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Incremental Innovation Method for Technical Concept Development with Multi-disciplinary Products

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Incremental Innovation Method for Technical Concept Development with Multi-disciplinary Products

Thesis for the degree of Doctor of Technology to be presented with due permission for public examination and criticism in Konetalo Building, Auditorium K1702, at Tampere University of Technology, on the 29th of January 2010, at 12 noon.

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Although nature commences with reason and ends in experience it is necessary for us to do the opposite that is to commence with experience and from this to proceed to investigate the reason.

Leonardo da Vinci

Abstract

Product development and innovations play an essential role in enabling enterprises to be continually competitive and profitable. However, even though numerous processes and methodologies have been developed for creating new artefacts; there is a paradox with regard to their applicability in industry; business drivers in industry strive to extend the life cycle of products with incremental development, while the main focus in literature strongly emphasizes the introduction of new products. In addition, the context of innovation in the language of business has become more of a marketing slogan than something that really does represent newness or differentiation from what has been before.

This may be confusing for a product developer, who struggles with numerous contradictory stakeholder aspects and requirements. Being crucial to the product origination process, developers search for practical methods and tools to evaluate, compare and justify their selections and decisions on various technical issues. The challenge facing developers is daunting as they must have the capability to interpret needs and requirements into a technical format and introduce innovative solutions.

Successful opportunity identification, idea creation and innovations form a path whereby an enterprise can keep its position in a marketplace. However, continuous technological development in different disciplines and their implementation into one technical system has challenged generic product development methods because product functions are now often executed with complex sub-system integrations. The increasing number of developers and disciplines in product development teams therefore calls for a better means of communication in order to share information about how total function behaviour can be accomplished.

The approach of this study is technical and has been initiated from a product developer's point of view. The problem and challenges inherent to incremental development are presented and are set against the theories and methods in the relevant literature. A constructive research method is applied to develop an understanding about product value creation, multi-disciplinary concepts and innovation. Based on industrial case studies, a new method has been developed to enable a more systematic method of opportunity identification and idea creation for the incremental development of multi-disciplinary technical concepts.

The core of the new method is the identification of the function execution chain, which, in particular in multi-disciplinary products, may involve numerous consecutive events in different sub-systems and disciplines. The opportunity identification explores the possibilities to change the operating principle of the technical transformation processes by utilizing integrations that come from several disciplines.

Ideas and innovations are generated by individuals and an explicit idea generating method is implausible. The method presented here deeply acknowledges the necessity of human creativity during the innovation process. However, the intention here is to enable the use and sharing of existing information in a development team to be utilized as a context sensitive stimulus to identify possible seed ideas for innovations.

The approach of the study and case studies comes from a manufacturing company, whose products are multi-disciplinary and tailored materials handling equipment at the static concept stage. The applicability of the newly developed method has shown promising results and thus requires further evaluation and development for other types of products and technical systems.

Acknowledgements

The origin of this study began back in the late 1990s when I was nominated as a project manager for developing a next generation container handling crane. Having already been involved in product development, engineering and the manufacturing of investment products since the early 1980s, the challenge of the task was obvious. The challenge was that a mature, static concept development had already received numerous improvements, in addition to different conceptual trials around the world. During the project, several brainstorming sessions were held to explore new alternatives to the current container handling crane, even radical solutions. However, we were faced with the reality that business drivers were directing us to adopt a different approach.

Having had the privilege to experience different duties in engineering, and witness the initiation of a few patented inventions, my curiosity to better understand how innovations are born and specifically, what gives the inventor the capability to identify opportunities was roused. In industry, in which my personal experience is mainly, the birth of inventions mainly arises from individuals, even though different creative and group techniques are promoted and used. However, I have found these techniques lacking with regard to static concepts, and particularly so when multiple disciplines are involved.

During the long co-operation and participation in research projects with the Tampere University of Technology, I was continuously encouraged by Professor Asko Riitahuhta to initiate this study and introduce the development engineer's approach to incremental product development. For his inspiring encouragement, I am deeply grateful.

In industry, any project execution is extremely goal oriented but a scientific study has a different nature. Fortunately, academia has provided me with great guidance to familiarize myself with scientific work, which started with some eye opening weeks in the Summer School of Engineering Design Research in 2002. The course was moderated by Professors Mogens Andreasen and Lucienne Blessing. I present my deepest appreciation for them for giving me practical insights into scientific research.

In addition, inspiring and challenging daily work in Konecranes and meeting with specialists from other companies has enabled me to share and discuss practical problems. In this special gratitude must go to Seppo Suistoranta for joint papers and numerous in-depth discussions during this study.

The Riitahuhta Research Group was established during ICED07 in Paris. It invites a great mix of researchers and industrial specialists to share and discuss research problems on engineering design. I am grateful to this group for providing me with a forum and networking capabilities for my study. Specifically, I express my thanks in this group to Antti Pulkkinen and Timo Lehtonen for their advice, comments and openness in sharing their ideas.

An important part of any scientific study is discussion and criticism. For this, I have been privileged to work with Kari Eloranta, who has challenged me in a positive and inspiring way.

Finally, this study would never have seen daylight without unconditional acceptance and support from my nearest and dearest. I dedicate this work to my wife Anne and sons Tuomas, Sampsa and Samuli, my deepest thanks to you.

Hyvinkää, January 2010, Hannu Oja

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List of Abbreviations

DFX	Design For X
DP	Design Parameter
DSM	Design Structure Matrix
EQFD	Enhanced Quality Function Deployment
FAST	Function Analysis System Technique
FMEA	Failure Mode Effects Analysis
FR	Functional Requirement
HuS	Human System in Transformation Process
IDEF	Integration Definition for Function Modelling
incPD	Incremental Product Development
InS	Information System in Transformation Process
I/O	Input and Output, communication signal interface in control system
MaS	Management System in Transformation Process
NPD	New Product Development
PLC	Programmable Logic Controller
PP	Part and Component
QFD	Quality Function Deployment
R&D	Research and Development
RPV	Resources, Processes and Value theory
SA/SD	Structured Analysis Design Technique
SS	Subsystem
TeS	Technical System in Transformation Process
TRIZ	Theory of Inventive Problem Solving
TSA	Total System Architecture
VCE	Value Chain Evolution theory
VDI	Verband Deutscher Ingenieure
VE	Value Engineering

1 Introduction

Product development and engineering in industrial companies today is not an isolated island that deals only with technical issues. In the business to business environment, the global presence of companies enables higher volumes to be sold through product offering in a variety of markets, and also enables a global price and technology awareness for customers. As the marketplace globalizes the possibility to dump old products in a state of decline onto a lower economy market is decreasing. On the other hand, profit orientation and focusing on economic key figures in companies has led to the evaluation of investments towards a shorter pay-back time. The technical merits, performance and reliability of advanced technology have been challenged by more traditional and cheaper products, thus creating new threats, requirements and opportunities for development teams.

In traditional product development, the design task is to create an artefact, which fulfils customer needs by means of functional and other properties. A product's requirements force engineering to search for an optimal technical system design. In addition, developers' requests for detailed specifications enable a pre-determined design environment that has constraints. However, in business to business acquisitions, a product is the means of exchange between the two main stakeholders, i.e. the seller and the buyer, or in a technical context: the manufacturer and the user. The exchange is valued in different terms; for the manufacturer it is valued as monetary income and profit but for the user its benefits are gained through the utilization of the product. As the transaction has two parties, the measures or metrics for evaluation and justification of the transaction vary between the stakeholders; the manufacturer acts externally to maximize the market attractiveness for sales opportunities by product properties and price, and simultaneously tries to internally minimize costs during the origination of properties. This raises problems in the content and nature of design concepts (Hansen & Andreasen 2002), in which the user evaluates the benefits against the cost of acquisition and aims to minimize the pay-back time.

This dynamic business environment has affected product development strategy and meant that fewer new products are introduced as the focus is more on developing variants for existing products, or new models based on the renewal of subsystems or assemblies (Cooper 2001). This is more apparent in business, where products are at a static design stage and have a long life cycle.

1.1 Motivation of the study

The motivation of this study was initiated during practical product development duties. It was noticed that generic product development processes assume that the initiation of development and innovation occurs at the beginning of a process when a need is identified. However, the author's experience of product development, engineering, manufacturing and technology management has shown that static designs require a different approach. With static designs, a need has been identified and served with various products for a long time and the development seldom starts from a white paper. Further, technological development has brought various disciplines into same product and resulted in the utilization of microcontrollers, PLCs and computers, which enable the purposeful behaviour of a product to be determined more by control software rather than its mechanical structure.

1.2 Research problem

In the industrial business to business environment more than two thirds of the product development activities are directed towards existing concepts in an incremental way (Cooper 2001). These concepts have evolved from the original design, and not even been invented within the company. Various new technologies may have been introduced along the concept life cycle and led to the implementation of many technologies from different disciplines being used in the same product. Simultaneously marketing and sales have promoted product features, which have been interpreted into the engineering language of functions, structures and properties.

Many companies allocate a significant amount of development resources to the exploring of new technologies. However, within enterprises doing business with static designs the implementation of new technology mainly takes place in existing products or concepts, as part of the technical system in one or more subsystems.

When the products become more complex, in the sense of combining different technologies and implementing them into existing products, the task assignment to development and idea generation differs greatly from one suitable for a new product development. Thus, based on the industrial viewpoint, there is a need to extend a designer's understanding and methodology. Therefore the research question is formulated as follows:

> *What kind of incremental innovation method is applicable for finding innovation opportunities for the development of multi-disciplinary technical concepts?*

The approach to the problem area is based on the author's experience in the field of product development and engineering design in industry.

The understanding gained from this study will support product developers by helping to improve product properties and reduce costs as requested by different stakeholders. Further, it will provide a method for understanding the diverged event chain in modern multi-disciplinary products, and show how functions and properties are delivered. This method may be applied to incremental product development to generate seeds for product innovations in more systematic way.

1.3 Scope of the study

The scope of the study is the divergent product value viewpoints of manufacturer and user, which direct product development, and which form the aspects of a technical product's conception, product development processes, product innovations and opportunity identification. In this study, the role of manufacturer refers to the stakeholder, who governs the product design and the role of user the one who decide the product acquisition.

Specifically the focus is on tailored products with static technical concepts, which are manufactured in small lots and include technologies from various disciplines. The static concept is referred as the stage in the product's life cycle, at which the variety of different solutions in the marketplace has reduced to few or only one among manufacturers.

The innovation process covers all activities from early development stage, opportunity identification, and all life cycle stages to final product disposal [Figure 1.1].

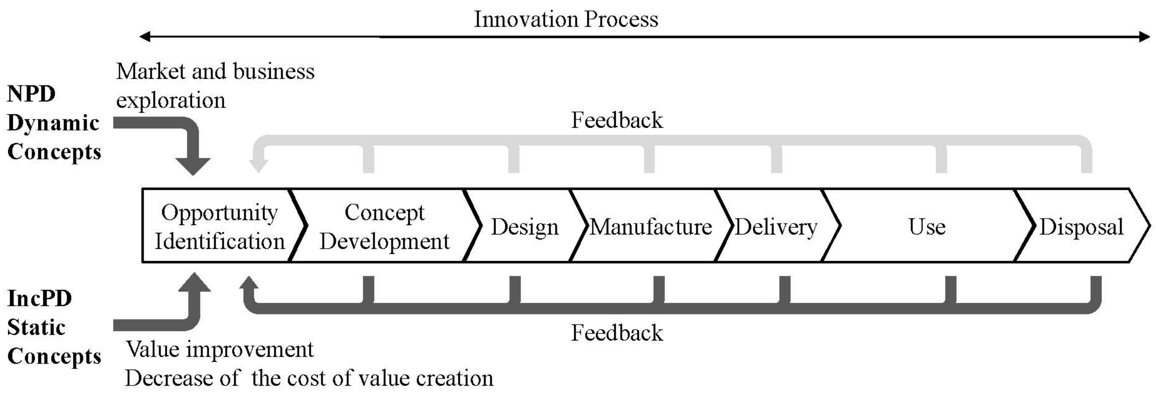


Figure 1.1 Innovation process and main alternative routes to explore innovation opportunities for concept development with new product development (NPD) and incremental product development (incPD).

The product innovations may get their birth through two main routes; (1) new product development process (NPD) or (2) incremental development (incPD). The methods of searching for innovative solutions differ in these cases. The NPD process explores different business models, products or conceptual solutions, while the incremental process utilizes knowledge based on existing solutions and feedback from later life cycle stages to find better concepts, improve product value or decrease the cost of value creation. The study focuses on the critical stage when alternative concepts are searched for in an incremental way by using the technical content and operating principle of the product as the sources for seeds of innovation.

The approach of the work is technical and strong emphasis has been adapted from the viewpoint of a product developer's daily work on industry. It is acknowledged that the results and success of innovations are strongly dependent on human nature and individual creativity, as well as business environment. However, creative techniques are excluded from this study due to it focusing only on the means which can be derived from the technical system itself.

1.4 Scientific approach and methods

The study is based on the theories and conceptions of design science [Figure 1.2]. Its approach is conceptual and strives to extend design methodology knowledge by supporting innovativeness for the development of technical systems. Its qualitative considerations try to answer the following questions:

i. *What are the differences between a manufacturer and a user when evaluating product properties?*

ii. *How does product function differ between design and reality?*

iii. *How do product development processes support an incremental conceptual design?*

The questions refers to the different contexts of the realization of a technical system, a product's origination and its life cycle, which refers to the theory of technical systems and design methodology knowledge, specifically the technical transformation process, conception and effects of the system (Hubka & Eder 1988). The main focus is to explore existing models to find and explain the differences between technical processes in the design domain and function in the reality domain and their applicability for developing static concepts.

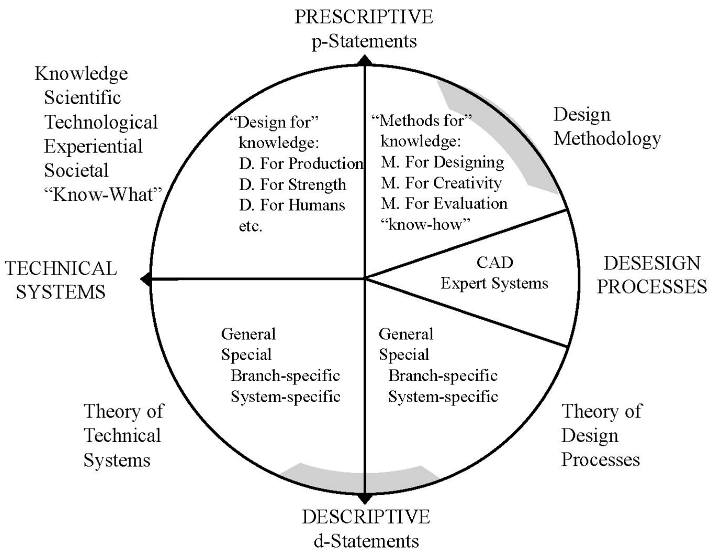


Figure 1.2 The dimensions of design science and the focus area of this study on design methodology. Adopted from Hubka & Eder (1988).

The starting point is a practical problem in industry, which is analyzed in the context of a theoretical basis. The constructive research methodology is adopted from Jörgensen (1992) [Figure 1.3], in which attention is equally divided between theory and practice.

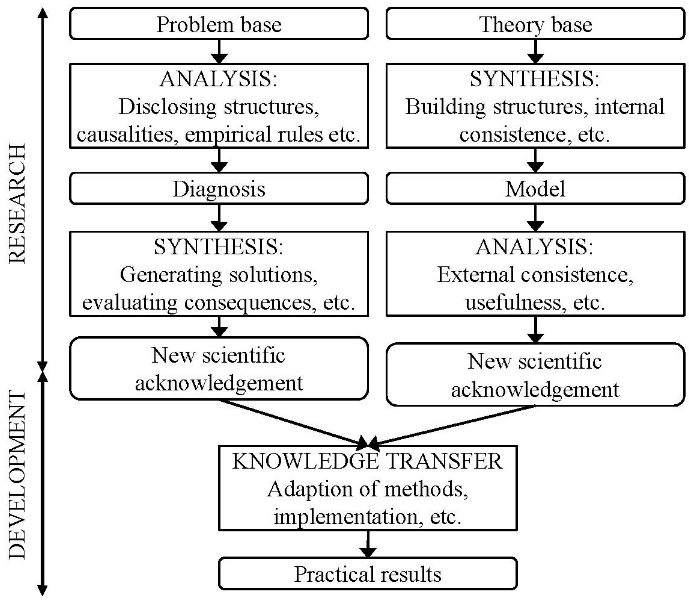


Figure 1.3 Applied constructive research method for parallel attention between theory and practice. Adapted from Jörgensen (1992).

The new understanding is developed on the base of selected retrospective industrial case studies, which have resulted in incremental innovations. A new method for a more systematic opportunity identification and idea seeding for incremental innovations has been formulated by using theories of technical systems, design methodology and innovation.

A new incremental innovation method has been developed that aim to identify seeds for ideas to be developed. A case study to show the application of the method is presented for the validation. It is acknowledged that the method will most likely vary between individuals and not explicitly result in innovations due to the necessity of the involvement of human creativity in the further processing of the seed ideas. However, the validity of the presented method has been successfully experienced as a communication tool between developers from different disciplines that enables them to focus on functional execution chains and systems integration during development sessions.

1.5 Structure of the study

In Chapter 2, an approach to product development prerequisites and processes was studied and reviewed for applicable methods for incremental product development. The industrial need for a business perspective that would aid a more knowledge intensive method for static design development is recognized here.

In Chapter 3, the viewpoints of manufacturers and users regarding product value are presented. For technical development, the context of the value elements of a product is presented. The specific value elements can be used to increase a product developer's understanding about a user's decision criteria and help them consider trade-offs while developing the product.

In Chapter 4, the applicability of generic product development processes for incremental development is reviewed and an approach is introduced that can help distinguish between different drivers of development. The specific nature of multi-disciplinary and incremental development that influences the development process and communication among the development team is also presented.

In Chapter 5, the different product concepts and conception methods for incremental product development are presented and studied in a multi-disciplinary context. The weakness of the functional structure in describing system behaviour is acknowledged and a definition of experienced behaviour is presented.

In Chapter 6, different product innovations are presented and their distinguishing features in a technical context are presented. The approach is presented from a product developer's viewpoint and the distinction between incremental and radical innovations is based on the operation principle of the system.

In Chapter 7, opportunity identification and its applicability for supporting idea generation for incremental development is studied in the form a case study. A specific phase that supports opportunity identification and multi-disciplinary mapping is presented to provide a more systematic seeding of ideas.

In Chapter 8, a new approach to advice opportunity identification with multi-disciplinary products is presented with reference to a case study. This finding is used to further develop a method for idea generation and demonstrated with a method application.

In Chapter 9, the results of this study are validated with a case study.

Lastly, in Chapter 10, with the discussion, the results and conclusions are presented and suggestions for further studies are made.

2 Considerations on Product Development

A lifting and transportation equipment manufacturing company's annual spending on research and development activities is approximately one percent of its net sales. Its business growth has been successful over the years, partly generated by acquisitions, but being mainly the result of organic growth.

One product family within the company, wire rope hoists, have been developed and introduced in generations. The first MT-generation was manufactured from 1936 to 1950, the second SN-generation was manufactured from 1950 to 1963, the third UN generation was manufactured from 1960 to 1985, the fourth, XL, was manufactured from 1985 to 2002 and the latest, which is the CXT generation has been manufactured since 2000. Along with company growth, production volumes have increased. The expansion of the market area and a successful multi-brand concept has brought volume, but also hard international competition and pressure for the faster introduction of new generations. Plans for the next generation have started and it is expected that the new product will replace the current one in five to eight years time.

Even though the development projects result in new products, they fulfil the same transformation process as the first ones did more than seventy years ago. It can be claimed that no new or radical product concepts have been developed as progress has seen rather incremental developments within existing concepts.

The realization of the technical system has naturally changed; product architecture, size ranges, new technologies like AC-motors, variable speed control, programmable logic control system, modern materials, manufacturing technologies and product modularization have been re-designed and/or implemented. However, all new technologies were familiar at the time of their introduction from other fields of applications. As the innovativeness of a product or its originating process in a scientific sense has been low, this led to assumption that in many fields the development of subsystems has been significant.

The development and evolution of the wire rope product is a typical example of a mature concept, where development occurs in incremental steps. Due to the long life cycle of the basic product concept, the concept has evolved into its current format through numerous enterprises and the main development drivers have been manufacturing cost pressure and market differentiation. The drivers are linked together because the market can accept a higher price and make a satisfactory profit on the product, which provides better value for the user than products which only compete in price.

Product development methodology in engineering science focuses greatly on new product development initiated by various drivers. Generic product development models identify different product types and processes, but not much attention has been paid to the development of existing product concepts. An incremental development task has a different starting point compared with new product development as various functional solutions and alternative concepts have already been proven and become obsolete.

2.1 Introduction

During the execution of development projects, any powerful tool that supports the creation of innovative solutions is welcomed by the industry. In the literature, innovation theories and methods are presented in different contexts of product, engineering and development. However, in industrial development projects, the practice may be more reliant on creativity techniques and multi-disciplinary teams than specific innovation methods. Even if methods are applied, only a few theories relate to how innovative solutions are generated at the solution level.

In industry, the development efforts aim for the incremental development of products and seek either improved performance in their use or during the manufacturing process. The benefits, which will be introduced into a product's purposeful behaviour, call for new product or solution concepts. Generic product development theories, models and methods are applicable for new product development, starting from need surveys, "market pull", or from technical opportunities, "technology push" type projects (Hubka & Eder 1988).

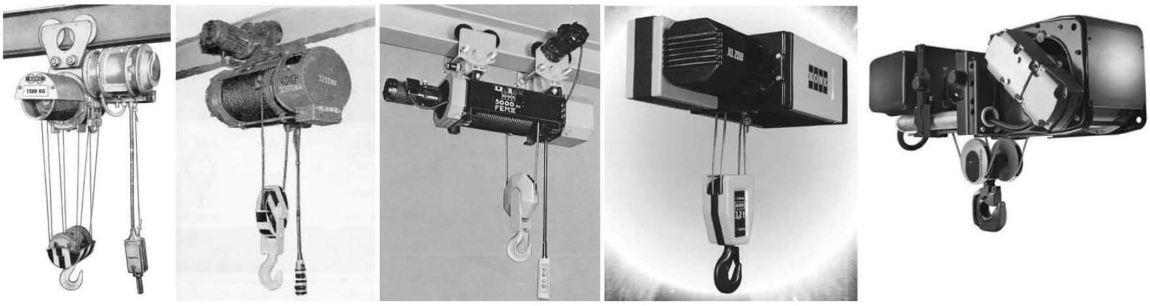


Figure 2.1 Wire rope generations to fulfil the transformation process of lifting goods have been realized in rather similar way due to maturity of the basic concept. Year of launch from left 1936, 1950, 1960, 1985, 2000 (Konecranes Plc).

The development of the wire rope generations [Figure 2.1] shows that great similarity exists between products in different decades, which also follows Utterback's (1994) finding that enterprises prefer to strengthen their competences in a particular technology rather than diversify. Established companies have experienced various product development projects and product launches, through which they have developed and chosen their focus and product portfolio.

In industry, the product development activities prefer to start from an existing product or concept with pre-determined business goals rather than from scratch.

Product existence in a market can be described with a model showing product generations. This S-curve concept theory describes how the product performance with a technology varies due to increased development effort over time. The theory claims that certain technology performance increases during development actions and eventually reaches an upper limit. The performance improvement rate is described by an S-curve, where the performance improvement is slow during the product introduction, faster during maturation and slows down at the end of the life cycle.

According to S-curve concept theory, significantly improved performance may only be achieved with a discontinuous step to the next technology with its own S-curve. However, the development and launch of the new technology may start below the maximum performance level of the previous technology, if it has the potential to pass the previous one [Figure 2.2] (Foster 1987).

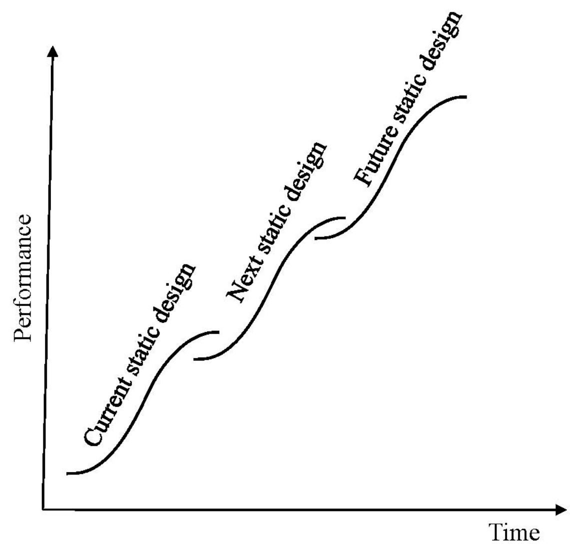


Figure 2.2 Theory of the S-curve concept showing the performance jumps followed by new static (dominant) designs (Foster 1987).

The product performance according to its properties during concept generation exists according to the S-curve model with some measures. A market launch is the preferred way to introduce a new generation, highlight the new appearance, features and improvements compared with previous models. Internally, from the manufacturer's viewpoint, the two main drivers for launching new product generations are cost pressure and market attractiveness.

Product cost behaviour is, according to the S-curve, obvious; after the market launch the product meets various manufacturing processes, which are streamlined during the volume ramp-up. The attractiveness to the manufacturers of the new model for a product already on the market can be divided into two main features; increasing its sales volume and extending the product's existence on the market.

2.2 Product life cycle

A product's life cycle behaviour according to the S-curve concept theory is commercially relevant. However, the new static designs of successive product generations are not necessarily much different from previous designs. If we study the product transformation process, concept or the functional structure, we may notice that S-curve type design generations actually seldom exist. Specifically, this is apparent with products, in which the static design life cycle persists for decades. Typically presented examples of product generations and different static designs are switches or combinations of ideas or objects from past technologies, such as the progression from steamboat to diesel engine vessel, propeller airplane to jet plane and VHS recorder to CD (Hargadon 2003).

