of the brief creation. The players should represent all business functions to address considerations of diverse aspects. It is essential to adjust the team structure after the type and the drive of a project has been defined to reflect and adapt to the features of specific projects. Efficient cross functional team work is a requirement of sorting out complex data to find a practicable development direction.

The process model has four main development phases and two main freezing phases. The three development phases are 1. data organisation, 2. data screen 3., development, definition and clarification, and 4. process planning. The two freezing phases are strategic review and design brief review (Figure 11.5).

Data Organisation, the first phase, is to analyse, translate and group the data collected in the discovery stage. Earlier sections have highlighted the importance of developing an adaptive management technique. This is why the team must consider the nature of innovations that potential opportunities will lead to in the front end. This will lead to the adjustment of the overall development process, as well as the plan of detailed methods and activities to apply throughout a project. This model suggests defining data based on the source of opportunities. This should be 1. user knowledge, 2. new technology, 3. customer requests and 4. strategic demand. A large volume of qualitative data from field interviews, open-ended survey responses, support call logs, or other channels may be received from the discovery stage, particularly from user research. To review these data efficiently, the use of an affinity diagram is an easy but efficient technique. This technique helps to sort numerous ideas into groups, based on the given criteria. It also creates an opportunity for active interactions between players, thus fostering greater engagement.

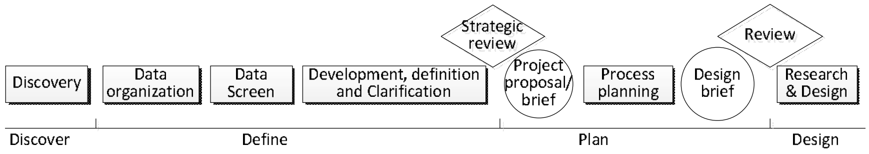

Figure 11.5. The structure of the brief creation process model

The values of the information are reviewed based on considerations from facets of 1. technical feasibility, 2. saleability, 3. economic feasibility, 4. market fit, and 5. user fit. This identifies the most promising opportunities from all those uncovered in the previous stage. Different criteria should be applied to assess data from different groups. For example, needs and wishes from product end users, technical feasibility, saleability and economic feasibility will need to be considered (Figure 11.6).

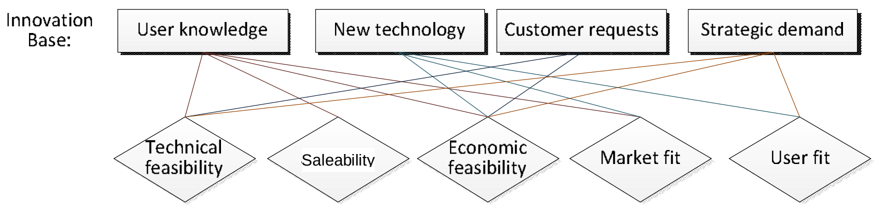

Figure 11.6. Screen data of different groups based on different criteria

The third phase is “development, definition and clarification”. The screened data will be further analysed and developed in this phase to become richer information to feed the project brief. The team needs to investigate the potential of opportunities from 1. market segmentation and positioning, 2. potential customer exploration, 3. regulatory requirements, 4. competitor review, and 5. capacity in innovation. They should also refine the type of the project, to see if it will lead to a highly innovative project or a variation to existing products and services. In addition, they must review all the work carried out, and clarify the core value, business opportunities, and challenge and risks from diverse perspectives. Ideas from all functions must be addressed in this step (Figure 11.7).

The conclusion and results of previous work will be summarised into project briefs to go through business hierarchy for review. If they pass, the proposed opportunities will be taken into formal development.

The formal development starts with process planning. This is the time for the development team to consider whether the in-house development processes will suit specific projects. They must forge a project-focused process which addresses all considerations in the project brief. Four activities – 1. exploring constraints, business considerations, 2. determining design functions (abstract level), 3. forging design strategy, and 4. mapping the players onto a project timeline to move forward in parallel.

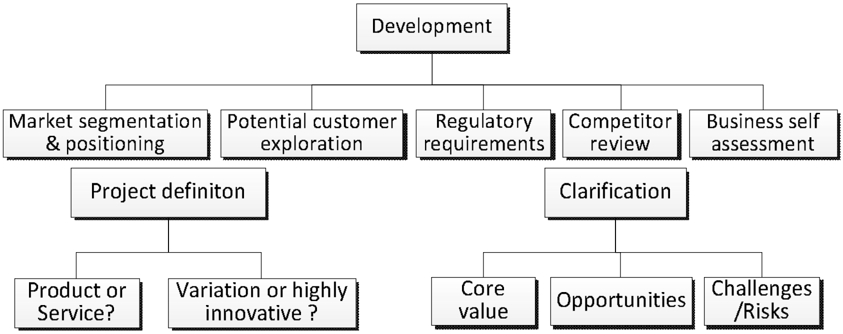

Figure 11.7. Development, definition and clarification

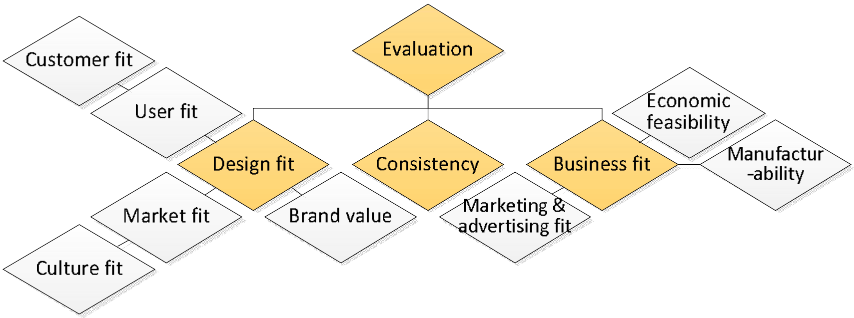

Figure 11.8. Evaluation of the functions

This model suggests that the development team determine the functions of the outcome in terms of both practical and aesthetics at this stage, which is earlier than in most of the existing development processes. The purpose is to promote an early consideration of the design needs. It also helps to ensure that a design agency understands the companies' requirements properly when the design will be carried out by a third party, which happens frequently in the sector.