After a new product's introduction into a market by a pioneering enterprise, it soon meets competing concept alternatives that are similar or divergent. During maturation, the numerous competing concepts develop, but the emergence of a broadly accepted core concept design will eventually replace all others. This concept is called the static design, which may exist for an indefinite period of time; even if the concept does not represent the best technical solution.

Even the product performance has significantly improved over product generations, the original transformation process (the transportation of goods or people, recording of sound) has remained and the changes have occurred within the product sub-functions or concepts. Specifically this applies with investment products.

As a consequence of the static design, development activities are directed towards production processes and/or search for new potential concepts or disruptive designs [Figure 2.3] (Utterback & Abernathy 1975).

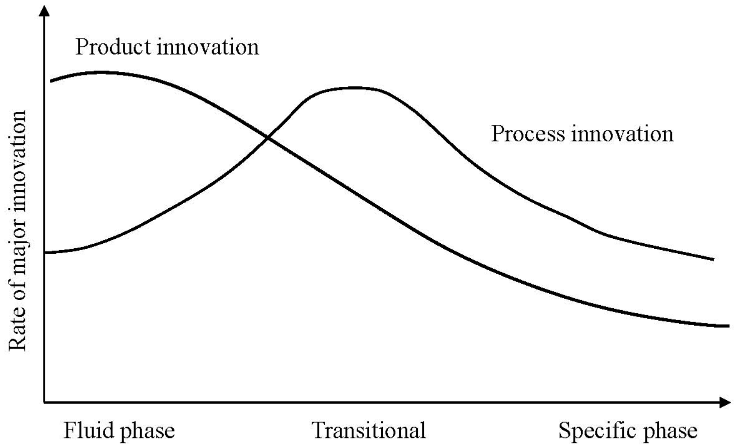


Figure 2.3 *Product innovations primarily take place during the early stages after launch and are replaced by process innovations after concept maturation. Adopted from Utterback (1975).*

The need for product development in companies originates from the need for the continuation of business and income. When considering the life cycle of a single product, cash flow follows a general path; first investment (spending on development and other related costs) followed by sales (earning) [Figure 2.4]. Depending on the sales volume, the contribution margin and length of existence on the market, the profit made after operational costs will pay back the investments made during product development and launch (Kotler & Keller 2006).

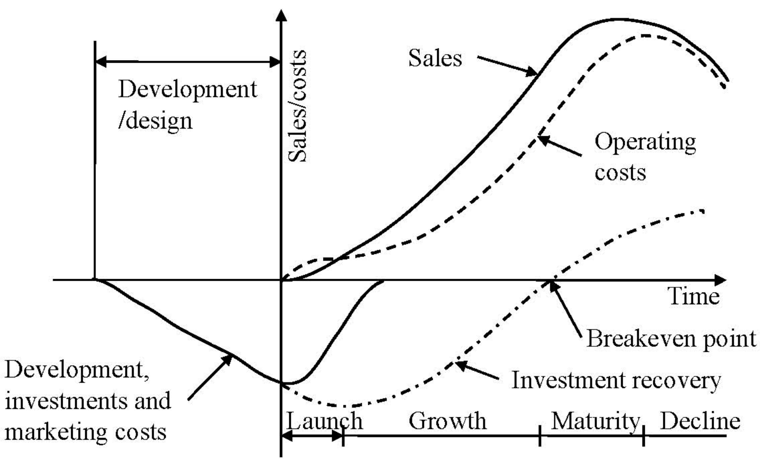


Figure 2.4 *Economics of a product life cycle; the market volume needed to reach break-even point and the need of extending the maturity phase to maximise cumulative profit. Adopted and modified from Kotler & Keller (2006).*

With reference to product strategies, Kotler & Keller (2006) have summarized the basic actions for each lifecycle phase;

- Launch; Offer a basic product. The challenge to design an optimal product for the market has three options; one product with preference on specific customer segment (a single-niche strategy), two variants simultaneously to capture two or more segments of the market (a multiple-niche strategy) or one product between two or more segments (a mass-market strategy).
- Growth; Offer product extensions, service and variations. If sales are good, new companies will enter the market and position themselves to compete against strategies chosen by existing companies in the market.
- Maturity; Diversify brands and models. Market fragmentation occurs as growth slows down, but is often consolidated by new attributes with strong market appeal.
- Decline; Phase out weak items as need declines or new technology replaces the old.

Product development justification is based on economic evaluation, of which the pay-back time is forecasted short enough to enable sound business over the product generation replacements. Thus, a development team has to consider different life cycle aspects and their impact on technical content, which includes:

- The product value created with design characteristics and properties, such as performance, reliability and quality, which may be degraded along the life cycle due to competitor actions or increased requirements. This refers to how product upgrades or new technologies may be implemented to maintain competitiveness.
- The endurance criteria for the product and the product's subsystems depend on the type of acquisition (investment, lease or rent), customer process (product involvement and criticality), maintainability (access and spare parts) and out of service strategy (disposal). In other words, endurance criteria refer to how the selection criteria for components are set and what kind of service modularity may be designed in.
- Adaptation and flexibility with product variations and options in the production process, how sub-assemblies and manufacturing modularity meet the sales configuration, supply chain, testing, logistics and start-up requirements.

The importance of each aspect obviously depends on the business nature, product type and selected company strategy, but significant differences may be found between commodity products, consumer products, business to business products and investment products.

The development strategy varies accordingly. Products, which will stay on the marketplace for only a few months, are important to make available fast and finished in order to maximize earnings. For this type of product further development activities after the launch are not reasonable and efforts have be directed towards the next product generation.

Accordingly, it may be assumed that products, which are designed for a longer lifetime, will stay on the marketplace and be acknowledged as static designs therefore require a different approach. This is because their earnings are spread over a longer time period and the price degradation and production cost increase force companies to maintain their contribution margin with consecutive development activities.

2.3 Product development challenge and design tasks

In the literature on the subject, a new product development process has been presented which can be initiated based on market need. Other identified and presented variants for development processes are the technology push, platform, process-intensive, customized, high-risk, quick-build products or complex systems. Such a development process includes stages and the design progress from identified needs to functions and, later on, detailing (Ulrich & Eppinger 2003, Pahl & Beitz 1996).

However, companies direct their resources in a rather different way. In fact, less than one third of the development activities is spent on new products (Cooper 2001). This may vary between industries with respect to the duration of a product's life cycle. The economics behind this resource allocation is simple: each product introduced to the market should earn its development costs as soon as possible and provide cash flow for financing the next development. The longer the product stays profitable on the marketplace, the better stability and forecasting it provides for the company.

The price and property competition pressure of a market mean that product improvement has to be launched to extend the lifetime of a product. Hansen & Andreasen (2002) have introduced two aspects for product conceptualization: the *idea in* and the *idea with*. The idea with refers to the use context of the product to fulfil the user need or value, while the idea in refers to the design context through structures that realize the product's function.

However, the business nature sets requirements for profitability and therefore the product development entity in an enterprise may be presented as in [Figure 2.5].

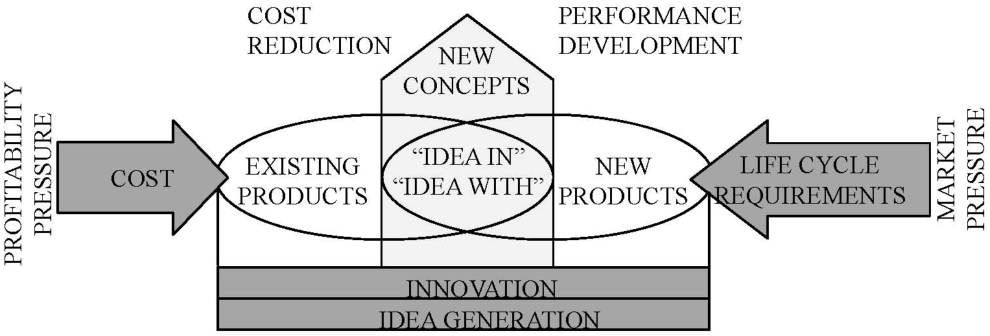


Figure 2.5 Two views of market pressure to companies for the product concept development (Suistoranta & Oja 2006).

The bottom of the figure presents the generic company R&D with idea generation and innovation, mainly the exploration of applicable new technologies. In the middle, the different viewpoints of profitability and market pressure meet; the new or altered concepts generated through product development activities provide improved competition in the marketplace.

Today's products utilize modular structures, at least to some extent. The drivers for modularity may come from different sources, but especially in industry the re-use of designs enables customization based on pre-determined subsystems or assemblies. The decomposition into subsystems or chunks also enables cost reduction or development activities to be focused on one or more selected subsystems without the need to re-design the whole product. These development activities call for new ideas to improve manufacturability, the introduction of optimized specifications or new technologies. On the other hand, the market has increasing expectations about the life cycle properties of products and thus the development of a product's performance along different measures calls for new functionalities, which carry new ideas. These goals obviously contribute to the ideas in (Suistoranta & Oja 2006).

In engineering all design tasks cannot be categorized as product development. Specifically configured, customized or tailored products include re-use, adaption or re-design of earlier concepts and solutions. Furthermore, also many new serial products originate from earlier designs that utilize re-use. The distinction between product development and applications engineering may be interpreted with reference to Hubka & Eder's (1988) definitions of the type of design task according to a design's originality, namely:

- Re-used design refers to the design activity of using a product configuration according to requirements. In this case the parts, sub-assemblies and sub-functions of the technical system are divided into usable chunks or modules to enable re-use. With regard to the development process, this type of re-use does not involve design activities or design process.
- Adapted design (variants); this design activity is aimed at creating variants for a product range or mix. The development partly modifies an existing technical system with respect to interfaces for new additions. Within development, the original technical system can be understood by its purpose and limitations. Additionally, new variants may impact on the interactions between the systems in the transformation process.
- Re-designed (an alteration in product construction or structure), this design activity involves a conceptual change in variant design as the existing technical system does not fulfil the requirements demanded of it. However, functions, some parameters and working principles remain but the alterations consider parts, construction and structures, their couplings and spatial arrangements.
- Original (a new system for required function), which is a novel design for requirements that cannot be fulfilled by any existing technical system.

The novelty of the design task may be considered the primary criteria for distinguishing which design tasks are more those for development rather than engineering. Engineering involves a more straight forward selection and implementation of pre-designed solutions and parts or design modifications to create variants and a change in characteristics, dimensions or materials (re-used and adapted designs). A development task involves the creation of something new or different compared with existing products, e.g. a new concept, a different operating principle or the application of modularity. In general, a development task requires a wider understanding about product application, conceptual or architectural design (i.e. re-designed and original designs) (Hubka & Eder 1982).

2.4 The origination of product properties

The product design and the performance of engineering tasks are meant to fulfil human needs by providing technical systems, artefacts that have a purposeful behaviour. This behaviour is realized through a transformation process in which separable connected elements synergistically affect. However, human needs exist in various forms and the selection of the means to fulfil a need is guided by the value system of a society, but is chosen by the technologies available at the time, the costs of the mean and the benefits expected (Hubka & Eder 1982).

An identified need may act as a trigger for a designer to invent a solution, but a design team may require a more exact task definition. To be more specific, the task assignment and clarification should include the collection of requirements, a specification of the desired properties of a technical system. As an artefact is a means for the transaction between parties, the most obvious view of property categorization is for an observer to distinguish between external and internal properties. Although, a designer tries to understand the design problem assigned with the design specification, there are various risks of failure. For example, the design specification can never be complete and therefore designers must set requirements for additional properties to solve the design task (Hubka & Eder 1982).

As the different classes or types of properties guide designers in their effort to solve a design task in the fulfilment of a technical function, other essential requirements, such as economic feasibility and human and environmental safety, must also be considered. Additionally, the solutions to technical tasks impose constraints and/or requirements which can be classified under the headings of: safety, ergonomics, production, quality control, assembly, transport, operation, maintenance, recycling and expenditure (Pahl & Beitz 1996).

Due to numerous and often contradictory requirements product development teams face challenges characterized as (Ulrich & Eppinger 2003):

- Trade-offs, which are the recognition, understanding and management of requirements and properties to maximize product success in the marketplace.
- Dynamics, which is decision making in continuously changing technologies, customer preferences, competitor actions and macroeconomic environment.
- Details, which are the choices and decisions about each property of every part and its assembly and the understanding of their consequences and implications.
- Time pressure, which is e.g. only being given a short time to reach the market requirement demand decisions and not having complete information.
- Economics, which is that the return on the investment in the development, manufacturing and marketing must be appealing and the result relatively inexpensive to manufacture.

In compiling the development specification, the most crucial document for success refers to how information is transferred, which then directly reflects on quality. According to Ulrich & Eppinger (2003) the philosophy behind the methodology of identifying customer needs is based on the premise that those who directly control the details of a product must interact with the customer and experience the user’s environment.

However, this is in contrast to Pugh (1996), who proposed that information should be organized according to major responsibilities in order to encompass core activities. However, each team member, even if they have a different level of responsibility should be aware and interested in the overall situation [Figure 2.6].

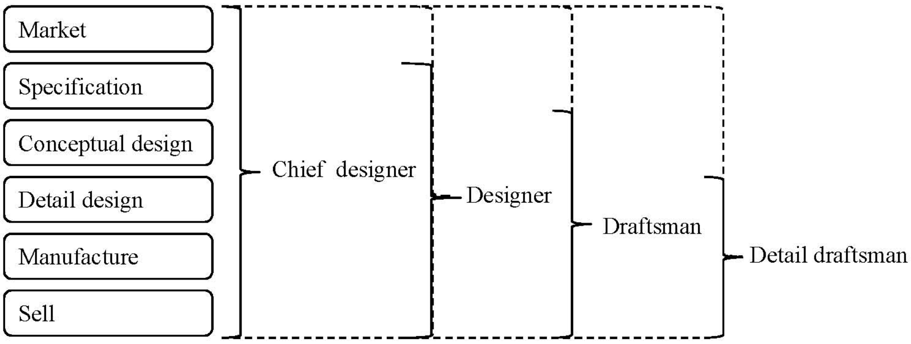


Figure 2.6 Differentiation of design team members' major responsibilities and areas of interest. Information and target sharing challenge during development project execution. Adopted from Pugh (1996).

In industry, development projects involve numerous people from different disciplines who have different scopes, which, in practice, prevent a thorough involvement with the customer and the product's user environment. The identification of customer needs is a process that includes various methods in capturing aspects and opinions from different user groups and markets. Ulrich & Eppinger (2003) define typical steps in the process are to:

- Gather raw data from customers.
- Interpret the raw data in terms of customer needs.
- Organize the needs into the hierarchy.
- Establish the relative importance of the needs.
- Reflect on the results and the process.

Thus the process and data acquisition is essential, even though further processing with organizing, evaluation criteria and judgement is challenging. In addition, different product types, markets and customer segments behave differently because none of those forms a homogeneous opinion, statistical evidence may be scattered and finally justifications are made by individual(s) in the development team (Mello 2002).

In industry, the importance of interpreting user needs into requirements is critical, because today development teams are often physically located outside front line operations and do not have close customer contact and as a result the documented requirements and specifications may form the only form of communication between the customer and designers.

An enterprise may approach a product portfolio and its development either by competitive differentiation or competitive strategy. The Boston Consulting Group has distinguished four types of industries based on their competitive advantage or size, namely volume, stalemated, fragmented or specialized industry. Within these, a company may choose its differentiation means with regard to its products (Kotler & Keller 2006). Those four types are similar to and may be compared with Ulrich & Eppinger's (2003) competitive strategies, namely technology leadership, cost leadership, customer focus and imitative.

However, the product portfolio, differentiation strategy and the product development and engineering functions should support each other. Basically two main approaches running a business may be identified and these are termed; product oriented and customer oriented. In the product oriented approach, an enterprise explores market requirements and provides products which satisfy the majority of the customers. The prerequisite for this approach is that the market and customer base are wide enough not to be dependent on any single transaction. The products may be developed according to generic product development processes. The customer oriented approach is applied in cases where the customer base and/or single transaction volume is important, as is often the case in project business or with other investment products (Treacy & Wiersema 1993).

The differences between these two approaches are in how customer needs are and can be identified and vary in diversity and content. Customer segmentation may be utilized when a large enough quantity of potential customers exists and a statistical confidence of preferences may be identified. With wider customer base, questionnaires and interviews may focus on general product properties. However, this is not the case with fewer responses, whereby the lead user interviews or customer specifications go much deeper into product details, even on the component level.

An example of different approaches with the same basic transformation process (lifting objects) that serves different applications (assembly line and steel mill) within two business areas of one company is presented below [Figure 2.7].

Figure 2.7 Two products with identical basic need and transformation process, vertical lifting and horizontal moving of goods. Assembly line (left), steel mill (right) (Konecranes Plc 2008).

The product on the left hand side is a standardized product from a pre-engineered configurable size range series and adapted to a customer’s facility by the modification of the main interface dimensions. Despite the configuration and adaptation the basic product is designed for wide market coverage with pre-determined features and properties.

The other product is a customized product designed to fit into a customer process and in addition to the adapting of its main dimensions, the customer requirements and specification call for numerous unique features and design properties, namely the load cycles for strength analysis, component design criteria, materials, surface treatment etc. These requirements vary between customers and a single common product level specification cannot be compiled.

Need identification as a basis for product development is ideal because the high abstraction level which is converted into requirements leaves many possible solutions and concepts open. Even if this generic process is valid for new product development, it is problematic for established companies, because:

- Companies have their expired product history and active product portfolio for sale. The products and their solutions respond to a particular need and business drivers prefer to focus on developing existing products and find new customers for them rather than diversify.
- New product development for new customers, markets or applications involves high risks due to lack of experience and knowledge beyond the existing operating environment. This risk exists even if development is supported by existing technologies or competence in a company.
- Customers and users may identify a need or have a wish, but it is expressed by describing a product, device, function, or property based on some existing product or experienced event.
- Customer behaviour varies depending on the type of business. In consumer markets, a new product or application from a recognized brand is welcomed due to its identification and image. However, in business to business transactions earlier references play an important role and new products or applications may raise concerns rather than promote confidence.

However, the behaviour of companies to put more focus on the development of existing products is logical, as this creates a visible line of product evolution in the long run. Nevertheless, several dramatic examples exist in the history with cases where new technology or a radical innovation has changed a whole business area and even collapsed large companies (Christensen, Anthony & Roth 2004).

2.5 Product requirements and specifications

The challenge and problem of establishing a product design specification has been approached by various means. Hansen & Andreasen (2004) identify seven different approaches, which all share the assumption that *it is meaningful to interpret an understanding of the customer's need and perception of value into a set of specification statements before actually searching for design solutions.* However, the authors questioned if this approach is based on theoretical considerations or empirical observations.

Hansen & Andreasen (2004) have presented their approach for product design specification content based on the identified relation between tasks and functions. They present four principal topics, which they argue a specification should focus on;

- Articulation and the transfer of the product idea; The means for the core design team of a product to communicate its idea, the understanding about customer needs, wishes and the perception of value in relation to desire, preferably in terms of customer characteristics and scenarios.
- Articulation and the selection of an attractive product, which involves the insight to confront and select the best solution for the user's need and solution space preferably exploited from the users' viewpoint.
- Navigation during the product development project, which occurs in addition to the performing of development activities to synthesize an attractive design, and means that the development team should be supplemented with insights into a product life cycle and business.

- Break down and maintenance argumentation, which is the development process progress within the sequence of design steps. In this, a product's complexity may be divided into sub-systems, within which the relevant specification elements have to broken down to correspond to the sub-systems.

Although the theory base for the product design specification is under development, the authors have proposed that one dimension towards the theory could aim to *show the relationship between user value statements, a property's specification, the structural element of a design carrying this property, a model of the actual structural element and the modelling result* (Hansen & Andreasen 2004).

The approach of this study includes the relationship between elements, which in contrast to earlier theories is not sought prior to the establishing of the design specification. Similarly, the last topic of the specification content, the break-down of the requirements and the subsequent argumentation into subsystems, refers to the process of incremental development – based on the earlier products. This is in accordance with the empirical experiences and studies referred to in Hansen and Andreasen's (2004) study. However, even the incremental development issues have been recognized by several authors (Ulrich & Eppinger 2003, Pahl & Beitz 1996, Altshuller 1996, Nadler 1963), although the theory base and practical methodology for industrial purposes have not developed into a mature and more applicable stage.

Today's products, specifically but not limited to investment goods, consist of combinations of various technologies, whose design competence is spread over different professional disciplines. Their purposeful behaviour and functions are the result of combining and integrating different subsystems and technologies to interact with each other. This has been recognized with terminology, such as mechatronic (Buur 1990) or hybrid system (Eder & Hosnedl 2007).

This raises a practical problem with the system characterization, which even the transformation process acknowledges, the concept of multi-disciplinary in the system. However, the suggested functional decomposition approach is hierarchical and provides definitions that each function or group of functions, which are capable of action, can act on as a definition for the transformation process for the next level of complexity (Eder & Hosnedl 2007).

Altshuller presented a trend for the evolution of technical systems in their transition to a super system, where technical systems merge and form bi- and poly-systems. Beyond the confines of engineering, analogous evolution can also be found in nature by means of continuous integration, the overlapping of functions and the convolution of systems. The formation of bi- and poly-systems involves the quantitative modifications of properties, links and internal mediums. The main purpose of using such systems is to help new properties to emerge (Salamatov & Souchkov 1999).

In today's products, the purposeful behaviour, i.e. the mode of action and produced effects is produced through embedded systems or integration, whereby direct functional decomposition cannot be explicitly defined within one function or group of functions.

2.6 Conclusions

In this chapter, the different approaches to product development initiation, design tasks and prerequisites for design specification have been looked at. Product portfolio renewal need and the external and internal drivers of a company have been presented and the principal conflict between the theory and industrial practice of product development activity initiation has been raised.

In literature, the generic product development process initiation, opportunity identification, is based on market need or technology push, resulting in a new product launch. With this, a systematic path to new product development is provided. Accordingly, the product generations are presented with the S-curve concept theory, where successive designs introduce a new dimension of the product performance. The product specification, derived from user needs and selected concept, guides the development team in designing properties and characteristics.

Minor attention has been placed on the prerequisites for incremental development, which challenges the relevance of S-curve concept theory and product generations in respect for concept newness for the original transformation process. Product development in industry influenced by economic constraints prefers to improve product properties with new subsystems and/or technologies rather than create totally new. Consequently, for each product development activity, the experience of existing and expired concepts may be utilized.

In industry, the product design specification has an essential role in the development process, which cause the low utilization level of the generic product development processes with feedback loops – forcing the actual development processes linear. This is the consequence of gate model application in project management, which separates the development process to specification preparation and actual design process. Accordingly, to avoid uncertainties during the project execution, the conceptual design is completed with the specification. Although the advantages with the project control are obvious, the dynamic interplay between the specification, concept and requirements is lost in practise during the design phase due to time and cost constraints.

3 Product Value in a Conceptual Design Context

A bid process to acquire an investment product was opened for equipment suppliers. Competent suppliers receive commercial and technical documents, but often an offer is accepted only with a bid bond that guarantees that the supplier does not escape during the process. In the documentation it is typical that the evaluation criteria are presented, that consist of technical, commercial and delivery justifications.

Suppliers submit their technical and commercial offers before the due date according to requests in documents and make their deviations and clarifications according to various details (which is typical because suppliers prefer to offer their standard solutions and not all tender requirements can be accepted).

The buyer makes the first review of offers and short-lists two or three suppliers, with which the final negotiations will be held. The offers of the short listed suppliers are evaluated according to the buyer's criteria and finally the deal will be granted to one. The weighing of the evaluation criteria varies; one buyer may go after the lowest acquisition cost while another may appreciate the total cost of ownership and performance. The suppliers typically know already from the beginning of the tendering process what the driving criteria will be – and sometimes participate accordingly.

Whatever the evaluation criteria are, the justification is based or explained with the value that the investment brings to the buyer. The new equipment will be a part of the buyer's business process or value chain, but simultaneously it is a part of the supplier's value chain. As a pre-requisite for a business case, the value aspects of the two parties of the transaction have to meet.

In a business context, the value concretizes and is priced within the change of ownership, which distinguishes the value viewpoints. However, a design concept as such has only an immaterial value, the product development teams have to explore methods and tools for understanding and direct their work to fulfil both viewpoints i.e. attract buyers with competitive product (acquisition) properties and meet the supplier's profitability requirements with product (delivery) cost.

3.1 Value in design science

The general definition of value, or the importance or worth of something for somebody (Woodford 2003), may be approached and organized according to different theories as philosophical, scientific and technological questions. The first one raises issues related to ethics and moral theory. The second approach uses the social sciences such as human and animal psychology, sociology and economic theories of value. The third involves value with respect to the goodness of an artefact, in other words its effectiveness, efficiency and flexibility as related to its properties and specifically its functions. In that sense, the value meets some need according to its function and in that respect the function is valuable, but not the artefact itself. In relation to products, technological value is addressed with three fundamental elements, namely:

- Effectiveness or goal attainment in comparison to ideal state of performance.
- Efficiency or the economy of means with respect to achievement in the end.
- Flexibility or adaptability for alternative options or uses during a life cycle.

However, the technological value is explained by the relationship between the attributes of the artefact, although the judgement of these attributes is subjective and reflects human knowledge or attitudes on how these attributes can satisfy needs (Seni 2007).

Value in a marketing context also defines a consumer's estimate of a product's overall capacity to satisfy his/her needs (Kotler & Keller 2006). DeRose (1994) adds the cost and benefit aspects and defines value as the satisfaction of customer requirements at the lowest possible cost of acquisition, ownership and use.

By combining business and technical approaches together, a definition of value may be formulated as *the relationship between the worth or utility of an item (expressed in monetary terms) and the actual monetary cost of the item*. Accordingly, the highest value is represented by *an item with the essential quality available at the lowest possible overall cost that will reliably perform the required function at the desired time and place* (Mandelbaum & Reed 2006).

Cooper (2001) argues that value is subjective and perceptions vary according to who the buyer is. Two people can look at the same product and judge it to have different value. When defining the value the first question shall be: Value to whom? Only after that can the relevance of the value or worth be raised. In a competitive market, a product and its position is always compared with similar products.

The contexts of value and value propagation through value chains have been studied widely in literature. The means to achieve customer satisfaction with a product or service offering varies between different businesses in which the physical realization of the product and its technical system forms one part of the total value. In this study, the context of value is focused on the technical value and how product developers interpret value aspects into technical solutions.

Hubka & Eder (1988) note that the value of a design includes various definitions, for example, how needs are fulfilled e.g. wellness. Value is defined according to product properties, specified by the means of technical, economic, ergonomic, aesthetic, use, performance, image or total properties. Value is accumulated during the engineering process, as the product requirements take their forms. This creation process is called "product maturity" and is dependent on the capability of the engineering team in question.

Altshuller (1996) presents the absolute value of a product through an ideal solution. This may be reached with an utmost solution, in which the function is realized without any sacrifice. However, the technical solution is considered as the only definitive merit for value, which, on the whole, neglects all other business approaches.

Pahl & Beitz (1996) refer to use-value-analysis, later documented in VDI 2225-1 (1997). This evaluation is used to determine the value of a product, and its usefulness and strength are also considered with respect to the objectives given because the value of a solution is not absolute. The value comparison of different concepts is made with pre-defined weighted parameters; from which the overall balanced value profile is calculated. The profile can also be used to show the weak spots of weighted sub-values or to determine satisfactory solutions. The method is also referred to when it is used to evaluate a relative value, which is a technical value compared with economic value. Ulrich & Eppinger (2003) have introduced a similar type of matrix evaluation chart in combination with QFD, which aims to mathematically choose the best solution.

Pugh (1996) approaches subject value from a more practical engineering viewpoint and warns that the numbers used in decision matrices have an entirely different meaning compared with the numbers used in an engineering analysis. Hence, assessments made according to numbers may not have any relationship in fact or to reality because the selection of criteria as well as the weighting of values presents the opinion of the evaluator. Pugh therefore proposes the use of relative measures, which can be better than, worse than or the same compared with other properties.

Value engineering and its applications are widely applied as a post-analysis of products or product functions while seeking out more economic and streamlined solutions. However, if the break-down structure of a product is not well known, as is typically the case at an early phase of a development process, the effort to put a cost/price tag on each function or property doesn't really reflect the market or user aspect. Thus the problem of directing higher level requirements down to assembly or part level in a product structure is obvious and is well acknowledged in the studies referred to by Hansen & Andreasen (2004).

3.2 Engineering challenges

Engineering is supposed to create superior cost effective products, which bring various challenges on how to specify a required engineering task. The first two problems are technical and deal with how customer needs are converted into technical properties and how the business challenges are met [Figure 3.1].

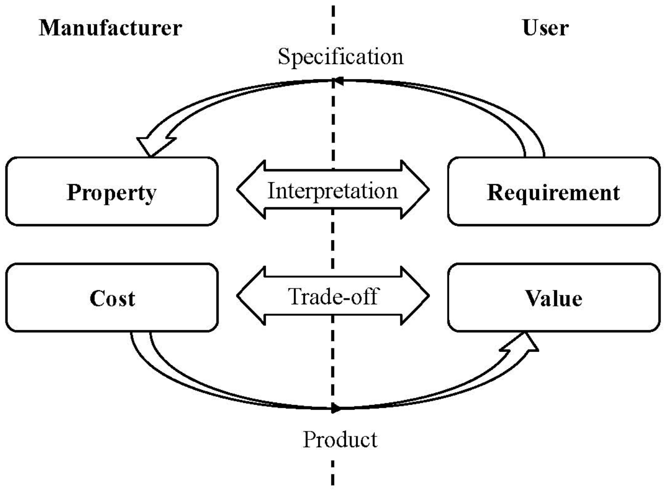


Figure 3.1 Engineering challenges while interpreting the requirements into properties and choosing the solution to meet value expectations (Oja 2008).

The first challenge relates to the understanding and interpreting of customer needs. Engineers like to formulate engineering tasks into the format of a development or product specification. The specification can present various aspects of product use cases, operating environment, performance characteristics and other relevant information, which marketing and engineering assume to be customer needs and preferences. However, as the developers seldom personally experience a user's viewpoint, all the requirements interpreted as specifications reflect their assumptions and interpretations.

The second challenge arises when a specification develops, either with the development team for a new product development or is given when development is based on an existing concept. In the latter case a new set of people are involved and the initiation of interpreting the requirements, functions and properties restarts. In the case of the modification of an existing design the main functions and properties already exist and development can focus on either performance improvements or a decrease in product costs. New product development, though, starts with establishing the functional structure and decomposing it, or more apparent in industry, the specification separation into different disciplines. As the purpose of the specification is to explicitly direct and co-ordinate development efforts, reference to the original customer needs and requirements begins to disappear or at least dim at this point. Developers should trust in the specifications given, even if that means looking at requirements and assumptions that have already been interpreted twice.

The third challenge arises as the design is transferred into manufacturing stage. Once the solutions, structures and bill of materials are initiated, the costs are involved by means of labour, facilities, materials and components. Here it is worth restating that products will be the means of transaction and at least in the long run companies must be able to collect more money from their customers than they use to produce their products. Thus, costs are not unlimited and they are carefully controlled and continuously under pressure. Product properties and characteristics are evaluated against the cost they incur and attempts to optimize will start as soon as the first product pilot series has been completed.

The fourth challenge is met during the product price setting. Over time the cost plus type of pricing needs to be updated as more often the market price is predetermined within certain limits by competition. Competing or products with similar functions will be compared with the manufacturer's product and customers will form an image about the product price. However this may vary in the case of a totally new product or service which has yet to be introduced into the market.

For a company, the product sales price should be as high as possible in order to maximize its profitability. The customer, who evaluates the value of the properties for her/him, will decide the maximum affordable price. The paid price reflects the product value for the customer and as an indication of a successful transaction, it should exceed the product originating costs and required profit margin.

3.3 Value in a business context

The main prerequisite for a successful business transaction is that the benefits of the product or service shall be significantly greater than the paid or given sacrifice (Suistoranta 2007). The benefit may be interpreted as the value to a stakeholder. In a business environment, there exist two main viewpoints: the product or service provider's (manufacturer) and the buyer's (user). Both of these two parties define and formulate their value aspects, which need to be reconciled during the acquisition process.

The pure financial analysis and key figures naturally set the decision baseline for investments. This business operational viewpoint may be called a primary assessment. However, each enterprise also has regulations that it must follow according to statute, strategic selections or tacit preferences guiding the values and their importance.

Within this aspect, the value develops much more varied elements beyond its technical properties – and is also much more difficult to evaluate and measure. The value assessment also differs between consumer and business-to-business products. Instead of a product image or personal preferences that deal with consumer products, it is assumed in this study that the evaluation of an investment product is more rational than emotional [Figure 3.2].

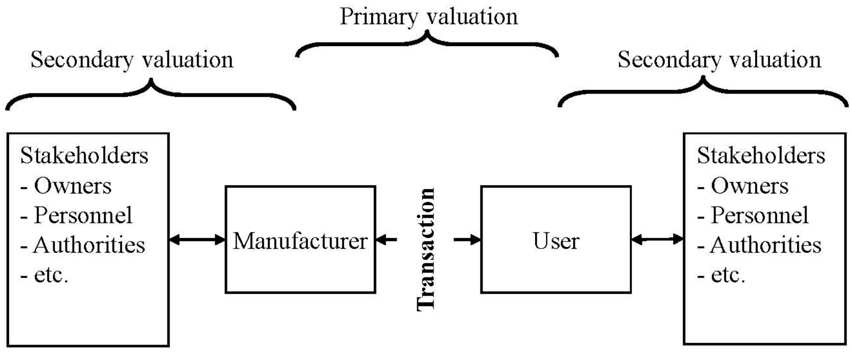


Figure 3.2 Value assessment dependencies; primary assessment between user and manufacturer, secondary between user/manufacturer and their stakeholders (Oja 2008).

The operating environment of an enterprise affects how value is evaluated. Specifically, a primary assessment for a product or service transaction is that the need and offering shall meet in terms of beneficial results. The secondary assessment defines the verified alternatives that follow the business strategy. What is evident is that due to the changing world, the preferences of valuation differ and depend on the viewpoints of the manufacturer and user as well as the time and place.

Product developers face the problem of valuation, what product modifications or improvements increase value and what is the correlation between them?

If we assume that the correlation is positive, then the more benefits we can receive with a product, the more we should value it. Additionally, there should be a means to evaluate, compare and justify value in the technical context.

3.4 The value chain and value propagation

Porter (1985) defines the value chain as a tool for identifying ways to create more customer value. Within any company, a value chain consists of nine strategically relevant activities in two groups that create value and cost. These activities in a primary activity group are inbound logistics, operations, outbound logistics, marketing & sales and service. The support group activity consists of procurement, technology development, human resource management and company infrastructure.

The engineering and product view of a value chain describe and define actions which create and accumulate the product or process value. This is considered in order to include only direct manufacturing and production actions. However, during the product originating process conceptual solutions and decisions are also considered within the value chain.

Different value chains can be identified during a product life cycle. The first value chain begins when the first actions of the product originating process have been taken and the last value chain ends when all product duties and responsibilities have come to an end, including disposal. The most simplified case involves only two value chains; the manufacturers and the users, where the switchover stage is the transaction. The manufacturer's value chain includes the engineering process from product idea or opportunity identification to the end of the product support cycle. In a business environment, company strategies define whether or not other consecutive value chains are to be included in the business scope and how they will be activated in organization, either within separate units or enterprises.

The user's value chain begins when the product is handed over for operation and ends as its disposal takes place. As an exception, among service products, when any concrete artefact for a transaction does not exist, the user's participation and her/his value chain already begins during the originating process (Kuusisto & Meyer 2003). Such overlapping of the value chains is typical as today's business trends often make demands that ensure the need to provide services along the whole of a product's life cycle. Hence, it may even appear that the manufacturer's value chain extends beyond the user [Figure 3.3].

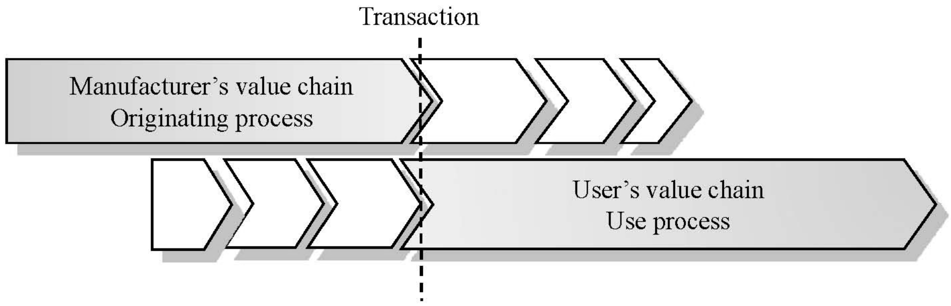


Figure 3.3 Overlapping value chains may begin and continue beyond the moment of actual product transaction (Oja 2008).

According to the chosen business strategy, the value chains can be consecutive, simultaneous or partly simultaneous and they may have common interests. However, the different value chains impact on product value depending on the value aspect and viewpoint. Two main viewpoints or value chains are the manufacturer's and the user's and these can be identified as meeting at the borderline of the transaction. The value chains have a different context and visibility for each stakeholder, even if they may share some elements.

For a product developer the recognition of a value chain in practice is extremely challenging, specifically when development work is spread over different disciplines and production is scattered in a supply chain network.

The versatile development environment and the earlier experiences of the developers cause that different meetings (between the product concept and the process stages) during the product originating process will have a different status in time and space.

3.5 Viewpoints on value, value profiles

Within a business transaction, the buyer may use different value evaluation criteria while making his decision between alternatives. The simplest and often used selection of a supplier is based on the lowest cost of an acquisition with an acceptable technical solution. However, this option does not leave room for value discussion because the decision is made strictly according to the immediate financial layout criteria.

A much more comprehensive selection option follows the value approach, which is defined to include the cost and benefit aspects as well as the selection of the supplier who offers the lowest cost of ownership over the life cycle with the acceptable technical performance solution. Accordingly, the value is the satisfaction of customer requirements at the lowest possible cost of acquisition, ownership and use (DeRose 1994).

Different variations of wider value considerations have been presented recently; Kelly et al (2004) describe the generic criteria for a value system, including capital cost, operations cost, time, community, environmental impact, exchange (earning potential), flexibility, esteem and comfort. More detailed advice and a clearer value evaluation for practical business is given in the United States Federal Acquisition Regulations (FAR 2005) that sets out a method by which the best value products or services may be delivered to the customer. In this context, the best value is defined as *the expected outcome of an acquisition that in the Government's estimation provides the greatest overall benefit in response to the requirement*. The evaluation criteria include:

- Past performance and the performance history of the supplier and the capability to provide support during the warranty period and spare parts for a requested time period.
- The special features of the supplier or service required for the effective execution performance i.e. the capability to provide competences and services for delivery and product set-up time.
- Trade-in considerations.
- Probable life of the items selected compared with a comparable item.
- Warranty considerations.
- Maintenance availability.
- Environmental and energy efficiency considerations.
- Delivery terms.

This approach widens the value approach beyond the realization of the technical system to include viewpoints, in addition to the value definition, that accord with the fulfilment of the desired product or artefact properties (Hubka & Eder 1988).

For a development engineer, the results during the design activity shall also take into consideration the impacts of the evaluation criteria for success in the evaluating process. As presented earlier, the two views of the manufacturer and user have to be combined during the conceptual design and followed later throughout the product originating process.

The approach of universal virtues (Olesen 1992) may be expanded to consider the user's point of view as the product is the means in the value chain in both the manufacturer's and the user's processes. Thus, similar valuation elements will be used for the evaluation. However, both parties set their own criteria, according to their business strategies.

The prerequisite in business transactions is that the diverse aspects of the product or service value match. Practically this means that the benefits shall justify the spending. The manufacturer aims to develop products or services, which match the customer's values. On the other hand, the manufacturer has profitability targets, which have to be fulfilled at least in the long term to ensure the existence of the enterprise.

During a business decision, it is typical that two or more alternatives are contrasted against each other and an absolute scale is not necessary or even relevant. Kano et al. (1984) has classified the selection criteria into four types in his model: basic characteristics, measurable performance characteristics, non-measurable performance characteristics and risk. These are evaluated with three variables according to how customer satisfaction is achieved [Figure 3.4].

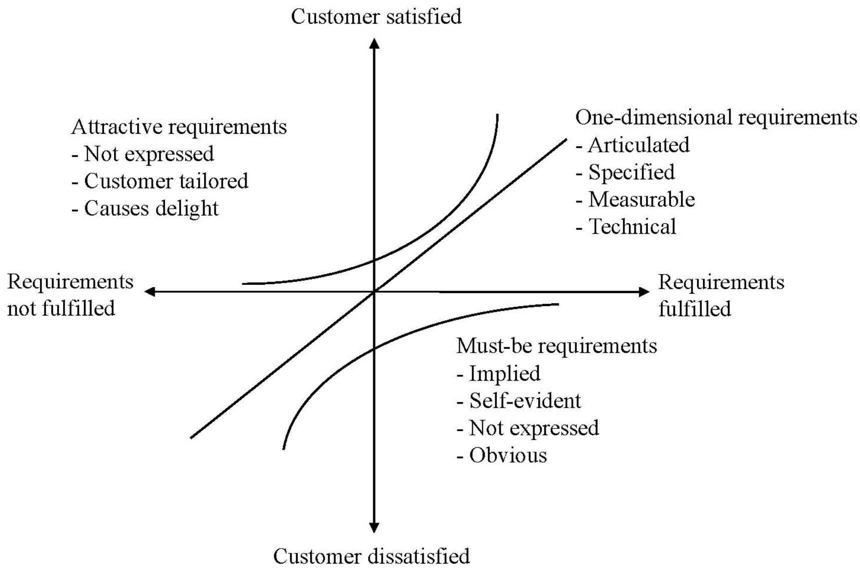


Figure 3.4 *The Kano model showing the dimensions of customer satisfaction; must-be and attractive requirements in contrast with one-dimensional basic requirements. Adopted from Kano et al. (1984).*

According to the classification and variables, products may be positioned into categories that show whether they provide basic, performance or delight characteristics. However, in business, the transaction decision is often based on maximizing one or more specific desired criteria and minimizing possible dissatisfying elements rather than choosing the alternative that gives the maximum sum of all criteria.

The value evaluation and measurement are challenging for the development team as the engineering science approach to value aims for technical fulfilment through function, which is then followed by the product properties. During the development, engineers continuously cope with problems like:

- How is product value created?
- Do the product value and cost have a relationship in the technical system?
- How do the value criteria and evaluation impact on an engineer's selections and decisions?
- How can the trade-off between product cost and product positioning be compared with competitors and addressed?

The design problem is not only a question of profitability optimization between product properties and cost as a pre-requisite for a transaction – it is also a time and sequence problem as the engineering trade-offs are done first and competition occurs in the marketplace later.

3.6 Value and concept development

The most important decisions during the product development process are made while concept alternatives are evaluated and selected. When considering the basics for a successful development project; i.e. the product commercialization and accumulated sales, the different value elements play a key role and they impact on the development process.

The challenge of the manufacturer is to develop and maintain competitive products for chosen customer groups, as well as find new target groups to increase or recover sales. Simultaneously, the manufacturer actively explores product improvements to increase his profitability. Profitability improvement can take place in two ways; either by decreasing the costs activated during the originating process or increasing the product value for the user (customer).

If we study the conceptual design stage, at the point when the comparison and selection of product function, architecture and properties take place, it becomes clear that, in a technical system, the manufacturer's viewpoint presents the "idea in" elements, e.g. how the product realisation concretizes. In contrast, the user's viewpoint is more like "idea with", as the use of the product is focused on (Hansen & Andreasen 2002). However, fulfilling both aspects, product innovations have to take place in order to bring benefits to all stakeholders.

The universal virtues, as originally meant for evaluating product design for production performance, can be used also for the two-sided evaluation of value [Table 3.1]. Whilst Olesen (1992) listed the attributes in each element for production performance and manufacturer's value, the attributes for user value elements may be interpreted as follows.

Table 3.1 Value elements of a manufacturer according to production performance and a user for decision making to acquire a product. Adopted and modified from Olesen (1992).

Value element	Production performance	User value
Cost	Direct labor and materials cost Overhead cost (indirect cost); shop floor management, space cost Production control, quality cost, Purchase, etc.	Direct acquisition cost (price) Indirect costs; inquiry, evaluation, testing, Operation costs, energy, consumables, maintenance, spare parts, repairs, disposal
Quality	The ability of the product to comply with the desired functionality (with a low level of quality control, rework, scrap cost).	The ability of the product to keep functionality, up-time, need of repair, aging and degradation of components and materials
Flexibility	The versatility and adaptability of the manufacturing (related to product design).	The flexibility to adapt changes in use or process, relocation
Risk	The major manufacturing risk embedded in the product design.	The risk of delay on start-up, skills needed for operation, availability of spare parts, need of maintenance expertise, break-down, liability
Time	The ability of the product to allow a short lead-time.	The ability of short delivery and start-up time, maintenance time, duration of warranty time, total lifetime
Efficiency	How efficiently can personnel be utilized? How efficiently can our resources be utilized?	How efficiently the process is utilized, performance, resources and energy usage, MTBF
Environment	Environmental consequences of the product design during the manufacturing process.	Environmental consequences during product use and disposal, sustainability

For product development, the user value sets different views on criteria and product specification requirements. The customer is not willing to pay for functions or properties, which mainly support the manufacturer's interest. Unfortunately, these two views are in contrast and the manufacturer has to cope with the challenge. However, this occurs only in comparison to its competitors if there are other potential alternative solutions on the market. Thus, if we measure the goodness of the product with value elements, we may assume that the product becomes more valuable as its goodness improves.

In Figure 3.5 two business viewpoints on value elements and universal virtues are shown. In business, the elements have different weights depending on the viewpoint. However, the scaling of the elements can be defined in a way which can then be interpreted to the development team. Different alternatives for grades and weightings can be found in the literature, but practically each numerical evaluation leads to the trap which Pugh (1996) pointed out; none of the elements can be measured with the same scale and the summation of the element scores erases any possible showstoppers. Thus it is more preferable to apply Kano's (1984) approach with relative evaluation criteria; dissatisfaction, neutral and delight.

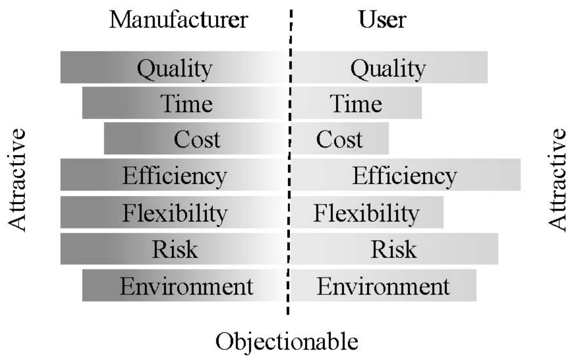


Figure 3.5 Two viewpoints of the universal virtues. Both parties aim to maximize the value of their own elements, but a balanced match between value profiles shall exist to enable successful transaction (Oja 2008).

If we study the value elements more deeply, we may assume that the goodness of each element is relative to time, context and viewpoint. At the moment of decision, a conceptual design or acquisition, the valuation is based on the best knowledge at that particular moment. The knowledge includes the estimation of the benefits during the expected life cycle.

As mentioned earlier, the weighing of the elements varies. In the case of an artefact, the function or technical goodness are not the only criteria for the evaluation as all related properties will be valuated within the elements.

However, even though electronic spreadsheet type inquiries have been entered into business to business transactions, individuals still make the final judgement. However, it may be pointless to even try to find an absolute scale for rational decision-making. History, experience, similarity, existing products easily affect and over-rule any fact-based evaluation due to the difficulty of converting a subjective mindset into a factual number. Attempts have been made to convert value into a monetary scale, but many of the elements, like quality, time, flexibility and risk, are difficult to measure. Specifically, if the evaluation involves the approach of the total cost of ownership, it may appear that neither the cheapest nor the most expensive is the most valued.

How then it is possible to cope with these elements during product development? If we study the value profile and the two viewpoints on elements, we notice that no absolute measure can be set. When the customer makes his/her evaluation between suppliers, it is a trade-off situation. Each provider has its value profile and some of the elements are neutral, or elements that just have to be there at an acceptable level. The real comparison is then the question of significant differences; even one very attractive element (often cost) can shift the selection – specifically if the decision does not consider a total cost of ownership type analysis.

In business, value is always relative and varies from case to case. Additionally, the relative importance of each value element varies depending on the time and context of justification [Figure 3.6].

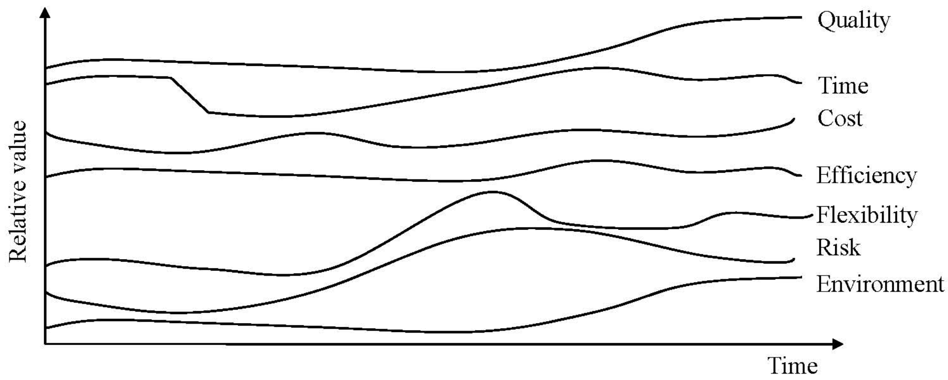


Figure 3.6 Relative total value consists of the combination of varying elements which valuation depends on time, context and stakeholder. Engineering challenge is to meet correct elements for business success.

The change of the value elements can also impact on product development initiation, requirements and processes. The manufacturer has the opportunity to develop and maintain competitive products for selected target groups and/or find new target groups. However, the manufacturer also has to continuously develop improvements in order to increase profitability. The natural consequence is that product innovations shall bring value improvements and benefits, for the manufacturer, the user or both

Different stakeholders have their preferences regarding how they adopt and accept new products or technologies. Quite often, if a product's improvements or developments initiate only from a manufacturer's own interests, customers may not accept them. Thus value elements provide guidance for the topics of the kind that may be used for idea generation. Value consideration has an important role to play during a designer's decision making as he/she continuously faces the trade-off paradox between product cost management and product positioning with properties, which are evaluated by the users. The extended business environment also challenges the consideration of whether or not only the optimization of profitability is the prerequisite for a successful contract. This is a sequential problem because trade-off is first made during development and contract competition comes later.

> The value approach and considerations raise concerns about how vulnerable product development is, specifically with new products.

Product innovations need not be revolutionary or radical in order to boost successful product sales. Incremental innovations for existing products or concepts may provide just enough advantage against competitors. However, the risk exists for large enterprises, and their R&D sections, that they become too focused on only incremental innovations. Numerous examples can be found of radical innovations that have superseded mature products and revolutionized markets (Leifer 2000).

3.7 Conclusions

This chapter studies product value in various contexts in engineering design. In literature the value in design context is qualified by the degree to which somebody's needs are fulfilled. Value is determined by properties, which can then be divided into various categories and the goodness of a technical system is measured by its deviation from an ideal solution.

In business, the product must provide greater value and benefit to a stakeholder than the required investment. This brings out the fact that value content is different depending on the viewpoints of the technical system, user or manufacturer. Accordingly, the product value is relative and dependent on a viewpoint within a certain time and place. Furthermore, customers do not differ from any interest group during decision-making as their judgements are also made according to benefit analysis. Benefits, consisting of different elements of product value, are evaluated case by case, in a relative fashion dependent on time and context. Variations between different customers burden the manufacturer's task of fulfilling internal and external demands.