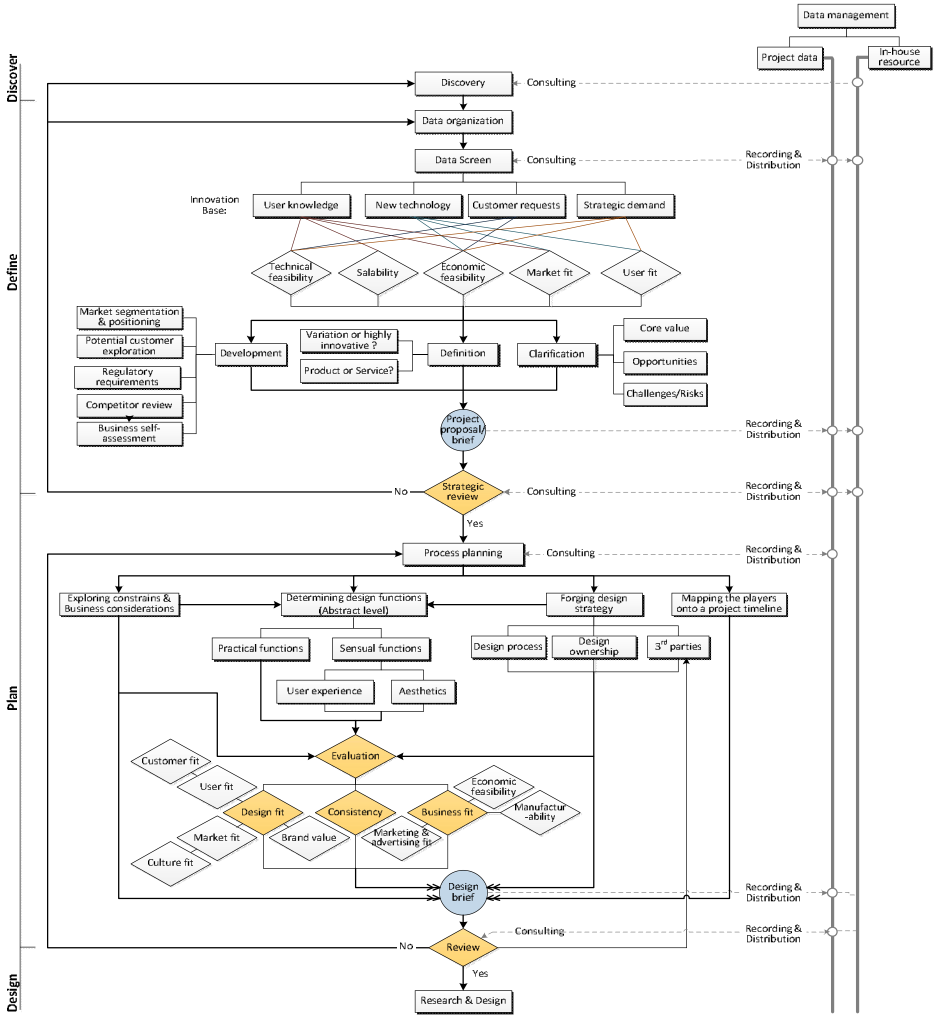

Figure 11.9. The complete brief creation process model

The design functions are evaluated from the facets of 1. design fit, 2. business fit, and 3. the consistency with the requirements and features defined in the previous work (Figure 11.8). The complete process model is illustrated as Figure 11.10. A larger version of Figure 11.9 can be obtained from: https://skydrive.live.com/redir?resid=71798F57E3A585F4!1056&authkey=!AMehFoMGAgNKXVo&v=3&ithint=photo%2c.jpg.

11.5 Conclusions and Next Steps

Our current analysis has shown that an improved brief creation process has the potential to significantly help SMEs in the HHC sector to deliver products and service of higher quality. We now need to further revise and develop the process model which has been presented in this paper, and to test its strengths and weaknesses in collaboration with companies in the sector. An interactive tool which can be applied to assist their daily work can then be fully developed.

There are two major issues which now need to be addressed:

- How should the effectiveness of this model be tested? In an ideal situation, it should be evaluated in real projects, but this may not be possible within the constraints of available time.
- In what format should the brief creation tool be presented? Should it be web-based, a tool kit, or something else?

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The current economic situation demonstrates that the design and development of innovative products is an imperative for every economy and industry to remain competitive on the world market. One key to overcome this challenge is the design and implementation of innovative processes in design and engineering. Academic research and management practice require a more detailed understanding of these processes, develop better management approaches and exploit hidden potentials to improve the business.

The aim of the second international conference was to showcase recent trends in modelling and management of engineering processes, explore potential synergies between different modelling approaches, gather and discuss future challenges for the management of engineering processes and discuss future research areas and topics.

This book is divided into three areas:

- Concepts
- Modelling approaches and virtual tools:
- Industry case studies:

The papers were selected by reference to the peer assessments of an international panel of reviewers from engineering design research. This book represents a sample of leading national and international research in the fields of Modelling and Management of Engineering Processes. We hope that this will encourage further inter-disciplinary research leading to better approaches, methods and tools to improve engineering work, processes and its outcomes.

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