Product developers are well aware of the contradictions in the business environment; products shall be superior to competitors to enable sales, but the product's costs have to be minimized for profitability. The tasks of developers are centred on technical details and as they are far from the user they have the difficulty of evaluating when a design is good enough and when not to aim for "the best" in all respects.

Here an approach from two value viewpoints was presented. These viewpoints consist of value elements, which may later be used for better exploration and evaluation and as a tool of analysis for product innovation. In today's business, the introduction of radical innovations in industry is rare, because the product concepts are a type of static design. Therefore, extending the product developers understanding about the user's evaluation approaches and criteria enables the consideration of what and how design decisions shall be addressed.

4 Considerations on Product Development Process

A company, selling, designing, manufacturing, and maintaining investment products for the material handling industry spends annually more than 200,000 engineering hours on application engineering while tailoring their products to meet customer requirements. Mainly the tailoring includes the modification of the main dimensions due to unique interfaces but also the scaling of existing solutions and the adaptation of new properties.

Within delivery project engineering, the time schedule is very tight. Due to time pressure, the main components and materials with long lead times need to be ordered as soon as possible. For an engineering process, this sets a requirement which is not considered within design processes, specifically; engineering results are often launched well before the detailed design is complete. Launching some engineering results subsequently allows the design process to be broken up into controllable stages and increases the possibility to sharpen earlier selections.

An objective in industry is that delivery project engineering includes as few as possible new developments or unknown properties, because the time schedule does not allow for any iterations or extensions that may affect the final delivery schedule. Enterprises tackle this problem by separating engineering processes into two. These are (1) the main process for delivery project application engineering and (2) another parallel process for product platform or new property design process. When the delivery engineering is a straight forward modification or tailoring activity the role of platform engineering is to provide pre-engineered blocks or modules that can be adapted for delivery engineering.

Neither of these two design processes is the type described in new product development. Both design tasks as their starting point have an existing product or concept, which needs to be modified or improved. While delivery engineering aims to create firm, robust, cost effective and reliable design for a particular case, the development process aims to produce innovative solutions that respond to the quest for improving market attractiveness and reducing manufacturing costs.

Volume wise application engineering represents more than 90% of the annual design activities and their effectiveness is subject to how well the product is structured. Furthermore, engineering systems prepared for pre- or layout design can choose known solutions. However, for maintaining and improving the competitiveness of the enterprises, an innovative development process is necessity.

4.1 Introduction

An engineering process that creates a design for an artefact, defined by Taylor (1959) as engineering design, is the process of applying various techniques and scientific principles to the purpose of defining a device, a process, or a system in sufficient detail to permit its physical realization. The pioneering work of Hubka & Eder (1982, 1988) on the theory of engineering design and technical systems has structured the way designers today create products.

Design processes at the early stages of industrialization initiated from a need or a problem and resulted in artefacts that were strictly made as “task to be done” type of solutions. Today, examining the products designed decades ago, it is obvious that during the design process, little attention was placed on anything other than a product’s functional requirements. Later, more systematic design processes were required as the design tasks became more demanding in their complexity and more designers were involved within the same design task. The development of systematic design processes was a natural continuation, as were the development of manufacturing systems.

The engineering processes originate from the need to develop a new solution. As technology development has brought its impacts to engineering, the business environment has also changed the scope of engineering management. Nobelius (2004) has presented a review of R&D management generations, starting from the 1950s with (i) technology push, which turned to (ii) market pull in the 1960s, and expanded to (iii) portfolio management in the 1970s. Rapid technology development in the 1980s created a need for (iv) cross-functional teams and disciplinary integration. Globalization and subcontracting created the need for (v) networking in the mid-1990s, which continued with (vi) open innovation environments in the middle of this decade.

The type of product development project obviously impacts on what kind of design process best suits a purpose. Thus, the study identifies different product development projects and classifies them according to their results. Ullrich & Eppinger (2003) introduced eight initiation modes of product development variants and three different processes which are presented below [Table 4.1].

Table 4.1 Variants of the generic product development process, their applicability and distinct features during execution. Adopted from Ulrich & Eppinger (2003).

Process	Process type	Description	Distinct features
Generic product development process	Market Pull	Market opportunity recognition and selection of technology to meet customer requirements	Planning, concept development system-level design, detail design, testing and refinement, production ramp-up
	Technology Push	New technology introduction and evaluation of market	Matching the technology and market during planning, concept by given technology
	Platform Products	Application of established technology subsystem	Concept with proven technology platform
	Process-Intensive Products	Production process constrained product	Utilisation of existing process or development of a new with product
	Customized Products	Slight variation of existing configurations	Streamlined and structured development process
	High-Risk Products	High risk of failure due to technology or market	Early risk identification, analysis and testing
Spiral	Quick-Build Products	Utilisation of rapid prototyping and testing cycles	Repeated design and test phases
Complex systems	Complex Products	System decomposed into subsystems and components	Separate parallel teams, system integration and validation

Based on these variants, three different development process descriptions have been presented [Figure 4.1], where the main differences between the detail design, testing and refinement phases are acknowledged (Ulrich & Eppinger 2003).

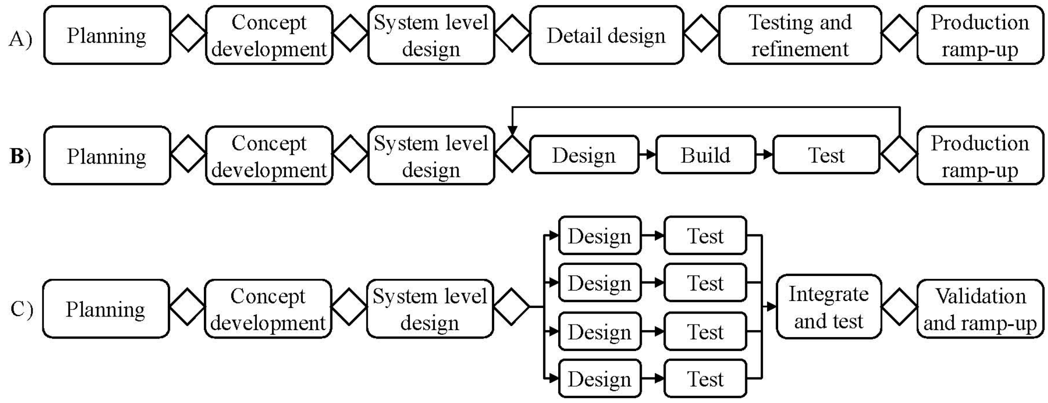


Figure 4.1 Three flow charts for product development processes: A) Generic, B) Spiral, C) Complex Systems. Main differentiation during the detail design and testing phases. Adopted from Ulrich & Eppinger (2003).

The development task involves a wider approach and the development process for new product development has been studied by various authors. In addition, generic product development models provide alternative approaches to different product environments.

In the early 1960's Nadler (1963) presented his approach on work design. He defined work design as Systematic investigation of contemplated and present work systems to formulate, through an ideal system concept the easiest and most effective systems and methods for achieving necessary functions. Even though he mentioned in the preface, that the book is experimental, the philosophy establishes the objectives for work design and clarifies the areas in which the objectives are applicable and determines how objectives are to be reached. The work design is a procedure for designing an answer to any type of situation and consists of ten steps, namely:

- Function determination.
- Ideal system development.
- Information gathering.
- Alternative system suggestions.
- Selection of the feasible solution.
- Formulate the work system.
- Review the work system design.
- Install the work systems and methods.
- Performance criteria established.

The presented steps are familiar to later design processes presented by some groups or individual experts. The initial development of Design Science started in Prague 1967 at a series of international conferences, in particular at the first International Conference on Engineering Design held in Rome 1981.

Systematic design processes divide design tasks into phases with defined inputs and outputs. One of the best known design process descriptions, greatly associated with the research of Pahl & Beitz (1996) is VDI 2221 (1993), which divides the product design process into seven stages resulting in specification, function structures, principle solutions, module structures, preliminary layouts, definitive layouts and product documents [Figure 4.2].

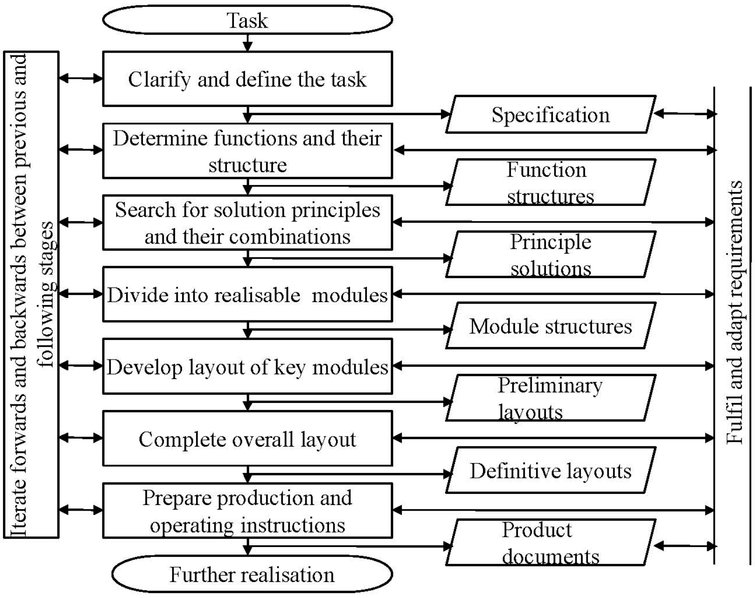


Figure 4.2 Product development process, stages and main results. Adopted from VDI 2221 (1993).

The VDI-process has a structured task separation and flows from abstract to concrete, thus enabling iterations between previous and latter stages that are typical of product development when uncertainties or constraints prevent linear progress. In this process, concept development is based on changing and varying the functional structure to enable the exploration of different solutions.

The definition of design as mapping between what to achieve and how to do it has led Suh (2001) to separate the engineering environment into four domains; customer, functional, physical and process. Mapping between these domains during design reveals function to be the definitive driver. Within multi-functional systems, as industrial products tend to be, the design process progresses towards breaking down the system into functions, in which finally design parameters with constraints can satisfy the functional requirements [Figure 4.3].

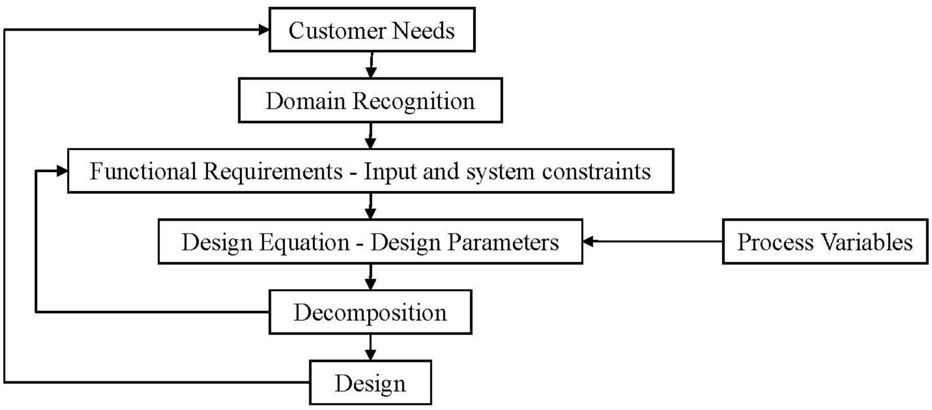


Figure 4.3 Multi-functional requirement design process steps to reach robust design by decomposition to fulfil independence axiom of one functional requirement. Adopted from Suh (2001).

The principle of robust design here leads to a reductive process, in which the function is decomposed to the simplest level, and where the different requirements can be separated and shown to be independent of each other.

The nature of a design situation between the two extremes of an existing practice and an unknown design during the conceptual stage was acknowledged by Pugh (1996) resulting in the definitions of dynamic and static designs. The dynamic refers to the application of a new product development, in which concept development follows the specification, as opposed to static development where the conceptual decision is already taken [Figure 4.4].

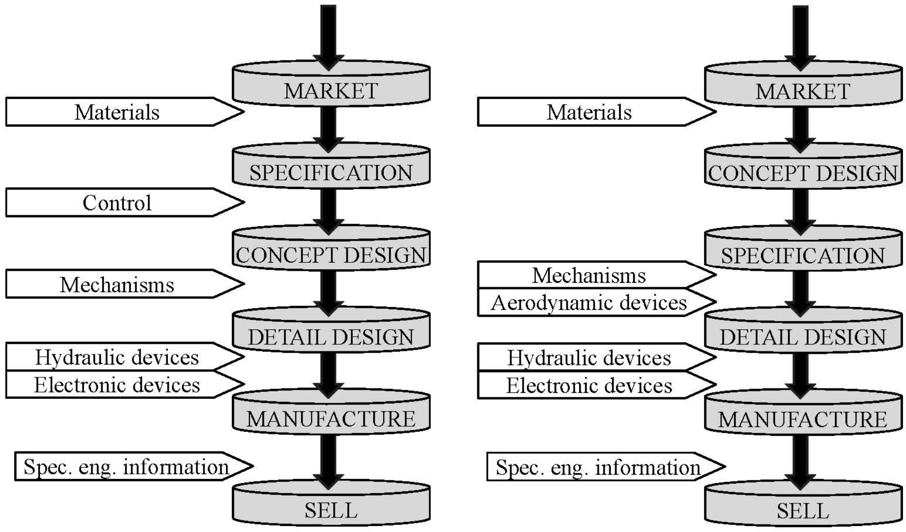


Figure 4.4 Design activity model examples for dynamic (ship design) and static (car design) concepts. Adopted from Pugh (1991).

With the total design product model, with reference to ship and car design, Pugh (1996) also showed that a product consists of different technologies and systems which cannot be developed separately. In his model, the stages where different systems are defined and a synthesis and decisions made vary depending on the type of concept. However, this will be further discussed while studying the core problem of this thesis in more detail with mechatronic products and incremental development.

4.2 Design task definition

A specification plays an essential role in development and engineering tasks. Different specification types have been introduced either for development or contractual purposes and which give scope and room for designers to work in. Hansen & Andreasen (2004) has reviewed the context and purpose of specifications and concluded seven approaches from different authors:

- Product functions and properties specification as an imagination of an ideal design solution (Hubka & Eder 1988, Pahl & Beitz 1996).
- Use of checklists for describing primary triggers from which the specification will evolve (Pugh 1991, Tjalve 1979).
- Re-use of a product design specification; taking an existing product as the starting point for a new version (McKay et al. 2001, Schachinger & Johannesson 2000).

- Requirements engineering; the involvement of users to comment and propose alternatives to design team proposals (Kaulio 1995).
- Voice of the customer; customer comments, the analysis of market trends and quality function deployment methods are used to capture perception and the experience gained from existing products for interpretation into specification (Hauser & Clausing 1988).
- Industrial design approach; the synthesis of activities and argumentation for the benefits of the products to be used in review meetings.
- Integrated product development; an integrated design process involving marketing research, engineering, designers and production specialists evaluating different viewpoints (Andreasen & Hein 1987).

Despite the different approaches, a consistent theory has not been developed and industrial practice differs from the methodologies presented in the literature, thus the importance of guiding product development is essential (Hansen & Andreasen 2004).

The engineering activities in today's industry are mainly targeted towards the development or modification of existing products rather than the creation of new world solutions. The design work is specification driven by the requirements. Weber (2005) has raised this issue with his CPM/PDD (Characteristics-Properties-Modelling/Property-Driven Development) approach to distinct developer's choices between product characteristics under his/her direct control and product properties under indirect control during the design process. The CPM/PDD approach represents the interrelations between characteristics and properties which are represented two- directionally; based on given or required properties, synthesis aims at establishing appropriate product characteristics and based on known or given characteristics analysis determines its properties.

A simplified presentation of a design approach within an adaptive design project in industry can be visualised as shown below [Figure 4.5].

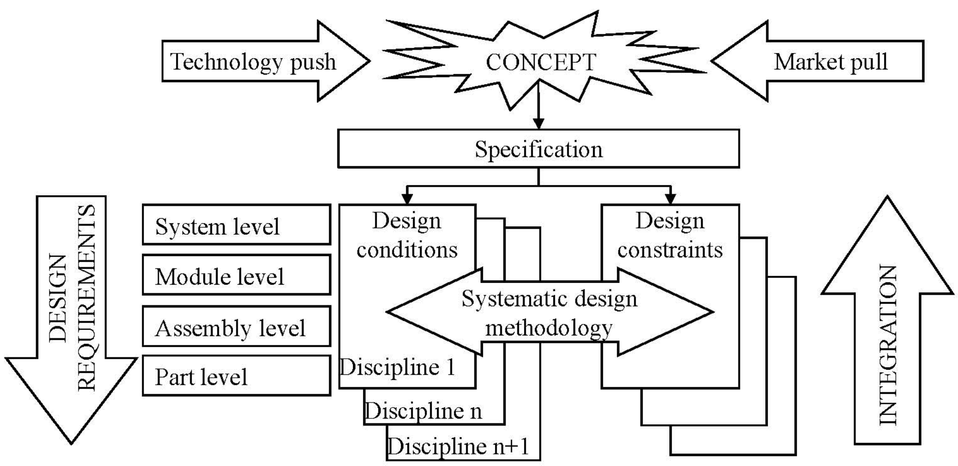


Figure 4.5 *An industrial design process in which the specified requirements flow from system level to parts level and the engineering challenges between design conditions and constraints.*

Basic product concepts are outlined promptly in a company's strategy, e.g. a crane company is supposed to develop lifting appliances, where the principal functions and properties are known. Naturally the technology push and market pull strive for new or innovative solutions – but within the scope. Once the product concept and the technical solution are defined, the design process flows from an upper level towards detailed design. Often, the division into disciplinary separation takes place already during the specification.

The hierarchy levels are shown, for example, by describing the flow of design requirements in detail. On each level, the design process follows a systematic methodology to find out an optimal solution, e.g. design conditions are reflected against design constraints. At this stage the design constraints cannot be changed: they are either based on standards (limit state), specifications (design margins), material properties (strength) or company practice (experience).

If we compare the formal VDI 2221 (1993) process and a typical industrial design process execution, we may raise several issues for further discussion:

- The formal design process begins with the function definition, which is not the case in industrial development projects. As the development activities within companies mainly focus on the further development of existing products, the functional structure, especially for overall function(s) exists. As the main functions are already known, the main activity is to develop alternative principle solutions for existing functions.
- The development of the physical structure of a product is driven from two viewpoints; the product management and configuration or manufacturability through modularization. Occasionally, but not necessarily, the modularization of previously mentioned drivers follows a functional structure; e.g. a module is constructed as a functional entity.
- The design requirements within the industrial design process flow from the upper system level towards detailed part design, which is a natural consequence of the concept and preliminary layout of the functional structure being defined as a prerequisite. The flow of requirements is divided to match with physical structural blocks (modules) and technology disciplines by means of interface definitions, which are expected to act as integration couriers towards the system level and result in the purposeful behaviour of the product.

This type of design process is built on the logic that the decomposition of the functional structure, and further detailed design into modules and parts, is explicitly reversible in order to result in the required overall function while parts and modules are composed together. It is claimed here that within this type of process, the solutions are directed to be developed as discipline-dependent, because the design conditions and constraints are set already during the specification. Hence, such systematic design methodology may provide innovative solutions, but only within each design level.

Within engineering design in industry, there exists a strong will to distinguish between development and design. Primarily the difference is with the timeline; if the aim of the engineering design is to create a new product to be offered within the portfolio (development), the schedule is internal to the company without contractual penalties from other parties. However, the development process includes uncertainties, which may lead to iteration loops or even drawbacks requiring alternative concepts. Alternatively, the design tasks may be considered in order to be straight forward and based on the specification, in which case the solutions are selected to be primarily on the "safe side" e.g. issues experienced earlier. As the design activities are predominantly adaptive and detailing, the break-down of tasks and their scheduling is easy.

Companies, which deal with the customization of products to fit them according to customer requirements, aim to distinguish adaptive design processes from development processes in order to avoid any uncertainties during the contract execution.

The follow-up of the development or design tasks execution is essential in industry. While the systematic development processes aims to control development tasks to fulfil customer requirements, the other dimension is to control the whole development project including other stakeholders. Primarily the scope of such a process is to ensure that the sequencing and complementation of tasks are confirmed before entering the next stage of the process [Figure 4.6] (Cooper 1990).

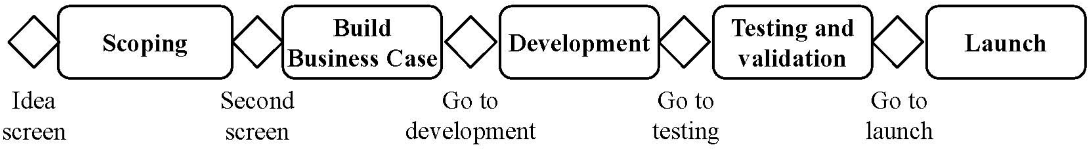


Figure 4.6 Stage-Gate process defining the inputs and outputs for complementation and permit of continuation of the activities. Adopted from Cooper (1990).

A product development project in industry is always a significant investment. Therefore the burden of activities is directed beforehand, e.g. a thorough analysis and planning is conducted prior to the start of the development and design phases. A natural consequence is that the early phases of a development process focus on preliminary study, conceptual design including the preliminary (feasible) technical solution and specification, which are followed with the final go-ahead decision or rejection of the project. In practice this means that the development process is divided into two main phases; conceptual design to generated specification and detailed design.

As discussed earlier, the purpose of the design task significantly influences the process and the approach with regard to how the development and design activities shall be arranged. Hubka (1988) classifies the technical systems, of which the design task requirements may be divided into three categories;

- Complexity in correlation to find a solution, which consists of an elementary system like single components, a simple system that can fulfil some higher functions, a system consisting of sub-assemblies performing a closed function, a complicated system that fulfils several functions and constitutes unity.
- The difficulty of designing, which contains the issues of the need for knowledge, skills and abilities to perform and plan the design work. The grouping depends on the complexity level of the systems, the criteria to assess the required originality, the complexity of functions, the forms and structures of the technical system, the difficulty of modelling and analysis, the physical size of the parts etc.
- The originality of the design, which refers to how it is re-used, adapted (variant), re-designed (change in structure) or original. Each of these reflects the implications and consequences related to economics, risks, hazards and reliability compared with previously designed and tested products.

Several other classification criteria for technical systems are presented, which influence the requirements of a designer, organization, manufacturing, logistics etc. However, when focusing on the creation of the technical system, the recognition of the task type influences how the work shall be managed. Consequently it should also offer advice, if the development process varies; e.g. can a similar type of systematic process be followed for all variations.

The complexity of the design task has been acknowledged with mechatronic engineering, whereby the implications of high integration become difficult to predict because of the lateral influences that dominate the hierarchical relationships [Figure 4.7] (Calvano & Philip 2004).

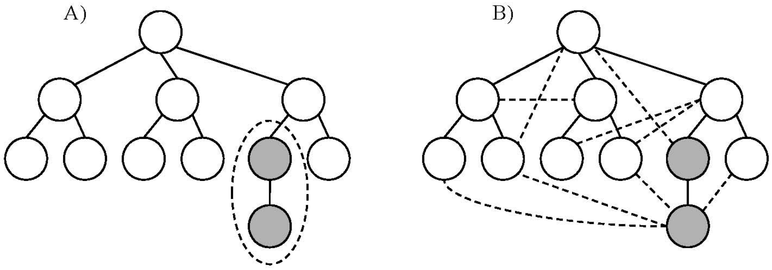


Figure 4.7 The impact of lateral dominance in highly integrated system (B) compared with hierarchical dominance (A). The interactions in highly integrated system may be different kinds compared with a hierarchical system. Adopted and modified from Calvano & Philip (2004).

> The interactions with a hierarchical structure are the result of functional decomposition and mainly present the physical relationship, which is also often constrained within one discipline. In a highly integrated structure, the physical interactions are complemented with a causal type of relationships over the hierarchical structural sections, or even between single elements in sections.

Similar conclusions with regard to unexpected interactions have been made with the development of multi-disciplinary products as the early separation into technological domains may become a hindrance to understand and estimate the impacts and connections of a highly integrated system (Reunanen 1993).

Industrial practitioners face the development problematic between static and dynamic concepts and mostly focus on their resources towards the incremental development of sub-systems within existing products (Pugh 1991). However, the methodology of this development process has not received great attention. Another aspect in industry is that, although originality in the concept and/or function is becoming more difficult to find, the pressure to use new technology applications is its natural consequence. However, even though multi or cross-disciplinary design teams have been acknowledged for a long time, it is recognized that each professional discipline still utilizes their own dedicated methodology to meet their own purposes and obligations during the design process.

4.3 Engineering disciplines and their integration

The product development process, once the mission statement has been established, starts with conceptualising and developing possible solutions. Different methods may then be used for decomposing the technical system into structures, which include the transformation processes, functions, organs and parts (Hubka & Eder 1988, Ulrich &

Eppinger 2003, Pahl & Beitz 1996). When the design process continues from abstract structures towards more concrete ones, the separation into technological disciplines may take place.

Each discipline has a long tradition through distinct education systems and has developed their own methodologies to focus on specific design problems. Bernardi et al. (2004) presents a comparison of development processes and their sequences [Table 4.2].

Table 4.2 Product development guideline for different disciplines. Basic development process phases between disciplines Adopted from Bernardi et al. (2004).

	Mechanics (VDI2221)	Electronics	Software Engineering
1	Clarifying and specifying problem	Specification	Problem definition
2	Detecting functions and structures	Description	Problem analysis
3	Finding solutions and principles	Algorithmic description	Requirements analysis
4	Structuring in feasible modules	Register interface description	Definition
5	Shaping important modules	Logic description	Design
6	Shaping product total	Transistor description	Implementing and components test
7	Manufacturing	Layout	Integrations and α-test
8		Manufacturing	β-test
9			Use and maintenance

The sequences with different disciplines cannot be compared as such; each of them has their own development history and dedication to their relevant design process stages. If we study the different approaches of each discipline and how the basis for the development is defined, it is significant that the functional aspect is drawn out only in mechanics. Consequently, the specifications for electronics and software engineering follow or are adapted from the mechanics. However, as the functional execution is controlled by software in mechatronic systems, the development is parallel thus separate and integration takes place during testing or commissioning.

As such, it is apparent that each discipline relies on the specification and early break-down of requirements for each of them. The known consequence is that integration into a final product cannot be successfully completed at once, which leads to corrective iterations and/or modifications.

The decomposition of the functional structure is followed by the development of the solution principles, which in generic product development processes ignores the multi-disciplinary view focusing mainly on a product's mechanical working principles. When the functional structure has been built, the development process, aiming to reduce complexity, splits the solutions into discipline dependent specifications and interfaces between disciplines [Figure 4.8].

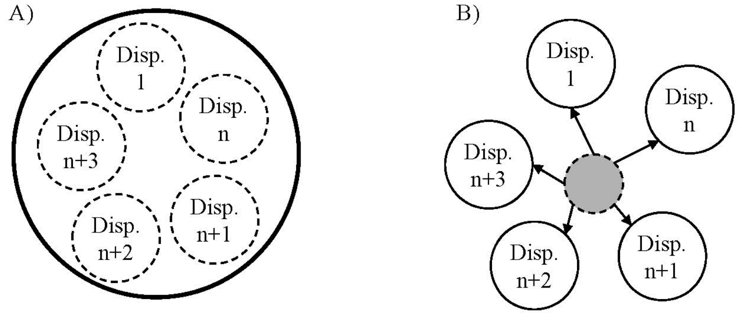


Figure 4.8 *Product entity as whole consisting of several disciplines (Disp. 1...n) before (A) and after (B) decomposition into discipline specific design specification and tasks during the development process.*

The more developed design process models like the VDI 2206 (2004) for mechatronic systems, introduce the V-shaped process adopted from software engineering. The process suggests concurrent methodology during design phases and integration at three levels; micro and macro cycles, and a process module. A cross domain solution concept is intended to describe the main physical and logical operating characteristics of the future product. As the design is divided into phases, the model emphasises the design validation and verification to be carried out in each design phase [Figure 4.9].

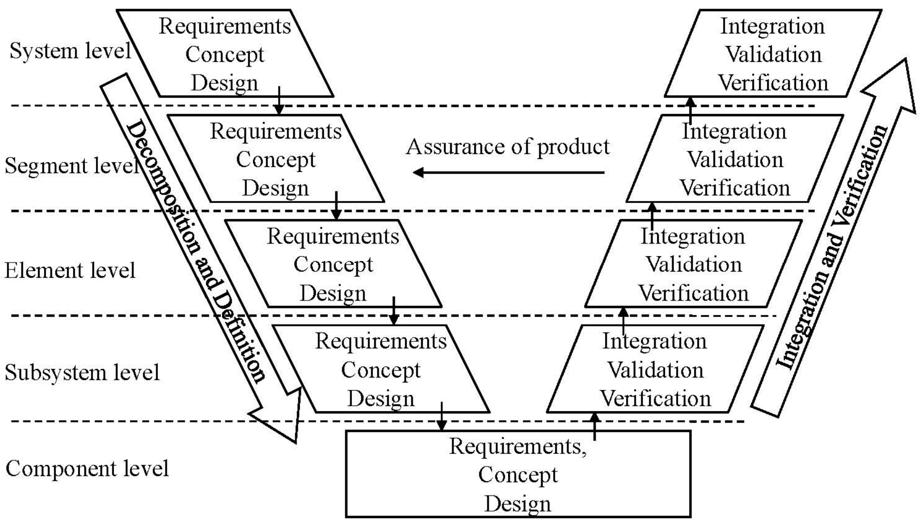


Figure 4.9 *The basic principle of the mechatronic product design process. Decomposition and validation according to the level of hierarchy. Adopted from VDI 2206 (2004).*

The main difference with sequential and linear processes is the verification during the phases and not only at the end of the full system integration, which decreases the probability of integration problems. However, the challenge with this model is how to develop the right verifiable requirements for the different levels of systems and elements. The links between the system, segment, element, sub-system and component level requirements may become an artificial hindrance to developers to cope with.

As a prerequisite for modern technical system engineering, professionals within different disciplines are taught to be more aware of other methodologies and realization means in the early stages of the design process. During the conceptual phase the crucial decisions on functions and properties are made, which are realized and integrated into the final product resulting in the experienced behaviour. The management of this integration in industry is often given to the mechanical chief engineer, who is responsible for the whole technical content of the product.

The generic product development processes approach the technical system as a hierarchical entity. Within the functional structure, the different technological areas are acknowledged, but their role and effect is assumed to be on other sub-systems or on the lower level in the structure. In an architectural aspect, the different disciplines are divided into their own entities or modules, which in turn lead to further sub-optimization within the module boundaries and interfaces.

The functional structure creates the principles for the product architecture, as the functional elements are identified and positioned into the physical product's structure. Once the separation into disciplines has taken place, it is a rather natural continuation that the physical structure is proposed in the form of blocks or modules involving the elements required for the function. This results in a set of assembled components within a greater entity, but having the nature of a single discipline.

As the disciplinary separation has taken place, all the following design activities are then consequences of earlier decisions. Each discipline follows the specification and pre-defined interfaces, naturally aiming for an optimized result. However, seldom is that any interaction or consensus exists between design teams, or is even encouraged by the engineering management. The general difficulty exists when a design problem calls for iteration because the borderlines separating the disciplines very effectively prevent communication, mainly because the iteration increases complexity and disturbance within the specification.

Product development processes have evolved and followed technology and social development, and during recent decades several systematic methodological approaches may be identified (Pahl & Beitz 1996):

- Need or problem oriented development, stepwise approach with continuous testing and balancing of contradictory requirements.
- Task division into subtasks and solution set reduction through evaluation, the introduction of abstract functions.
- Technical and economic criteria, function principles, problem definition towards solution variations, sub-functions, functions means, discipline integration.
- Problem formulation towards functional and embodiment phases, concurrent engineering.
- Integrated product development; multiple driver or stakeholder acknowledgement e.g. safety, reliability, environment, Design for X approaches.

The scope of systematic product development methodology has changed and expanded, but still a request for an improved methodology exists in industry; the speed of the technology development has increased and advanced solutions have become more and more attractive cost wise, which are taken into use when developing existing concepts and specifically multi-disciplinary products. As a general approach, the new development process shall be more focused on drivers such as product value elements and experienced behaviour in addition to functions and properties.

In conclusion, it is claimed that the primary causes which make the generic product development processes adaption linear and limit their application among industrial practitioners include:

- Development project management process strives to freeze the technical solution prior to actual development which leads to manage product architecture through the creation of physical single discipline blocks or modules.
- Professional disciplines and their development processes that aim to manage complexity by separating functional structures into different disciplines and defining interfaces between them. This directs design activities to partial optimization within the borderlines of each discipline.
- Development process approach aims to associate one-directional logic of requirements-specification-properties-characteristics whereby the purposeful behaviour is achieved later when physical integration of part structure is assembled.

This is in contradiction to the principal approaches to complex systems which consist of large numbers of parts that have many interactions, and in such systems the whole is more than the sum of parts (Simon 1996).

The implementation of several disciplines within one product concept is challenging and is followed by principal concerns on traditional product development processes.

> The realization of functions is no longer only the result of mechanisms, the definitions and modelling of function structure, product architecture and organ structure as well as part structure has to be reconsidered.

In consequence, it is obvious that the creation of innovative solutions may need to be initiated in a different way.

4.4 Incremental development

As briefly presented above, industrial product development seldom initiates from "scratch", e.g. scoping the market and generating product requirements from customer needs or an identified problem. Enterprises, specifically the ones which run their business on capital goods, direct their product development investment on developing existing products. In practice this means that the principal product concept exists and is known.

The initiation of incremental development has three basic drivers that result as a consequence of business economics;

- Customer dissatisfaction due to missing or aging product properties, quality, usability, reliability, maintainability, industrial design etc.
- Profitability pressure to compensate for price degradation, inflation, manufacturing cost increase etc.
- Change management due to technology aging or new technology utilization.

These drivers make a significant difference between new product development and incremental development, both in product development management on the enterprise level as well as product development process on the project level.

Many enterprises have dedicated research and development (R&D) sections with varying scopes depending on their resources and competence. However, as the new product development includes numerous financial, technical and scheduling risks, R&D activities on the enterprise level explore new technologies regardless of at what stage any particular product development project is. Consequently, new technologies and solutions are implemented into the subsystems of existing products according to the incremental development drivers. However, new technology introduction in existing products is only one driver for incremental development which leads that the development task setting, purpose and applicable methodologies differ from new product development.

> Idea generation and innovativeness are challenged to respond to the quest for enterprise success with the development of existing products or concepts.

Incremental development has received mild interest within the engineering literature, regardless of its need in industrial application. Hubka (1988) identified two major aspects for product development; the development of a particular technical system from idea to realization and developments over a longer time period as a succession of technological developments. The first aspect relates to new product development and the latter refers to incremental development. The technology development, evolution and the increase of the main useful functions and systems transitions were also presented by Altschuller (1996) as one element of the TRIZ- methodology for solving contradictions within problems or existing concepts.

Different product development types have been identified that have the distinction based on the influence of a product portfolio; new product platforms, derivatives from existing product platforms, incremental improvements and fundamentally new products (Ulrich & Eppinger 2003). In addition, Cooper (1993) has acknowledged types of repositioning and cost reduction. Furthermore, generic product development processes (Ulrich & Eppinger 2003, Pahl & Beitz 1996) focus on new product development, thus acknowledging the incremental aspect, but also suggesting the utilization of similar process flows and methods.

Multilevel hierarchical matrices were introduced by Eekels (1990) as a continuation of the basic design cycle, in which goal setting is followed with a stage analysis, a set of requirements, synthesis, simulation, evaluation, selection and implementation. When design problems exert pressure on many dimensions, they are difficult to address. Based on this approach, different viewpoints on design evaluation and environment were built into three-dimensional matrices – cubes – to map out the design domain. The two cubes, design and evaluation include the dimensions: basic design cycle – innovation career – aspect and design problem – design career – design object. As the primary purpose of the use of matrices is to structure evaluation and decisions over a design task, the multiple dimensions introduce the nature of different interactions within a design problem.

Pugh (1996) identified the conflict that exists with reference to the spectrum of design activities and in relation to the variety of the designer's boundaries within the conceptual envelope regarding innovatory or conventional design tasks [Figure 4.10].

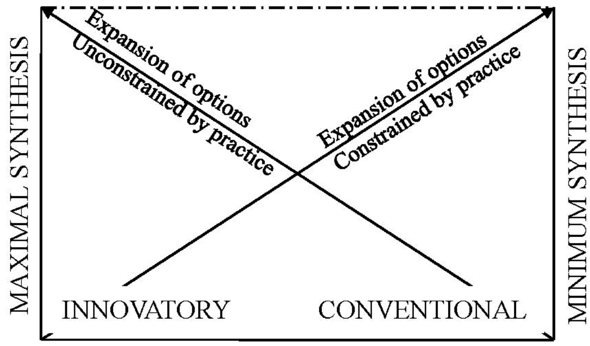


Figure 4.10 Variety of design tasks, the spectrum of design activities of innovatory for "white board approach" and conventional for re-engineering or re-use of proven solutions. Adopted from Pugh (1996).

The distinction between conceptual and embodiment design was raised by Pugh (1996) in reference to dynamic and static product concepts. The finding from industry was that mostly the tasks of embodiment design were already made during the conceptual stage with static concepts, and were more of a subset of conceptual design. For the management of development work, Pugh introduced the enhanced QFD (EQFD) concept selection method [Figure 4.11].

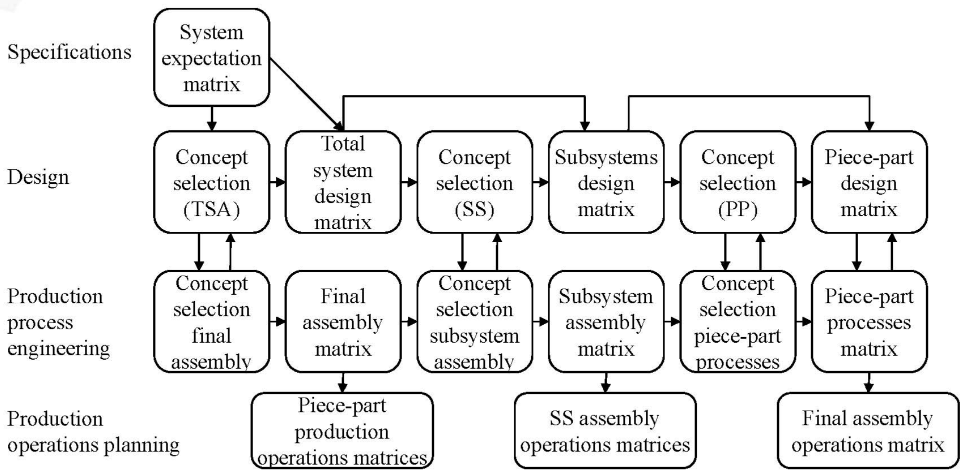


Figure 4.11 The basic process of EQFD, dividing the concept selection into total system architecture (TSA), subsystem (SS) and component (PP) levels, enabling the evaluation of static/dynamic concept on each level. Adopted from Pugh (1996).

The process model is an application of quality function deployment and decision dispersion into three levels of the system. The static and dynamic concept evaluation is also considered on each level and further development follows the previous concept and matrix. The total system expectations are built on the requirements received from the collection of the opinions of the customer. The sub-systems expectations are further led from the total system decisions into the matrix with total system expectations. The matrices are continued to the lowest part-piece level by decisions from the upper level and requirements from the current level (Pugh 1996).

Incremental development has the advantage of having a concept to build on and compare. However, a distinction between product improvements and incremental development needs to be made. Product improvements are the type of modifications which include the change of material, part content or manufacturing technology for lower costs or better quality, the improvement of some property or performance characteristic or other activity, which maintains the product concept and operating principle. In contrast, incremental development involves a partial conceptual modification, where the operational principle of the product or some subsystem is changed.

> The principal difference between incremental development and new product development is that the new product development process progresses from idea to solution and product, while the incremental development begins from a product or concept to idea and again to solution.

As said earlier, enterprises tend to bring developments through subsystems to existing products and therefore the design process has some analogy with types of reverse or re-engineering design.

Otto & Wood (1998) have presented an evolved process of reverse engineering and redesign methodology. The process consists of three phases; reverse engineering, modelling & analysis and redesign. The first phase includes investigation, predictions and a hypothesis, which assumes the product to be a black box that is experienced with respect to customer needs. During the second phase, the development of design models takes place, with which the analysis and experimentation are executed. The third phase initiates the product redesign based on the results of the earlier phases, either as parametric redesign, adaptive redesign or original redesign [Figure 4.12].

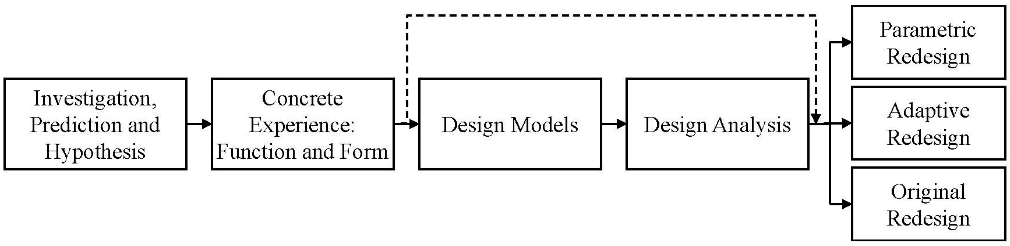


Figure 4.12 Reverse engineering and redesign methodology leading to parametric, adaptive or original redesign. Adopted from Otto & Wood (1998).

The methodology involves the reconsideration of functions and structure, the evaluation of properties utilizing quality function deployment (QFD) and the application of value engineering (VE). As any new solutions for functions are explored, the methodology proposes the use of brainstorming, discursive bias, morphological matrix and theory of inventive problem solving (TRIZ). As all previous tools are familiar from new product development, an additional view of functional modelling was introduced, which is the flow of physical phenomenon intrinsic to product operation. The context of flow in reverse engineering enables a reverse view on the design process, which moves from abstract to real, but here moves in the opposite direction.

In case of incremental development, the product and function structures already exist and the design process and documentation is strictly divided into technological disciplines: mechanical, electrical and control systems. This separation is a natural result of discipline based product specifications and development teams. However, function structures may be directed towards the separation of disciplines already during the conceptualization stage.

4.5 Conclusions

In this chapter different product development processes are studied in respect for the type of the design task, disciplinary acknowledgement and industrial practise. Different studies have contributed to the area of product complexity and found challenges in managing the design process. The generic design processes focus on new product development that initiates from the identification of needs. Less attention has been given to the industrial approach; process development, multi-disciplinary products and incremental development.

Furthermore, the theory of technical systems does not classify transformation processes differently according to how many disciplines are involved or how many times or in which order the technical processes are involved in order to achieve the desired state of the operand after the transformation process. Additionally, incremental development challenges the generic processes with a different approach to alternative or new solution identification, as the methodology of new product development originates from different sources.

However, even cross- or multi-disciplinary teams have been involved in development projects in industry; their typical problems in project execution include the following issues:

- The adaption of the staged development process emphasizes the role of the development specification with the product technical concept, which prevents innovativeness later.
- The assumption that the design process is linear and unidirectional, where the total entity of the product is divided into hierarchical subsystems, which when combined will conclude the total product with desired properties.
- Design specifications and tasks are separated by technology and discipline, which lead to sub-optimization within the disciplines. Accordingly, each discipline has their own methods and models to focus on their specific design tasks.
- There is lack of practical, context sensitive ideation tools for new or alternative solution finding, specifically with incremental development.
- The functional properties of a static concept cannot be significantly improved by optimization within a single technology or discipline.
- Generic product development processes ignore technology integration and its impacts.

The incremental development of multi-disciplinary products differs clearly from new product development and expands the requirements for the design process to manage complexity. This identification and understanding about the design problem challenges the communication and modelling of the transformation processes in and between the development teams. Accordingly, three aspects are suggested in order to develop a more applicable design method for multi-disciplinary products in an incremental way:

- Method of describing, defining and analyzing functional interfaces, and the interdependence that exists and impacts that occur between technologies and disciplines.
- Method of identifying the real function execution chain which activates the transformation process from initiation to the end state.

- Method of identifying and describing experienced behaviour, e.g. how and with what consequences the transformation process performs.

As a result, the development of existing concepts may be directed more systematically to the identification of opportunity with multi-disciplinary integration and create a new dimension that can improve product value for stakeholders and not only focus on functions and properties from a technical aspect. The following chapters will look in greater detail into approaches that initiate alternative solution exploration for static concepts.

5 Product Concept Development

While initiating a product development project, the different organizations in an enterprise have a different opinion and viewpoint as to what a product concept is. Management consider the product concept as a means for business transactions, for which the operational environment shall be organized in the most effective way. For marketing and sales the product concept is a tactical tool for coping with variations and options in competition with other vendors on the market.

The viewpoint of engineering is technical, i.e. how functions and properties meet requirements and how the product architecture is to be organized to provide possible tailoring opportunities and cope with manufacturing systems. Manufacturing, logistics and assembly are the first to deal with a concrete artefact and its components and look at how manufacturing technology may be utilized.

As the results of product development are versatile and crucial for the success of an enterprise, the different conceptual viewpoints need to be considered as the product originating process is initiated. Rapid technological development and its integration in various products is present, which gives an additional viewpoint on conceptual development. In addition, the product functions are not more the result of easily visualized mechanical systems, they consist of various integrations from different disciplines. Accordingly, the products intended for transformation processes, which generate added value, require maintenance and upgrade capabilities during their life cycle.

Product developers should be the best experts for coping with all the relevant issues for creating successful products. However, any development activity on a product has to focus on the production of value improvement for one or more stakeholder in order to maintain market position and business continuation. Product concept development plays an essential role as a framework for discussion and co-operation within and between different organization's functions.

5.1 Introduction

The concept, in terms of engineering design, is a line diagram of a proposal for solving a problem. This presentation is a transition stage from function structure towards the preliminary layout of a technical system, where the organs are visible but the final arrangement and dimensions are to be defined later (Hubka & Eder 1988).

More specifically, Pahl & Beitz (1996) draw a product concept as a description of the product purpose and function. The concept is the determination of the principle of the solution made by abstracting the essential problems, establishing function structures, searching for suitable working principles and combining those principles into a working structure. Within product development, the concept includes specifications, characteristics and properties in the format of written text, graphs and/or tables.

Beyond the traditional definitions, Hatchuel & Weil (2009) prefer to use "concept" as an *innovate proposition to be used as a basis for initiating a design project*. This approach is further utilized with their C-K Theory and modelling the interplay between the concept and knowledge.

The content of a product concept may also be seen as a stage during the product originating process. If expanded beyond the use stage to include business aspects and product life cycles e.g. market, manufacture and sales, numerous product characteristics may be identified at different system's levels and life cycle aspects [Figure 5.1] (Olesen 1992).

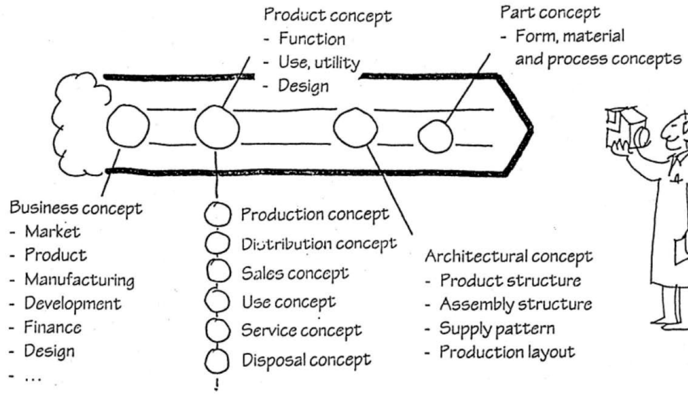


Figure 5.1 The content of the concept along different product life cycle stages for product development. Challenge for development team to cope with different stakeholders and viewpoints. Adopted from Olesen (1992).

Thus, product or business concept development may be differentiated with respect to their appearance along a time horizon. Kokkonen et al. (2005) make a distinction between visionary, developing, definitive and constraining concepts, where each is based on an alternative scenario. The concept creation for business and product levels based on scenarios takes into account the difficulty of forecasting the future and the risks involved and accordingly different tools are needed for each concept creation.

Therefore the identification of different concepts may be presented and the decisions for the product development are then made at the very early stages of the development process. However, the development teams may find it very challenging to interpret and apply various, and even contradictory requirements in specifications.

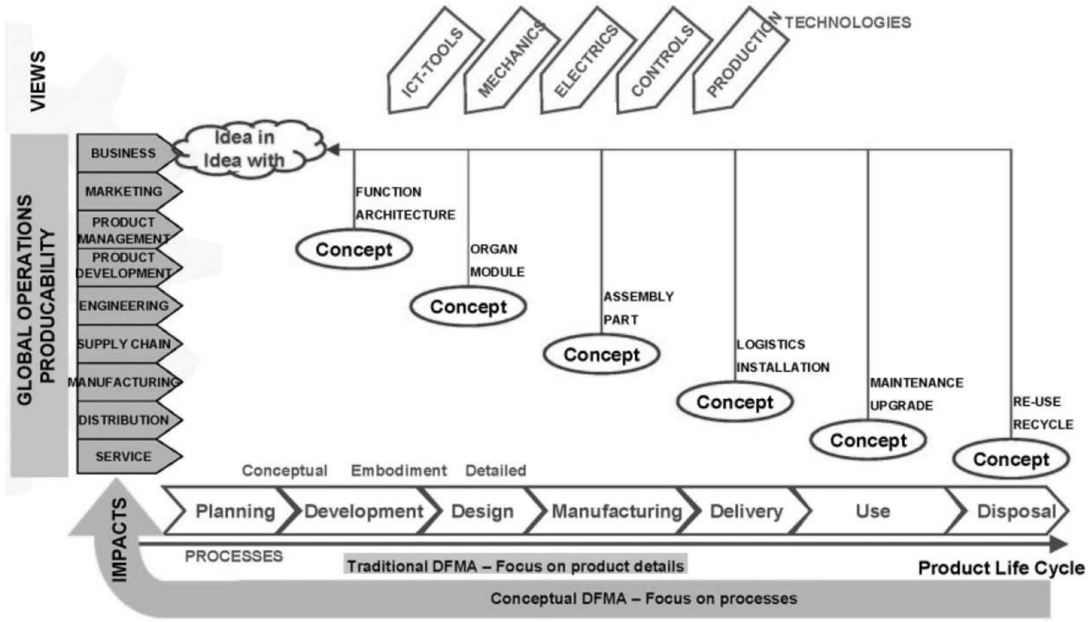


Figure 5.2 Different product concepts during the product life cycle, influenced by organizational viewpoints and technologies to be applied during product development. Adapted from Suistoranta & Oja (2006).

The Conceptual DFMA research project (2005-2008) recognized the multi-concept approach [Figure 5.2], where a product's conceptual development is influenced by all life cycle stages, organizational viewpoints and different technologies. However, the product properties to be included need consideration at the beginning of the origination process, even if their impacts and influence may only be clearly recognized, at a certain time, later in the life cycle (Suistoranta & Oja 2006). As said, numerous conceptual elements can be identified which all influence the business processes and the preferences and selection depend on the various drivers determined by the company or its stakeholders. Each conceptual element and/or driver also impacts on the product development process, on which the product development teams shall focus.

> Eventually, the product developer at his/her workspace makes the choices and decisions within the technical context of the product concept to meet the versatile multi-concept requirements.

Engineers prefer to design and optimize with quantitative measures to meet given targets. Therefore product specifications are expected and requested for more prompt definitions concept requirements and properties to ensure a successful and measurable development project.

The success of a development project has two distinct measures, which unfortunately cannot be justified simultaneously;

- How the development project targets are met. In other words, the realizations as they compare with the specifications and project execution.
- How the market, sales and profitability targets are met. In other words, the meeting of customer expectations and acceptance compared with the manufacturing costs.

The evaluation of the first measure takes place when the results are released for manufacturing and the latter well after the product launch on the marketplace. To be more specific, the value of the concept is not static and dependent only on the internal actions of an enterprise. The value of the concept is consecutively measured in every transaction event against the comparable products available on the market, which defines a floating yardstick along the life cycle. However, each enterprise chooses and applies their marketing strategy according to the most attractive product properties or services.

During the initial product launch, a concept should provide better value than its competitors to penetrate into the market and gain sales. The higher the production volume is the more it can provide the economies of scale to enable quality improvements and the decrease of manufacturing costs. However, in the marketplace, competitors will react to change relative to product positioning and take actions to improve their product value. The resulting competition causes the relative position of competing products to fluctuate as long as the product is in the portfolio of the enterprises.

> The technical concept of the product is continuously challenged to be improved by the value approach during the originating process to compete in the market place rather than requirements created by needs.

5.2 Product concept evolution

The evolution of the means to fulfil human needs has numerous examples in literature. As a reference, Hubka & Eder (1988) present the development of logging or forestry and draw out aspects for examining the development of technical systems;

- Technology; the application of effectors to a dedicated situation to produce change.
- Technical means employed; the ways in which changes in a situation are accomplished.
- One set of technical means; the realization of a single sequence of sub-processes which were commonly used at the time.
- The sequence of operations; a viable sequence of transformations needed for the change.
- The mode of action; the principle of the action to be applied by different technical means.
- Description of the process; an illustration that represents the process.

While Hubka & Eder's example describes the evolution of a process as a whole, the development of a technical system by a development team may be outlined to consider the aspects of the technical means, the sequence of operations and mode of action.

Technical product concept evolution over time is represented with a series of S-curves illustrating performance improvements within a product and a discontinuous jump up to the next level with a new product (Foster 1987). The improvements within the product are said to be the result of minor modifications based on customer responses and the jump with the new product can be seen as the result of an application of new technology or a fundamental change in product architecture (Otto & Wood 1998).

However, the product evolution aspect also includes other viewpoints than just the customer. As described earlier, the product efficiency is one element in product value consideration for customers, which is also relative to competition within the marketplace. This refers to the situation, when a manufacturer aims to maintain market attractiveness through customer value improvements; it also has to put effort into reducing cost accumulation while producing a value creation.

A product's value decreases along its life cycle due to altering and competitive actions. The same applies to profitability resulting from price degradation and cost increases. When considering the two viewpoints, product value and cost, the manufacturer has several options to impact on the value-cost positioning of the concept.

A concept (A) includes a chosen structure and set of elements to define its realization of one possible solution (a dot in the ellipse), which has a limited sphere on the value-cost scale (ellipse). The development activity can aim to create a new or modified concept for a significantly lower cost (B), improved value (C) or a combination of these (D) (Suistoranta & Oja 2006) [Figure 5.3].

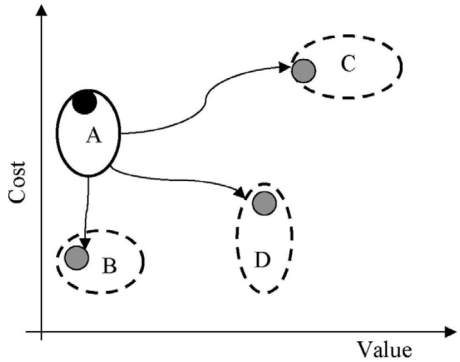


Figure 5.3 *Concept development alternatives to improve value, decrease cost or the combination of both. Adopted from Suistoranta & Oja (2006).*

The development potential with continuous improvement methods on the value-cost scale of each concept is limited and presents the contradiction between value and cost that; within one concept the cost decrease cannot significantly improve value. The transition to a new level through value or cost requires a change in concept.

In industry, new concepts are unique and rarely introduced, and more often it is the case that the product concepts have matured and reached their static (Pugh 1996) or dominant (Utterback 1994) stage. The maturing process of a concept takes place like a natural elimination, while during the new product growth stage the number of different introduced concepts shrinks to a few or only one. Therefore the improvements of the static investment and consumer goods concepts take place through the development of internal sub-systems. Accordingly, the realization of value improvements and/or cost decrease is enabled with new sub-concepts and is recognized by the relative value change.

The two dimensions, value and cost, are in the business environment not absolute; they vary and the development drivers vary case by case and at different times. However, the two business drivers for product development may be concluded as:

- The product value improvement (improved product functions and properties to meet increased customer requirements and/or diversification from competitors).
- Decreasing the cost of value realization (profitability pressure and/or technology development).

The relative variation of the product value during the life cycle of a product can therefore be explained by changes in product sub-systems, in which evolution behaves on the micro level as product evolution on the macro level [Figure 5.4].

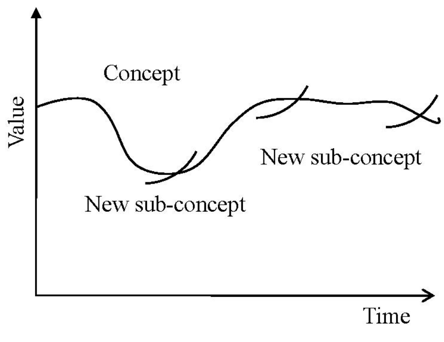


Figure 5.4 *Development of product positioning on the value scale through new sub-system concepts.*

Complex products consist of the different nested hierarchy of subsystems, which undergo technology cycles and impact on product value through incremental developments within one dominant design. The interactions within and between the systems have been identified, thus the approach concludes that the standardization of core components and interfaces leads to modularization and benefits that direct development activities beyond the dominant core components (Murmann & Frenken 2006). However, this approach can be argued in respect for Hubka & Eder's (1988) evolution aspects i.e. limiting the development work within one set of technical means (one module or discipline), commonly leads to a linear optimization process within one subsystem.

5.3 Product properties and the technical transformation process

The theory of the technical systems includes all types of technical systems and does not make any distinction between technologies nor disciplines. The evolution and development of technology has enabled different types of combinations for designers to realize the transformation process.

If we consider the two dimensions of the classification of the technical systems; the degree of complexity and the difficulty of the design task, we may notice that the challenge to understand, present, communicate and model the technical system increases. While the developers have their specific specialization according to their discipline, the transformation process of a technical system involving more than one technological discipline becomes problematic with current methods based on functions.

However, the solution with the implementation of multiple disciplines is created by the designer's decision and is not any peculiarity within the theory of technical systems. Different approaches to products (or technical transformation processes) with various disciplines are considered below.

The theory of technical systems presented by Hubka & Eder (1988) introduced the transformation process for an operand from an existing state to a desired state through a process consisting of interactions with systems that are human (HuS), technical (TeS), information (InS) and management (MaS) [Figure 5.5].

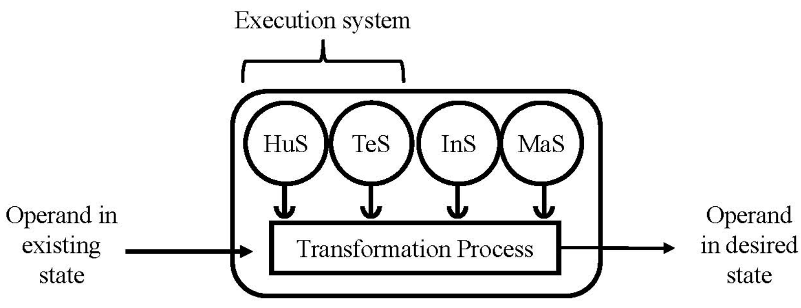


Figure 5.5 Model of the technical transformation system. Mechanism to transform operand from the existing state to the desired state. Adopted from Hubka & Eder (1988).

In a technical system, all operators interact with each other by exchanging material, energy and information. In the technical system, assisting inputs are available for the transformation process and each of the system operators. With secondary, inputs the synergies in the system complete the purpose.

The relationship between properties and their adaptation to existing conditions is essential to reach the required effects of the technical system. Hubka & Eder (1988) distinguish three classes of properties that are affected by the demands of the environment;

- Design properties, which are elementary design and manufacturing properties.
- Internal properties, which are supporting properties that connect design and external properties.
- External properties, which are economic properties that meet external pressure.

The numerous properties may be classified in many ways into different categories, depending on the viewpoint of interest. Some of the properties a development engineer can influence directly, but some he/she has to address indirectly in order to affect with his/her selections and decisions.

As the product is designed to serve a certain purpose, the technical system must provide a purposeful behaviour by means of its functions. The functions are realized with the system structure consisting of a set of connected elements. Accordingly, the behaviour of the system is determined by its structure. As Hubka & Eder (1988) define; *the behaviour of a technical system is always directed towards executing a set of transformations. Behaviour is determinate and controllable under normal circumstances, except if the system is damaged in any way.*

Within a technical system, purposeful behaviour requires both the sum of the behaviours of the elements and the coupling relationship of those elements (Hubka & Eder 1988). However, every technical system is hierarchical and every system consists of sub-systems, divided further into sub-systems, which have a meaningful purpose (Eder & Hosnedl 2007).

Three basic statements of a technical system challenge development engineers in their efforts to reach their goal to construct a product;

- The hierarchies of the system: The decomposition of a technical system is made based on its functional structure, e.g. the definition of functions to fulfil the specified requirements. As a consequence, this break-down creates a natural hierarchy of the mechanical system through sub-systems or functions. The hierarchy also enables the simplification and parallel engineering of complex systems on different levels or disciplines.
- The purposeful behaviour of elements: An element, may be interpreted here as a sub-system, assembly or single part, for which the decomposition has given its specific requirements. The engineering activity aims for an optimal solution within the sphere of the element according to the down-to-top approach, e.g. with optimal elements the combination should perform.
- The relationship between elements: The relationships between elements are versatile and complicated. As the relationships can be physical, causal, consequent or unattended, their definitions are given on a higher level based on the hierarchical structure. Due to this, the system approach is divided in a top-down manner.

As the behaviour of the systems results from the functions, there exist various different technical means (concepts) on how to realize the product function. As the first step for a product developer is to explore and generate feasible solutions, develop alternatives and finally choose one. The concept in this purpose means the “black box” of the transformation process, in which the operand is changed from its existing state to the desired state.

The concept can involve different functional structures divided between main and auxiliary functions. These functions can all call for different organ and component solutions. The evaluation and comparison between alternative concepts may take place with a different analysis. According to the theory of the technical systems, an ideal solution may be considered as a reference. The ideal solution is described by several authors (Hubka & Eder 1988, Altshuller 1996, Nadler 1963) as a solution that provides function with zero effort.

> The design drivers or stakeholders' preferences strive to accept compromises and sacrifices with solutions in industry.

Thus, we understand that the ideal solution is not reachable or absolutely measurable. The evaluation of a concept is always relative and depends on time and context.

5.4 Evolution from mechanical to mechatronic product

The context of the function in machines has its origin in mechanical structures. This has led to the principal methodology among engineers to break down functions into more simple sub-structures that either decrease complexity or achieve more robust design with uncoupled design parameters (Pugh 1996).

The realization of the function of modern machines introduced during last decade is mainly executed through programmable logic controllers (PLC). It is clear that function, or more specifically; the purposeful behaviour, is no more delivered only by mechanical structures. As the control system governs the details of the functional execution, they also play a significant role in how the purposeful behaviour (performance) and internal and external consequences (loadings, impacts) are experienced. Modern control technology has been seen as an enabler for improving product value and decreasing the cost of realization – even simultaneously.

The development and phases of technology among machine power train systems may be presented in order to illustrate the expanding relationships between technical system elements, which challenges the engineers currently have addressed.

Direct energy utilization

Every machine with functions consists of one or more mechanisms, which are actuated by a direct force flow from a source. A primitive way of directing the force flow is mechanical, origination either from rotational torque or linear force, e.g. a wheel, lever or cylinder. During the function initiation, the start of the actuation, the force flow is uncontrollable and the behaviour of the system depends on the physical characteristics of the mechanism and the related subsequent system parts. The function suffers from lack of control in connection by force, speed and acceleration, which causes inconvenience with regard to positioning, accuracy, displacements and vibrations, and results in poor performance. Within the history of industrialization, many practical examples may be found.

Mechanical adjustment

As the problems with direct force flow control were experienced, the next development aims to create the means to smoothen rapid actuations by decreasing acceleration and deceleration. This was achieved simply by adding inertia to the movable elements, stepped transmissions or applying throttle type of devices along the force flow, e.g. the use of (friction) clutches or adjustable valves. By this, the speed of the function could be varied and/or the initiation sequence could be extended over a longer timeframe. Accordingly, part of the power was transformed into another type of energy, typically heat, but with limited characteristics and lower efficiency.

Electrical adjustment

The expanded utilization of electrical motors, such as resistance and thyristor controllers for DC motors, multi-pole stepped speed AC motors, electrical soft starters and variable speed converters, provide the inbuilt property of stepped or stepless speed control enabling requirement based speed selection. This step in technology development may be considered one of the most critical stages for engineering management, as the clear distinction between mechanical and electrical engineering occurs due to the force flow control being turned into an invisible format in the electrical system.

Programmable adjustment

The introduction of programmable logic controllers (PLC) in machine control enables system adaptation into the actual state or mode, semi-automatic or automatic sequences and even autonomous operation with almost endless opportunities for adding product properties. However, as the first distinction between disciplines took place earlier, controller technology involved a new group of specialists that actually govern functions and behaviour. Although the utilization of various decision logics in machine control enables to challenge traditional design criteria and the realization of properties, the roles and integration of different technologies and disciplines in technical systems become more essential.

Each stage of the development of power train systems introduced a new technology into the realization of the function and properties, which has resulted in the accumulation of different disciplines into one product – creating a multi-disciplinary product.

The term ‘mechatronic’ was presented and defined by Buur (1990); Mechatronic is a technology which combines mechanics with electronics and information technology to form both functional interaction and spatial integration in components, modules, products and systems. Even though the terminology is more familiar within robotics and smaller devices, it is applicable and common today in all machine industry.

The introduction of multi-disciplinary approaches to machine systems has significantly improved product function and properties; simultaneously the complexity of engineering management has increased due to new interactions and impacts between disciplines.

Designers today shall be more aware of the applications and solutions of other disciplines, especially during the conceptual phase. While the product specification is being established, the mental intention among development groups is to begin the break-down of specifications into structure, which is followed by the technological disciplinary split and management of integrations with interface definitions. This addresses a problem; who is responsible for managing and coordinating the final integration which results in the desired purposeful behaviour of the product and with what means can this be ensured?

Generic product development processes are rather weak from the practical point of view, even though they have identified the problem and introduced frameworks with the system hierarchy and verification accordingly. Technical systems with multi-disciplinary technology applications create very challenging environment and requirements for product development and engineering management, in regard to which we can address the following questions:

- How does a multi-disciplinary concept affect on the definition of function, functional structure and properties?
- How does a multi-disciplinary concept affect on the product architecture?
- How does a multi-disciplinary concept affect on the product assembly and part structure?

From a product developer's viewpoint it may be concluded that multi-technology implementation, product value and purposeful behaviour is not dependent solely on the physical functional structure of the system. This leads us to the conclusion that a new concept for fulfilling business drivers for value improvement or cost reduction shall involve an integrated approach and the management of all technological disciplines applied in a system.

5.5 Conceptual design of multi-disciplinary products

When examining the conceptual design phase, we may understand that industrial product development initiation is driven by value and/or cost pressure. Accordingly, the starting point is on existing products, concepts or partial new technology implementation. As described earlier, in reference to the product or concept life cycle, existing concepts have several evolution stages that they passed through. Accordingly, it may be concluded that with existing concepts numerous improvements and optimizations within different disciplines to reduce costs and improve performance have taken place.

Depending on the maturity of a concept, the improvement steps and effects between generations or evolutions is becoming smaller and smaller. Sometimes optimizations within a discipline have caused unexpected or negative changes in product behaviour, which indicates that the single disciplinary approach has come to its end (Liedholm 1999). This is typically the result of a linear product development process, which has ignored the dependences and integrations between different technologies.

Incremental development actions and continuous improvements are a necessity for maintaining a product's competitiveness; however these development actions have to be sufficient to reach the necessary changes in organ and/or part level of a product structure. The main challenge for further development is to break out of the linear product development process which restricts the opportunities and innovativeness of a development team.

> With multi-disciplinary products, the development perspective has to be enlarged across disciplinary borders to enable changes with the purposeful behaviour.

This type of changes involves a new approach in generating innovative solutions even for mature concepts. A multi-disciplinary approach provides enormous opportunities to enhance product's purposeful behaviour and realization, but it also challenges the conventional means to convert requirements into concepts. Specifically, this challenge calls for a more specific approach to function and how function is delivered throughout the product - a missing or an unutilized means to recognizing opportunities beyond the generic development processes.

In technical systems, the functional break-down and structure contain the ability to transform an operand from its current state to a desired stage through a process involving the inputs of different systems. However, as the focus is on the means of changing the state, less attention will be placed on how the change takes place. Function also has various modes, which are the consequences of each structural element and the interactions between them.

As described earlier by simple examples with the evolution of the power train system, we may notice that a linear, unidirectional design process leads to a consecutive action chain that is lacking in feedback and iteration. This process pattern has to be broken to enable the recognition of how the product behaviour is executed. In other words, this requires a description model or language of the functional delivery mechanism from activation to physical action.

The function delivery mechanism is no longer a break-down of the functions, a set of technical means or a part structure. Once that is acknowledged, the design process shall be able to focus more on how the function, properties and performance characteristics are realized.

With the study of dominant design, Murman & Frenken (2006) have referred to the approach developed by Polanyi (1958) that states that the differentiation and classification between concepts shall be made according to the operational principle. The operational principle enables the distinguishing between the product variations within a product class that shares the same operational principle from variations between product classes that are characterized by different operational principles.

The term 'operational principle' has a direct analogy when we make a distinction between concepts. The physical part structure which realizes the mode of action may be equal between different products or concepts, however, in the case of a multi-disciplinary product the differentiation between two concepts may result from other technologies or disciplines and make a significant difference to product behaviour by the operational principle in function execution. This approach has received rather low attention while the technical transformation process and functions are considered in generic product development processes.

> A different operational principle within the same physical structure may result in a significantly different response and behaviour.

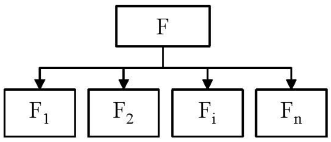
Therefore, the consideration of the operational principle shall be an essential part of the conceptual design while generating alternative solutions.

When the important difference between different concepts is the behaviour, a new measure for evaluating this difference is required. A measure like "experienced behaviour" may combine the two domains of design and reality as the behaviour is evaluated with the consequences, interactions and impacts that occur between the different disciplines.

5.6 Product concept development methods

Systematic design methodologies for a technical system development examine the functions that are required to transform an operand from its current stage to the desired stage. Within a generic new product development, the methods and various creative and systematic techniques are introduced to generate solutions (Hubka & Eder 1982, Pahl & Beitz 1996). These methods approach the development task from "scratch", meaning that no previous solution is utilized as a starting point.

Concept development is based on the break-down of the functional structure, for which the solution alternatives are explored. Further on, as alternative solutions have been identified, different combinations of sub-functions are evaluated for the realization of the required overall function or behaviour [Figure 5.6] (Pahl & Beitz 1996).



Solutions / Sub-functions		**1**	**2**	**j**		**m**
1	F_1	S_{11}	S_{12}	S_{1j}		S_{1m}
2	F_2	S_{21}	S_{22}	S_{2j}		S_{2m}
i	F_i	S_{i1}	S_{i2}	S_{ij}		S_{im}
n	F_n	S_{n1}	S_{n2}	S_{nj}		S_{nm}

Figure 5.6 Functional structure broken down as black box sub-functions and classification scheme to organize solution alternatives towards Morphological graph to combine concepts. Adopted from Pahl & Beitz (1996).

As noted before, a typical industrial development project originates from other drivers, typically the need for performance improvements and/or cost pressure. Concept development based on existing solutions and the search for better alternatives are essential for maintaining the competitiveness of products. Like any development activity, concept development begins with an analysis of the current state and then evaluates how product functions and properties are built into the technical system, how the functional structure is built and how relations between sub-functions and system modules interact. The various techniques, which may be applied in search of product improvements and as a basis for concept development, are presented:

QFD

Quality Function Deployment (QFD) provides a methodology for assessing how product properties can be interpreted as measuring design parameters. When fully utilized, QFD provides a comprehensive matrix that can compare and judge the importance of different product properties, different solutions and benchmark against competing products

The utilization of QFD provides a systematic tool for developing product quality by identifying properties which are either in contrast with the requirements or in conflict with another property. The methodology provides a measurable means to understand customer requirements and maximize those positive qualities that add value [Figure 5.7] (Akao 1990).

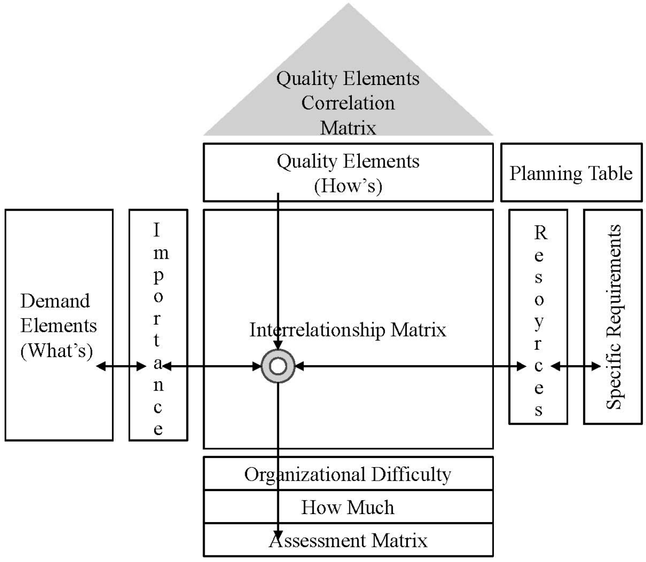


Figure 5.7 QFD, the elements of the house of quality showing the principles how design requirements and their impact on a design concept is evaluated. Adopted from Akao (1990).

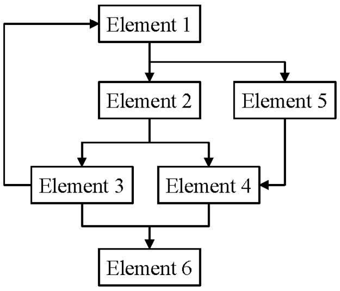
However, as QFD aims to provide explicit measures for a designer, the principle of the defining product into properties which can be characterized with one or few design parameters is challenging. For instance, how can interactions between functions and properties be considered? QFD has a similarity with the axiomatic design principle, in which the isolation of design parameters aims for robust and stable design (Suh 1990).

With QFD, once the product and its most important properties are separated and their parameters set, the importance of the evaluation guides subsequent development actions. The weakness of the tool is similar to all numerical assessment methods in that the results reflect the opinions and preferences of the one who made the selection of the grading and weighting of each property. As it has been widely applied over decades, QFD has great advantages for comparing properties and identifying potential development issues, its utilization for generating or developing alternative solutions is poor.

Dependency matrices (DSM)

Interactions and impacts modelling method, Design or Dependency Structure Matrix (DSM) in various forms originates back to the 1960s (Steward 1981). Due to a wider attention given to the design process-modelling arena, the DSM-method was developed through research at the Massachuset Institute of Technology. (McCord & Eppinger 1993, Pimmler & Eppinger 1995).

The origin of DSM was based on the graphical modelling of a system with elements, which are assumed to completely describe a system and characterize its behaviour. The elements are connected with nodes to present relationships between them. The directionality of influence is shown by an arrow, in comparison to a simple link which is shown without arrows. The later format of the dependency between elements in a matrix representation becomes binary, and in the matrix layout the system elements names are placed down the side of the matrix as row headings and across the top as column headings in the same order. If there exists a relationship from one element to another, the value of the crossing element is 1 (or x), otherwise zero (or empty) [Figure 5.8].



	Element 1	Element 2	Element 3	Element 4	Element 5	Element 6
Element 1		x			x	
Element 2			x	x		
Element 3	x					x
Element 4						x
Element 5				x		
Element 6						

Figure 5.8 Presentations of Design Structure Graph and Design Structure Matrix visualizing the relationship between system elements. Adopted and modified from DSMweb (2009).

Binary DSM-matrices can represent the presence or absence of a dependency between pairs of elements in a system and the ability to provide a more systematic mapping through the organization or grouping of system elements. Various applications, examples and further developments of DSM matrices have been presented widely in the literature.

While the development and application of matrices has expanded, the context has also changed; the dependencies are no longer directional, e.g. the structure of the product is considered static and the relevance of which elements are important to each other can be determined (Lehtonen 2007).

Malmqvist (2002) recognizes different methods of analysis with dependency structure matrices, i.e. clustering, partitioning coverage, index computation, interaction, change propagation and alignment, of which the latter three may be more applicable to concept development as they focus on the element relations and effects of change.

However, although the application of matrix methods is rather easy and their advantage, especially with element clustering is clear, the problem of what relations should be examined and how the results may be applied to concept development is ambiguous. This is addressed as the concept development takes place at an early stage of development, and thus the analysis of detailed elements enlarges the matrix presentations beyond a practical size. That also occurs with the Multiple Domain Matrix presentation when it aims to define several domains or disciplines.

Function Analysis System Techniques (FAST)

The design strategies approach the exploration of requirements fulfilment through the functional view. Accordingly, the concept modelling and analysis method that uses that viewpoint is found in literature. Already in the 1960s Bythaway (2005) introduced one of the first analysis methods, Function Analysis System Technique Diagram (FAST). The first applications were used for Value Engineering, but were proposed as being also successful for Engineering Design or any systematic design strategy. The systematic design strategy establishes a functional structure from the input-output nature and should be solution neutral. The FAST diagram aims to prioritize the objectives or functions of a product, it is possible to evaluate from the options which would return the most value based or predetermined value, namely;

- Targeting true customer needs and wants.
- Delivering requirements but still enabling cost reduction by focusing on "what the function accomplishes" versus "what the product is".

- The elimination of unimportant requirements.
- Adding incremental costs to achieve a larger performance benefit.
- Improving performance and reducing cost simultaneously.

The difference between FAST and functional decomposition is the two opposite approaches; as the functional decomposition from the left builds on how the functions will be accomplished, the approach from right asks why the function exists [Figure 5.9].

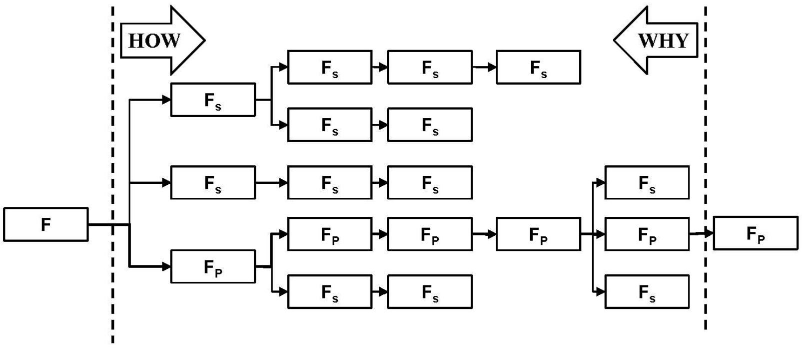


Figure 5.9 The two approaches of FAST diagram on functional decomposition, how and why the functions are designed and distinction to primary (F_P) and supporting (F_S) functions. Adopted and modified from Bytheway (2005).

As the functional presentation includes essential basic and secondary supporting functions, the elimination of unnecessary functions is recognised through the primary function path and questioned from the right hand approach.
The FAST-technique approach is linear and as it breaks down function into smaller secondary functions it has a similarity with axiomatic design [Figure 5.10].

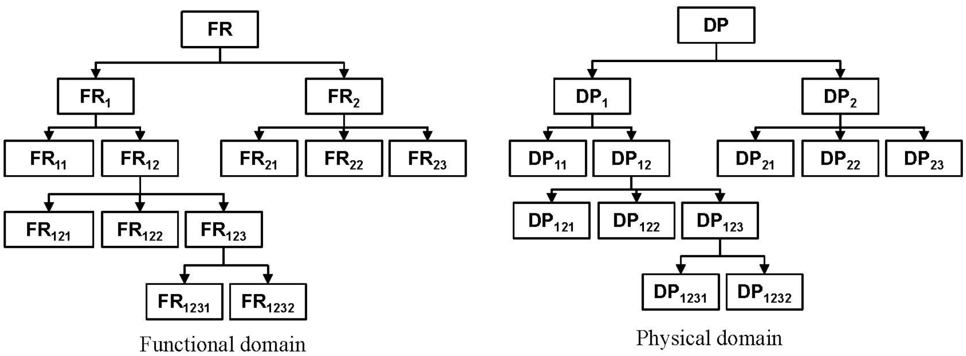


Figure 5.10 The representation of functional requirements (FR) and design parameter hierarchies (DP) where the first layer (overall function) is not uncoupled but next are. Adopted from Suh (2001).

FAST aims to eliminate unimportant requirements and search for better alternative solutions; in contrast the goal of the axiomatic design is to uncouple design elements by breaking function into pieces or modules where the function is affected only by one design parameter (Suh 2001).

However, even though both methods systematically split total function into smaller sub-functions, and simplify and limit the complexity of one particular design task, their support for developing concepts is poor. The methods for the identification of opportunity and what needs to be developed do exist, but further development is needed for the methods to be applied.

5.7 Experienced behaviour

The model of the transformation system describes how the combination of material, energy and information is transformed from an existing state to a desired state by the execution system, operators of technical and human systems. Different modelling techniques focus on what functions are needed and how the realization of functions shall be organized to achieve the requirements.

In addition to functional analysis techniques, the literature also presents methods for modelling the purposeful behaviour of a system by focusing more on its consequences, e.g. with respect to properties on functional execution flow. The following methods are known as Root-Cause Analysis, Failure Mode and Effects Analysis (FMEA), Fishbone, Structured Analysis (SA) or variations of Integration Definition for Function Modelling (IDEF). These techniques are mostly known through troubleshooting, failure or risk analysis, but are also know for system modelling. The approach of these methods is on the effects of a system; their domain is mainly different from the design domain. Although their analysis may be performed prior by if-then questioning, their main strength is in working backwards and reasoning consequences or effects. The intention of analysis modelling techniques is to describe the cause-effect mechanism of a function, either within technological disciplines or a combination of them.

The challenge of engineering is to comply with product requirements in a satisfactory way. The generic design processes distinguish between product characteristics and properties, which accordingly are under the direct or indirect control of the designer. Weber (2005) addressed that with an unfinished product, as a mechatronic product is, the properties can be analyzed only by means of appropriate models presenting the relations. Accordingly, a product may have more properties than considered earlier in the process.

However, the design feedback loop of product behaviour tends to be given less attention due to its linear application of development processes. Thus, even if the feedback from a later process stage to a previous stage has been recognized, the purpose is more iterative and towards optimization. Wilson (1981) developed the design loop schematic with three feedback loops to illustrate the requirements for a more effective synthesis on a decision basis [Figure 5.11].

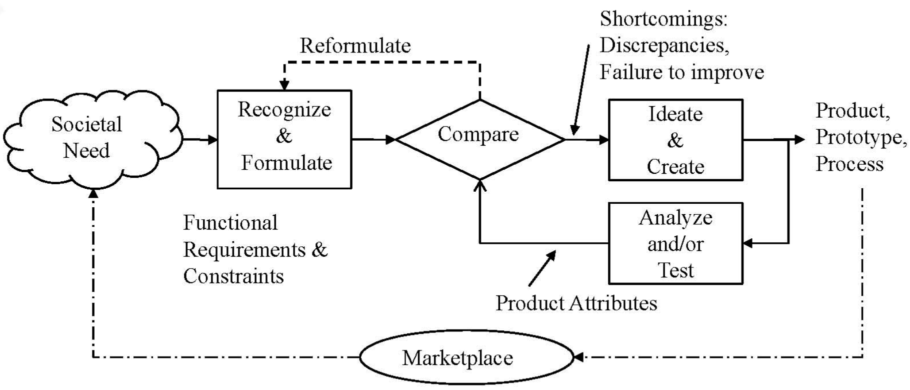


Figure 5.11 The design loop with three feedback paths to the design base. Adopted from Wilson (1981).

The outer loop naturally reflects the product's position in the marketplace, the compliance with the need, which does not have so much relevance to conceptual design. The inner loop within a concept for ideation and analysis reflects the product attributes for comparison in case shortcomings are identified. The third loop, is feasible in the case of an unsatisfactory concept and is accepted through comparison and directed back to the formalization of functional requirements (Wilson 1981).

However, even the feedback loops within the design process are essential; the actual behaviour at the use stage can be identified in a more direct way than through market feedback. As a system becomes more complex, the estimation and evaluation of how the overall function and product properties are achieved can be delivered because the product is in service. Simultaneously, the transformation process focuses on what modes of actions are needed to affect the operand during its progression between states, and thus ensure that the conceptual development focuses on finding how the effects perform in the operation state of the system.

Multi-disciplinary products are typical examples of how experienced behaviour and properties are the result of an integrated system. Because this behaviour is used as a feedback loop for modelling and analysing how the functional execution chain reacts, the further development of existing concepts can take place in a much more systematic way.

The characterization of the experienced behaviour is problematic; typically the evaluation is more qualitative than quantitative, which is beyond the scope of the typical engineering data or justification methods. Accordingly, the difficulty with decision making is to decide how much is enough to win the competition in the marketplace.

5.8 Conclusions

In this chapter, a product's conceptual nature was examined and further understanding about conceptual development challenges faced in today's industry is built. The multi-concept approach (Olesen 1992) describes how the versatile aspects of the product developers shall consider during the development.

Purposeful behaviour, function, how the product actually meets the use context has been the primary approach to present the requirements to development teams. However, the evolution of products towards the type of multi-disciplinary, the observation on industry is that functional decomposition approach does not provide adequate support for developers.

The weak point of the generic techniques is their application in a linear nature, in which each methodology aims for the decomposition of functional structure and the simplification and isolation of the multiple impact design parameters. The techniques are able to introduce effects; relationships to some extent and measures for comparisons between alternatives. However, critics have noted how well the techniques assist analysts or engineers in their search for alternatives.

The evaluation metrics with matrix methods is questionable, as they seldom reflect the real user's preferences and/or are the result of a weighting or summation, which negates the impact of single criteria. Matrixes, as systematic as their outputs are, suffer from multi-dimensional interactions modelling capability, which, in the case of function or impacts are results that are not paired.

The focus on each methodology is functions, but not much attention is paid to the functional response, e.g. how the function is delivered, or how the transformation process reaches the desired state for the operand. The feedback loops presented in generic methods aim to provide verification for developed sub-systems prior to integration, however as addressed by Weber (2005), the success of the verification is dependent on the acknowledgment of the relevant characteristics. Accordingly, as a product may have more properties as considered during the development phase, the behavioural consequences of a function are seldom noticed as the chosen characteristics are considered automatically fulfil those.

Referring to Hubka & Eder's (1988) approach; the behaviour of a technical system is always directed towards executing a set of transformations. Behaviour is determinate and controllable under normal circumstances, except when the system is damaged in any way.

However, this can be argued to be a regular occurrence in the case of multi-disciplinary products, as the linear application of the product development process and techniques aim to manage complexity by separating functional structure into independent sub-systems and/or disciplines. As a result, decomposition directs design activities to partial optimization within the borders of each discipline. Consequently, the behaviour of the product, in its real operating environment, cannot be explicitly determined during the design phase, thus many of the system interactions and impacts are unidentified before that point and can lead to damage.

The presented concept analysis techniques are not comprehensive, thus only the main approaches in this field were presented. These techniques are well known and applied for product development and fit with at least a few of the industrial drivers for product development; namely those derived from the following two approaches:

- A decrease in a product's costs (the internal pressure of an enterprise for the profitability).
- The improvement of product properties and/or characteristics (market's external pressure to maintain competitiveness).

More specifically for engineering science, the first refers to the cost of producing the product value and the latter to the experienced value of the product.

Focusing in the technical context and properties of the product, which is under developers' direct or indirect influence, the search of different operational principles requires the utilization of feedback from the reality domain. The term 'experienced behaviour' is presented here as an extension to the interpretation of the behaviour which is the result of product properties and characteristics in design domain. This specifically applies to mechatronic products, which functions are governed by control systems and may involve different operational principles in the same physical part structure. Based on studies and findings in industrial projects, this framework is utilized for further work aimed at developing a new incremental technical concept development method.

6 Product Innovations

A company launches a new product generation, which provides better performance, properties and cost reduction, thus performing the same function and duty as its predecessors did. However, does this new product generation meet the definition of an innovation?

In today's business, every enterprise, organization and stakeholder announces itself to be innovative or at least declares innovativeness to be one of its most important strategic drivers. Innovation is a word which raises a positive mindset by suggesting the image of something new, dynamic, performing and attractive, but without necessarily addressing any specific subjects or properties. People freely take the opportunity to interpret and use the term innovation according to their interests.

The nature of innovation is relative; to make an evaluation of the originality of a product it must be compared with what existed before the new idea of the product, process or service was introduced. Accordingly, originality is also relative to whom it is presented and naturally with what measure of the magnitude. In consequence, all these indefinable measures enable the free use of the term innovation in a business context.

Innovations are sometimes misunderstood as inventions; however, an innovation may lead to invention, if the person or institution expresses their will to officially claim a privileged status. Not all inventions may become innovations, as they may not be applied as the protective barriers of some core competence against competitors or may just not excite interest for marketing purposes.

The uncontrolled use of the term innovation in different business contexts alters definitions. Thus, for a product developer it is not the most relevant issue if a new solution is innovative or not, a sharp distinction between product improvements and different types of innovations is necessary. Nevertheless, a distinction also enables the search for applicable methods for each type of development and product idea and concept to be focused on.

6.1 Introduction

Innovations may be categorized or classified according to various principles depending on one's viewpoint. When one talks about product innovation, we may refer to a new product, application or service, new technology or new product property. Within a business context, the word innovation has gained an almost inflated sense of importance as every enterprise announces its own innovativeness and innovative products and solutions, and sometimes in common language innovation is used without any specific context.

Innovations exist on all levels of business or product originating process environments. Various viewpoints can be taken for a review of how different studies and articles reflect the applicability and position of innovation theories and methods. Here the product developer's viewpoint is chosen as the central viewpoint and an approach is developed where the developer's influence may be positioned in three dimensions [Figure 6.1].

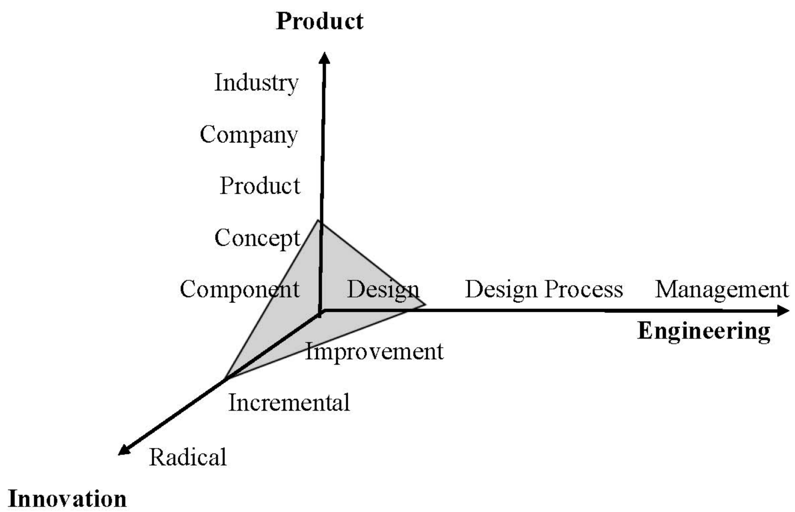


Figure 6.1 Development engineer's dimensions of product, engineering and innovations and the working and influence sphere close to origin (Oja 2007).

The area closest to the origin describes the practical work and impact area of a design engineer (shaded triangle). In general, the further away from the origin on each axis we go the broader and more abstract the impact and influence of a particular task, problem or solution become.

The product dimension describes the different levels and aspects of product concretization in business. The further the distance from the origin, the more the technical context decreases and the more a business strategy and management and marketing become more relevant. Literature on the issue presents the multiple aspects of innovative industry changing success stories and the failures of enterprises. Common to these studies is that different types of innovations are considered with respect to organizations and business environments, but the technical context for product design has been minor (Christensen et al. 2004, Nadler & Chandon 2004, Skarzynski & Gibson 2008).

The engineering dimension presents product development processes with various methods for abstracting the design task and further developing the functional structure and solutions. Different methods and models may be used for decomposing the technical system into structures e.g. functions, organs and parts. However, the theoretical means presented in literature for finding solutions during the conceptual design stage are rather weak once a design becomes more concrete. Thus, the methods and tools for generating innovative solutions need to be more context sensitive.

The innovation theories and concepts followed by enterprises may be categorized according to their approach and behaviour in the marketplace. Christensen et al. (2004) has summarized seven main streams found in industry:

- Disruptive innovation theory. For this theory differentiation from the main market stream results in products that may offer a poorer performance but have a more attractive pricing. This, attacks against products, which performance is developed faster than customers initially expect or need, which is something that could have the threat of overshooting people's requirements. The issues here can be briefly summarized as the cost trap and value conscious customers.

- Resources, processes and values theory (RPV). In RVP theory, organization, management and the prioritization of the development activities are based on the selected values which may lead them to ignore the potential development areas like disruptive innovations.
- Jobs-to-be-done theory. This theory refers to understanding the core product's operating circumstances and developing matching applications to improve its use.
- Value chain evolution theory (VCE); VCE looks at specialization within critical parts of the value chain and the management of complex products with modularization and interfaces to enable faster development and market entry.
- Schools of experience theory. Central to this theory is the utilization of past experience, the development of competence while recruiting development personnel and managers that can overcome problems and difficulties in order to achieve high performance.
- Emergent strategy theory. This addresses the identification and adaptation to market signals in order to modify product development strategy, specifically in highly uncertain situations.
- Motivation and ability framework. This theory involves the utilization of non-market forces like industry standards, unions, cultural norms, government regulations etc. to affect innovation.

The innovation landscape was presented by Hansen (2004), when he presented different dimensions of innovations and their contributions to the product (improvement or something completely different), process (improvement or radical change), position (extend, deepen or find new application fields) and/or paradigms (improve, repackage, integrate or rewrite the rules).

In engineering design, innovation has a broad context and may show up in different contexts with:

- Product itself; introducing originality or newness into a market.
- Product function and/or properties; extension or the application of an existing product.
- Product or technology use; the new application of an existing product or the transfer of technology to another product application.
- Manufacturing technology; the application of something new during the product originating process.

In addition to context with a physical artefact, innovations may also exist in the wider business context, such as:

- Business models; value adding operations or services, with or without an artefact.
- Organizations; way of working or collaboration.
- Product supply chains; networking and logistics.

In engineering design, the forms of innovations are directly or indirectly linked to the physical artefact itself or its originating process and have an impact on design context. The division into two principal categories was presented by Hansen & Andreasen (2002) as (i) innovations in the product idea and (ii) innovations with the product idea. The first one refers to the physical artefact's design context, its technical transformation system, functions and properties. The latter refers to the use context of a product and the experience of it during acquisition, ownership and use.

Customer value is an important indication and may be used as an ideation tool for innovations. In a business context, an innovation cannot be limited only to "what" is offered to customers by means of functions and properties, it is also about the changes in the customer context with regard to when, where, why and how to provide the product or service. All this, with reference to enterprise profit requirements, brings opportunities, synergies and trade-offs to the product design context (Logman 2008).

> The linkage between the two idea types with use and design contexts and innovations is natural because many solutions within the design context enable experiences within the use context, although visual or physical appearance is not necessity. Consequently, an innovation may appear without any impact on design context.

As the innovation may exist in different contexts, studies in the literature classify innovations by their magnitude or impact. However, measuring the difference between different types of innovations is challenging as the evaluation is often relative and depends on the particular environment of a case, e.g. what may be new to one product or business, may be familiar with another.

If we exclude the most radical type of innovations, a world new product, application or technology, we must assume that products and services evolve during their existence. Consequently, the distinction between improvement and innovation in the technical context needs to be defined in more detail, as does how we identify the fulfilment of innovation.

Innovations in a technical context are further studied in this chapter, and a preliminary approach and distinction between innovation and improvement is presented as:

- Improvement is a type of modification in product detail while maintaining the same operating principle, which is the result of a more optimized calculation or simulation method, e.g. a change in design constraints, an improved originating process or better product properties.
- Innovation is a type of product variation that changes partly or totally an operating principle, which is a result of changed design conditions or concept and the introduction of better system usability and or behaviour, performance or reduced originating process cost.

Hubka (1988) presented technical system properties with a wider scope and classified them into three categories around the core technical system. These property categories are: design, internal and external properties. Each property element is at least in some respect considered and influenced by the designer's choices on the design parameters, and it may be claimed that design can be executed from a viewpoint considering one or more properties simultaneously or from a selected preference, such as the "Design for property" or "Design for X" (X as the chosen viewpoint for engineering) approaches. Consequently, each property in these categories presents an element, which may be subject to improvements or innovations.

According to generic new product development processes, the initiation of product innovations is considered in order to take place during the early development phase and is seen as a primary driver for development activity. However, even if a utilization of concurrent engineering and Design for X approaches is used, the personnel involved in different life cycle processes may participate in and impact upon the product during the product creation. Thus, the different sources may be used to initiate seeds for product improvements and innovations and these may come beyond the engineering viewpoint. In consequence, when an artefact delivers its content, it is much easier to apply systematic methodology due to the higher concretization level [Figure 6.2].

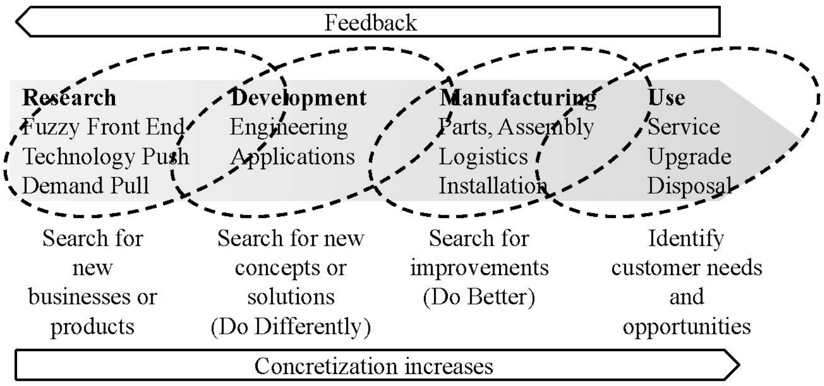


Figure 6.2 Innovation sources during the product life cycle, more specific as the concretization increases and giving feedback for more abstract phase.

Product use and manufacturing phases and the application of DFX-methods provide an excellent means to follow the assembly and parts during the originating process creating the product function and properties. This approach can be considered as an opportunity for generating seeds for innovations in a systematic way, especially as the feedback loop towards earlier product development phases is essential.

The nature of product improvements and innovations is broad and numerous studies and articles may be found in different contexts. This study focuses on innovations in a technical context, specifically in the technical transformation system and its operating principle.

6.2 Considerations on Innovation

The definitions of innovation presented in literature vary according to one's perspective; either from a narrow view on technical issues only, or a broader business view that includes success in the marketplace. A distinction occurs according to the magnitude, impact or type that has driven the authors to divide innovations into categories with the aim of explaining originating processes and/or the consequences of different types of innovations.

The primary distinction between engineered and innovative solutions with product development results was made by Altschuller (1996) with the introduction to the TRIZ-method (a theory of inventive problem solving). A quantitative measure of innovativeness was made with the comparison between trial and error methods and five levels of innovativeness were presented. The classification refers to the number of required engineering attempts to reach an innovative solution [Table 6.1].

Table 6.1 Levels of innovations categorized in comparison with trial and error development effort. Adopted from Altshuller (1996).

Level of innovation	Description	Degree of challenge
Micro inventions "non-inventive inventions"	Trivial and do not contain or require elimination of contradictions.	Not more than 10 trial and error attempts.
Common inventions	Solution easily found within one area of study or borrowed from other section of science.	10-100 trial and error attempts.
Average inventions	The problem and its solution belong to one area of study and attained through combination of several physical effects.	100-1000 trial and error attempts.
Macro inventions	Synthesis of a new technical system. Contradictions are eliminated using methods belonging to another field of science.	1000-10000 trial and error attempts.
Major inventions	Produce new novel technical systems and design products lie beyond the scope of modern science make a discovery and solution with new scientific data.	10000 trial and error attempts.

The classification is purely a statistical approach to how difficult or probable the exploration of a new solution is and technical to what level of adaptation compared with other fields of science an application is.

In general, adapting the definition from Drucker (1994), innovation is a new or different solution, which brings benefit to one or more stakeholder during the product originating process, its taking into use, use and/or disposal. Hubka & Eder (1988) have a similar approach which states that an innovation is an implemented new process or product that has been made available. In this context the adjective "new" has an important role and is interpreted by Woodford (2003) as:

- Recently created or having started to exist recently.
- Different to one that existed earlier.
- Not yet familiar or experienced.
- Not previously used or owned.
- Recently discovered or made known.

New is a relative measure depending on the viewpoint of a stakeholder's existing situation. By adding the business approach, success in the marketplace has been added to the definition. Campbell (2004) frames his definition of innovation as *the successful creation of new market value through the satisfaction of customer needs with new technology*. However, this definition increases its complexity; how can we measure success and customer satisfaction with innovations, as well as consider the requirement of new technology implementation? Additionally, the definition is post-cyclical as an innovation cannot exist until it succeeds in the marketplace.

The included value or benefit aspect of an innovation for a stakeholder must make a distinction between an invention and innovation. An invention is a new solution based on an idea, thus not necessarily providing any benefit aspects. The characterization of an innovation should include or bring something additional to something that already exists – and in the business environment that also means something that somebody is willing to pay for. However, value as the means for a transaction, consists of at least two viewpoints and various elements, as referred in Chapter 3 earlier, are the consequence of activities during the originating process. The engineering challenge, as engineers design artefacts, with value is; what innovations and how do the innovations and the technical content transfer value?

Cooper (2001) classifies innovations into three categories according to their originality or magnitude of improvement:

- High innovation degree; new to the world products or new product lines to the enterprise.
- Middle innovations; new product variations or the renewal of existing product lines.
- Low innovativeness; product modifications, re-engineering, the re-positioning of an existing product.

According to this categorization, Cooper (2001) refers to studies on industry that show that only 30% of the innovations belong to the highest category, new to the world or new product lines. However, according to the same study, the highest return on product development investments has been gained with the lower innovative category projects. As a natural consequence, the product development activities in enterprises focus on the existing products or applications of current or past designs.

A stricter distinction of different types of innovations was made by Leifer (2000), who classified innovations into two groups: radical and incremental innovations. Radical innovations are the type, which create a dramatic change in a product, manufacturing process or service, which significantly influence an existing market or create a new one. Accordingly, he defined quantitative measures for a radical innovation as:

- An entirely new set of performance features.
- Improvements in known performance features of five times or greater.
- A significant reduction in cost, at least 30%.

Other types of changes are categorized as incremental innovations, which typically appear in the form of cost reduction or improvements in the properties of a static concept. The quantitative measures given may be argued if they are applicable to all types of products or services, but the intention is to provide a distinction that a radical innovation cannot be reached with a concept similar to one used earlier.

The technological change of an innovation in two dimensions, or the impact on components and the impact on the linkages between components was presented by Henderson & Clark (1990). They present different types of innovations in a two by two matrix format and make distinction between radical, incremental, modular and architectural innovations [Figure 6.3].

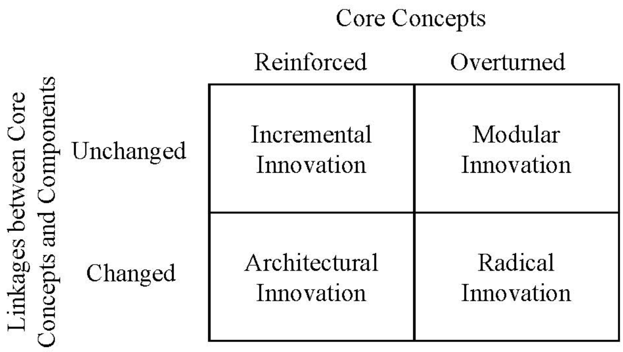


Figure 6.3 Types of innovations categorized according to change on a core concept and linkages between the concept and components. Adopted from Henderson & Clark (1990).

The types of innovation are introduced as matters of degree and provide suggestion rather than strict classification. However, the classification gives insights into which the type of changes may occur.

- Incremental innovation refines and extends an existing design on the component level thus retaining the core concept and the links between it.
- A radical innovation establishes a new dominant design with a new set of core design concepts. In contrast, an incremental innovation refines and extends an established design and produces improvements in an individual component within existing core concepts.
- A modular innovation is a type of change, which changes the core design concept without changing a product’s architecture.
- Architectural innovation is the reconfiguration of an established system to link existing components together in a new way, while keeping each component in that particular core concept the same.

While the main focus of the authors has been on architectural innovations, the approach outlines an alternative viewpoint on innovation by focusing on the change dynamics within the marketplace as presented by Christensen et al. (2004) in relation to the concept of disruptive innovation. This approach distinguishes between low-end disruptions and new-market disruptions while product evolution along the maturity line curves from the dynamic launch concept moves towards a static or dominant design concept. The low-end disruption refers to the least profitable customers who are over-served by existing products and the high-end disruptions to non-customers where new attributes, typically simplicity and/or convenience appeal, despite otherwise poorer product performance on traditional criteria. Disruption occurs when an emerging innovation offers superior performance in a new dimension, even if the performance is poorer on conventional measures. Disruption is however relative: what may be disruptive to one company or customer group might be sustaining to another.

The nature of innovations is not limited to the technical realization of the product itself. Benefits and newness may occur during all product life cycle stages and processes. Utterback (1994) made the distinction between a product and its process innovations according to their intensity of appearance during the product’s life cycle. Product innovations may be directed towards the deliverable, or the product or artefact realization itself and/or what the product is designed for. Process innovations occur during various meetings of the product originating process that deal with how the product gets its design and physical content and what is provided for the user.

As studied earlier, innovation has gained different definitions from different viewpoints and become a fashionable expression to be used in numerous contexts, specifically in business literature. The reference for all these has been more on a commercial basis rather than having any substantial scientific background to technical systems. For engineering and product development purposes, the approach, context and definition of innovation need to be studied and focused on with respect to a technical transformation system, product concepts and solutions.

6.3 The division of innovations according to their operating principle

The question of what is new with reference to innovation may be discussed more precisely in order to define the difference between two concepts or solutions. Muurman & Frenken (2006) refer to the earlier work of Polanyi (1958) developing their approach to the classification of concepts where the distinction between concepts is based on the operating principle, which captures the knowledge of a designer to design an artefact to work in a desired way. The concept of the operational principle enables them to compare concepts, and see if they work according to the same principle. The classification may be used for different purposes, like categorization into product classes (different operating principles for the same purpose) and variations within the product classes (a different operating principle within the product class).

By combining the two definitions of innovation from Hubka & Eder (1988) and Drucker (1994), it is possible to argue that an innovation is an implemented new process or product that has been made available and which brings a benefit to one or more stakeholders during the product originating process. It can, thus be taken into use, used and disposed of, while including the concept of an operating principle. We may, in a technical context and limited to the artefact itself, distinguish the types of innovation based on the conceptual change;

- The characteristic of a radical innovation involves a **difference** in the total product concept compared with earlier products for the same purpose, or a new technology, or its application in other field and thus introduces a new product class.
- The characterization of an incremental innovation introduces a **better** solution within an existing total product concept, which involves a different sub-system or partial solution and introduces a new variation into a product class.

> The distinction with the operational principle opens up the possibility of evaluating the technical systems in more detail with respect to innovations.

The origin of the product innovations and their relationship with development processes and their methodologies can also be further explained. A radical innovation introduces a new product class, it is obvious that this type of innovation includes various aspects, such as scenario building, market exploration and need identification. The aim of the innovation process is to extend the product portfolio of an enterprise which better enables coverage in an existing market or penetration into a new market area. Even the initiation of a radical type of innovation may be versatile and occur during any product life cycle stage; the magnitude of change involves the rethinking and restructuring of a total product and its originating process. The generic product development processes specifically cover this approach.

Incremental innovations focus on the further development of existing concepts, where the initiation may also be identified from various life cycle stages or processes. However, within enterprises the business environment drives the economic justification and thus a reference to value viewpoints is essential. An incremental development faces questions from two sources because both the market and customers expect a continuous improvement in value per investment (note; value improvement shall not be interpreted as a product property or a performance increase) and an enterprise to increase profitability by means of decreasing the costs that deliver the value.

The two different types of innovations, radical and incremental, have a totally different nature. Innovations have a high correlation with human creativity, especially between the two innovation types in the phase of the creativity; e.g. when the seeds for the idea are sown and when the results are harvested. In literature on the issue there are numerous examples, where great (or radical) innovations have been brought into existence almost randomly, by hit and miss, or as the result of a maturation process of years. What is said to be common with these cases is that each has been considered unique and followed by the conclusion that no systematic approach could be applied because each problem was different (Leifer 2000, Nadler & Chandon 2004).

In this study, the focus has been on the context of innovation from a technical viewpoint and specifically incremental development, which has received rather scant interest in literature. Consequently, the earlier presented framework and distinction between innovations enable us to evaluate the differences between technical systems and further study the operating principle with respect to the functions and product structure in relation to the functional delivery chain, in other words; how the experienced behaviour is realized.

The concept of the operating principle, a difference within a product class, enables us to expand the evaluation made here beyond its conventional functional structure. Whilst the functional structure and its solution landscape act as the backbone of new product development processes, they ignore the existence of other disciplines during the early stages of product development. However, specifically with mechatronic products, significant differences may be found in operating principles, as a result of power train and control system properties.

The evolution and development of product properties resulting in better performance over time are presented in the form of an S-curve (as discussed in Chapter 2 earlier) and may be better interpreted in a technical context with the concept of the operating principle. Naturally much of the performance increase may be achieved with product improvements, but a more significant rise in an S-curve may require a change in some subsystem, which causes a change in an operating principle within a product class, i.e. an incremental innovation within a product class.

Enabling the jump up to the next S-curve and a performance increase beyond the earlier platform may be explained by the development of a new product class, resulting from a radical innovation that introduces a totally new concept for an existing purpose.

The concept of the operating principle, describing the functional execution chain, enables us to explore sources of innovations within a product class and understand the opportunities within a nested and integrated product hierarchy and structure.

6.4 Conclusions

If we study the nature of an innovation as presented by authors in literature and their classifications, we may notice that product development and innovations have two diverse dimensions. Based on the concept introduced by Hansen & Andreasen (2002), the two domains, "idea with" and "idea in" the product divide the development landscape into different approaches. Thus, development engineers face the challenge of meeting requirements within a customer's "idea with" domain with the solutions created in a technical system.

The context of innovation has expanded widely and has done so specifically within business literature and this has also influenced approaches in design science. The classification of innovations has taken place in order to fine-tune specific viewpoints. However, even though the classifications have expanded our understanding about innovations, their context within products and their impacts on business management, consequences and impacts on engineering processes and technical systems have been rather weak.

In this Chapter the division of innovations into two types has been made by separating radical and incremental innovations based on the concept of the operating principle. With this approach, the pure technical system of a product has been taken as the viewpoint and excluded other business and product originating processes and use viewpoints. With this distinction, a more solid understanding about the engineering approach to product development has been built. Consequently, the problems inherent in generic new product development processes have been identified with regard to how their approach to innovations originates in the early stages of the development process. Accordingly, the concept of the operating principle opens up the possibility of understanding the nature of incremental development and its opportunities, in relation to modern multi-disciplinary products, with highly integrated systems. In brief, modern product development can be carried out by approaching incremental development from a product's sub-systems.

7 Considerations on Opportunity Identification

Companies have widely adapted systematic process models to control product development projects with different modifications of the Stage-Gate process (Cooper 1990). However, despite the wide acceptance of this process model it is more a project management tool, which controls the project execution rather than assists in creating context for development tasks or a technical system itself.

Organizations, which claim to operate in accordance with an innovation process, refer typically to the process of new product development. Applications of idea funnels, fuzzy front-end models and creativity techniques have been presented but these are mainly used for describing and communicating the development process to their organizations. One target of the applied innovation processes is to divide confusing and iterative development flow into more controllable phases, where the creative idea generation (divergence part) of the development process is separated from the evaluation and selection (convergence part) and further phases between development and detail design.

The example in this study is a company providing equipment and maintenance services for material handling applications. The company has a central R&D organization, which employs engineers from different disciplines. The product development project execution process is adapted from Cooper's Stage-Gate model (Cooper 1990), which has three variations according to development task type; new product development, small development project and software development project.

Any larger project activates resources from different operational business units in addition to the dedicated R&D personnel. With this arrangement, a smooth hand-over of responsibility transfer and product launch is enabled in addition to the involvement of theoretical and practical knowledge throughout the organization.

The nature of global business has increased the demand for speed and controllability over product development. The consequence has been that product development activities have been divided into three main activities;

Research: The exploration of new technologies and opportunities as a continuous parallel process without a specific new product development project.

Development: The preliminary study, concept development and compilation of the product specification for the dedicated product development project. For the management of the development project, the principal schedule and its milestones are defined and followed with a Stage-Gate model.

Design: Product engineering based on the selected concept and specification according to the strict schedule and targets.

The development projects of existing products and concepts follow the same process, which challenges the methods used during the development and design activities, specifically when innovative solutions are searches for.

7.1 Introduction

The quest of powerful tools for supporting the creation of innovative solutions exists in industry. In literature, innovation theories and methods have been presented in the different contexts of products, engineering and innovation. The approaches have mainly focused on business and product management rather than on the technical product context. Product architecture, product family and modularization aspects have an important role in strategic aspects, but diverge from a designer's problems with regard to executing particular design challenges. For product developers, the most interesting approach is addressed on technical systems. The daily burden is on generating new or better product concepts or even innovations. However, very few studies or methods have penetrated deep enough into a developers' world to be able to show how ideas and innovations may be developed in a more systematic way.

The innovation process during its broadest approach consists of three phases; namely the front end of innovation, new product development and commercialization. Within this process, the traditional product development stage has been expanded to cover the early stages before actual product development (fuzzy front end) and post launch activities (commercialization) (Koen et al. 2002).

The role of the early stages in the product development process is opportunity identification, which acts as the trigger for further activities. However, this approach supports better the new product development framework and the methods for collecting, developing and evaluating seeds in search of dynamic concepts. Less emphasis has been laid on specific methods for static concept development, except proposing to apply similar methods to those for new product development.

For a technical system, the most important phase for innovations during a development process is the conceptual design stage. Different solution alternatives, concepts and operational principles are generated and evaluated, and finally one is selected. However, generic design processes provide rather weak practical support for product developers at this critical stage;

- Engineering design (Pahl & Beitz 1996), VDI 2221 (1993) and variants of development processes (Ulrich & Eppinger 2003) suggest literature search, the analysis of natural and existing technical systems, analogies, intuitive methods such as brainstorming, gallery, Delphi or discursive methods.
- Total design (Pugh 1996) distinguishes qualitative and quantitative methods, namely in the first group analogy, inversion, attribute listing and T-charts and in the second group non-numerical decision matrices.
- Axiomatic design suggests the development of a solution by means of design parameters, which are explored while mapping from the functional domain to the physical domain with benchmarking, reverse engineering, QFD or copying.

The presented methods for idea generation with generic processes may be distinguished into two categories; creative techniques and interaction or numerical charts. These methods identify themselves with a broad landscape to generate new ideas.

The intuitive methods are very generic in their nature and require a case specific introduction before applying. The purpose of these methods is to generate a great number of ideas. Out of these, via selection and further processing, an applicable solution may come into existence. However, these methods lack the context and the subject and could be used for any problem consideration with the assistance of an experienced moderator and a group of individuals. However, the experience in industry is that the number and quality of ideas decrease as the task assignment becomes more specific and detailed. This may be explained by the limited use of abstractions and associations, which on the other hand suggest that they should be used in early development stages.

Chart and matrix methods enable the organization of data into different patterns and showing interactions for identification purposes. However, those methods are challenged by the data types and the level of detail required, which are applicable to conceptual idea generation. The method is powerful for indicating a comparison or relative difference and identifying what issue to develop, but provides less support on how to explore ideas for changes.

In industrial development projects, organizations tend to rely on the initiation of innovations through intuitive methods and multi-disciplinary teams rather than more formal or dedicated innovation methods. That observation is supported by business and management literature, which highlights the use of all human creativity resources in an organization. However, there exists a gap between creativity and application in the development of a technical system that could help the birth of innovative solutions during concept development or at the solution creation level.

Industrial products, which have reached their static design phase, often bring the majority of the cash flow and profit to a company. These products provide the backbone for financing new product development and therefore their contribution margin is carefully monitored. Consequently, companies with established organizations tend to reinforce their capabilities and competitiveness with improvements to existing products (Utterback 1994).

More than two thirds of the development efforts in industry aim at the incremental development of products (Cooper 2001). The benefits, either improved value for users or decreased costs for the manufacturer shall be introduced in regard to product's purposeful behaviour and/or properties. This calls for new solutions which can be implemented into existing static concepts. However, this addresses a contradiction between generic new product development processes and industrial practice, which prefers to start product development activities from existing products or concepts with pre-determined goals rather than from scratch. Accordingly, the utilization of the knowledge and history of existing concepts has a specific role in the development process.

With static concepts, the design context is more concrete and development methods and tools for generating innovative solutions need to become more context sensitive. An example of more detailed and context sensitive systematic innovation method is presented within the theory of inventive problem solving (TRIZ) (Altshuller 1996). Within this method, the substance-field analysis acts as an abstracting model of the system. Utilization of contradictions in the system, the method directs to generate innovative "zero sacrifice" solutions. The backbone of the method in order to identify new or alternative solutions includes a comprehensive list of physical phenomena and the list of 40 inventive principles. With the method application on a problem, phenomena are first applied and/or combined, and then the inventive principles aim to modify the subject or the process to reach the desired transformation process.

The method works best in applications where either a physical or chemical environment (field) exists in a system. Even with acceptance and commercial applications on the market, developers in industry have found the method laborious or less applicable in full extent to engineering tasks on the concept or solution level (Moehrle 2005).

7.2 Towards needs in industrial projects

A systematic design and engineering process is essential for ensuring the requirement driven specification, conception, design and execution of a project according to a planned schedule and costs. However, a systematic process itself does not guarantee or support the creation of innovative solutions. More often the practical developer's problem in industry is in generating seeds for new ideas rather than developing or improving ideas further.

Theories and models formulate the development and design process into stages, where customer requirements are transformed into specifications, functional structure and solutions. In the process of new product development, the interpretation of requirements towards functional requirements and properties is essential, especially if an earlier product or concept doesn't exist.

The quantity of innovations along a product's life cycle decreases as the concept variations on the market diminish. A strong development stage with numerous product innovations is usually followed by a significant decrease in development, which indicates that the product concept has reached its maturity and can be called either a dominant or a static design. At that stage, the main technical solution and main function are very similar between different manufacturers. When the static concept stage has been reached, development activities are directed towards manufacturing processes and are mainly driven by cost pressure (Utterback 1994).

Today, industrial products consist of either medium or large systems, including technologies and components from various disciplines. Even if the solution for the main function is similar between different manufacturers, differentiation takes place at the lower level of the product's structure and the operational principles may vary. The moment when different manufacturers end up having specific solutions can be seen as the stage in the development process when the main function structure has been decomposed into sub-functions and corresponding solutions. At that stage, the drivers for different solutions may be explained by different evaluations of the product's value, past experiences or competence in the company.

Different solutions are not automatically consequences of innovations, more often they are engineered according to specifications within the constraints. Engineered solutions are the kinds of design which fulfil the specification, but are not ideal nor inventive (Salamatov & Souchkov 1999). A typical development project in industry is initiated either by recognised opportunity (or problem) or severe cost pressure to meet value improvement requirements. This type of development may be called incremental development, which may occasionally result in incremental innovations.

Models of development processes and technical systems introduce iterative and feed-back loops, thus applied in industry in a linear design sequence, where product requirements are transformed into functional structure in a hierarchical manner. This type of sequence has an assumption that the total product function is satisfied with the result of different sub functions. The axiomatic design process (Suh 2001) even suggests that functional requirements and design parameters shall match up to reach an uncoupled design, which is supported with the further decomposition of functions. This working principle has merits in relation to robustness and stability, but is more powerful for optimization and hardly supports creativity or leads to innovations.

The development process for a static concept has a different set of sequences, because in addition to the concept, solution and part structure, a lot of product experience, information and data already exist (Pugh 1996). However, no matter how many properties and design parameters an existing concept provides, the challenge is how all knowledge can be formulated during the conceptual stage and used as a catalyst for generating innovative solutions.

The characteristics of a new product and incremental development differ in their targets and context, as shown below [1.1].

Table 7.1 Design process differences between new product development and incremental development. Adopted and modified from Pugh (1996).

New Product Development (Dynamic Concept)	**Incremental Development (Static Concept)**
Opportunity identification, idea	Existing concept
Requirements	Opportunity identification, idea
Specification based on requirements	Conceptual design (partial)
Conceptual design	Specification based on concept
Detailing	Detailing

The comparison of stages between dynamic concept (new product development) and static (incremental development) development show that the predecessor stage before opportunity identification defines the starting point for idea generation. This difference is also acknowledged and used as the basis for more systematic methods aimed at developing static product concepts.

A new approach to develop innovative solutions for existing concepts needs something to work as a catalyst for the creation of ideas. During incremental development, opportunity identification may be assisted by known product structure, properties and design parameters, enabling the understanding about how the function is delivered, in other words how the purposeful behaviour is executed. However, development teams are often trapped with a problem and thus opportunity identification may ignore potential paths for solutions because the experienced behaviour is not expressed while applying the design process in a linear way.

> The development teams have to enlarge the opportunity identification landscape by questioning the traditional processes and thinking patterns while communicating with different professional disciplines.

A case study has been conducted to demonstrate the kind of knowledge and experience that is available within a technical system and can be used for the improvement of an existing product. It also demonstrates an understanding about how opportunity identification in incremental development can be improved.

7.3 Case study: "The hydraulic grab power train system"

The case study presents an industrial development project on a static concept. The purpose of the development was to remove repetitive failures in the power train system of the hydraulic grab and improve the product reliability.

The grab is suspended by a rope system from an overhead crane [Figure 7.1]. The primary use of the crane is to transport community waste from a pit to an oven at waste-to-energy plants.

Figure 7.1 An overhead crane and hydraulic grab in waste-to-energy plant to move community waste from pit to oven (Konecranes Plc).

The main function of the grab, opening and closing the jaws, is actuated by hydraulic cylinders. An electrical motor inside the grab operates the bidirectional pump, which generates the working pressure and fluid flow to and from the cylinders. The power supply to the grab is provided via a cable, accommodating the length variations during lifting movement by wounding the cable on the drum of the hoisting machinery, simultaneously with the hoisting ropes.

7.3.1 Problem description

The power train system of the grab was mechanically simplified; the opening and closing movement of the jaws was arranged by changing the rotation direction of the motor. This operation principle eliminated the need for any control devices in the grab, as a specific hydraulic block with relief valves fulfilled the functional requirement [Figure 7.2].

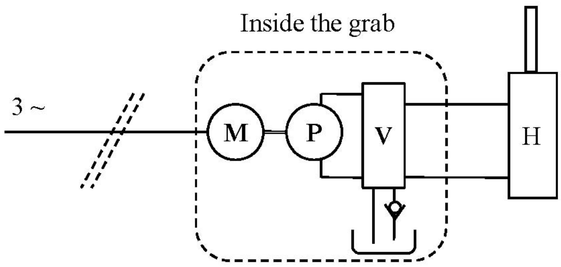


Figure 7.2 Original grab control and actuating system, based on the change of the rotation direction of the electric motor (Konecranes Plc).

The existing power train is the result of a single disciplinary approach; the bidirectional use of the motor matches with jaw movements, additionally all sensitive components (the phase change contactor of the power supply) can be located on the crane level beyond the rough environment of the grab. However, the arrangement has caused continual problems for the power train system and led to a call for improvements. The identified problems were:

- Overheating of the electric motor.
- Breakages of the coupling between the motor and pump.

- Failures, leakages and the jamming of the hydraulic block.

The root causes of problems were investigated and recognized to be the consequence of the motor starting and the activation of jaw movements against full load, as well as the repetitive change of the rotation direction of the motor on each working cycle. Both of these cause additional motor and hydraulic system heating, which were the ultimate sources of failure. The original operating principle was simple and done well in its early stages. However, during the life span of the grab, many upgrades on grab size and capacity have occurred and it seems obvious that the concept scaling, architecture and part structure have reached their limits. Earlier development actions had been taken in a single-disciplinary way, e.g. mechanical breakages had been solved by reinforcing the components.

The development task includes constraints to restrict the solution landscape;

- The change of the grab interface to the crane must be limited to a minimum to ensure changeability to existing installations.
- Power requirements shall not be greater and thus affect the dimensioning of the existing power supply system of the crane.
- Power supply means to the grab via the power cable shall not be changed to a different type due to the cable coiling system.

Constraints with the space inside the grab, power requirements, cooling, control and power supply caused that the problems cannot be solved by component sizing, thus an alternative concept was necessary.

The new power train system consists of a unidirectional hydraulic pump and a separate valve system that directs the oil flow to meet the jaw movements. The actuation of the valve system was controlled in a new way, enabling the change of the operation principle. The control commands to the valve system were carried through the power supply cable. The command signal was arranged on the crane level so that a short interruption of one supply phase was caused, which was identified at the grab and interpreted correctly so as to allow the operation of valves and ensure that they let the drive grab jaws open, close or keep steady [Figure 7.3].

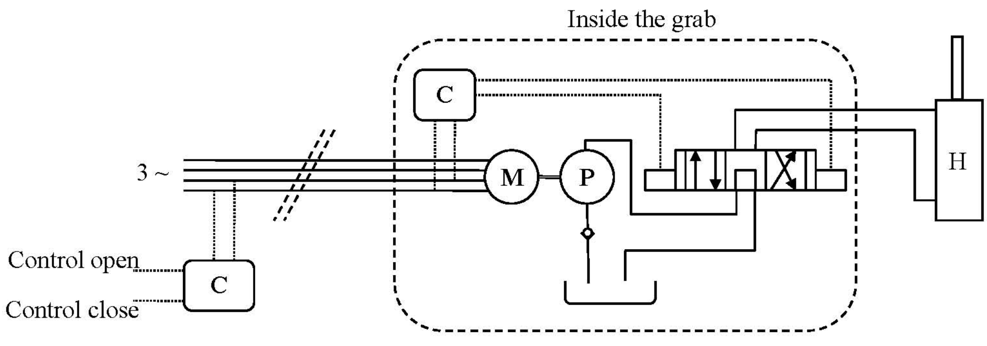


Figure 7.3 New grab control and actuating system, including innovative control message transmittal through power supply phases (Konecranes Plc).

The new control system enables to construct the power train system in a manner that enables the continuous run of the motor and pump and removes additional load peaks that cause excessive heating. The new operating principle removes problems and additionally enables the decrease of motor size due to lower torque requirements at start-up.

Additionally, a shorter response time was achieved due to action by the immediate availability of the hydraulic pressure and flow. The main constraint with the crane interface was maintained as the power cable was unchanged; however additional control electronics should be installed.

7.3.2 Synthesis

The new solution was developed based on an invention and was also awarded a patent. The change involved a different part structure thus remaining the function structure the same. The new sub-system combination and control system introduced the changed operating principle. However, the innovation was not consciously created by using any systematic method, at the time of creation it was purely the result of individual intuition. A retrospective study was carried out with the purpose of understanding how the innovator may have unconsciously collected and organized the information and ended up with a new solution. Capturing and imitating the mental process provides direction and advice for developing a general method for incremental product development.

The start-up of the development process analyzed the defects and problems. It was found that the scaling of the power train system was the root cause. The operation modes of the grab and jaws opening and closing were executed by rotating the pump and the motor back and forth. The repetitive starts of the motor; as the power and inertia increase, acceleration and deceleration generated excessive heating due to tight encapsulation. In addition, loaded starts and stops against pressure relief valves generated repetitive load peaks. Finally, after several upgrades, the design margins within the space limitations were exceeded.

A linear design approach to this problem would solve it through the analysis of design properties and parameters. Simulations and dimensioning could be used to find out the operation limits by means of forces and thermal capacity. The improvements may have been a new heat exchanger, special materials or motor technology. Alternatively, an obvious solution would be a common hydraulic circuit with a continuous running motor and pump with a separately controllable valve block. However, this alternative was constrained because of the power supply cable had only four wires for the power supply and could not be used due to interchangeability. Wireless data transfer systems were considered, but they were rejected due to reliability issues in rough environments.

The case identifies a typical problem in industrial development; a feasible solution to an original problem or root cause creates a new problem or is restricted by constraints. The case study also showed that constraints may transform the problem from one discipline to another; as here the original mechanical problem may be solved but then creates a control system problem. However, the nature and formulation of the problem changed which may cause a shift in the solution landscape beyond the competence of the original problem owner.

If we approach the case retrospectively from the inventor’s view, the situation is a kind of transformation process from problem to solution. Before the intuition, when the invention took place, the critical phase was how the opportunity was identified. Referring to the problem solving methods (Goldratt 1990), the problem verbalization and search for the root cause are the key elements towards finding a solution. Constraints, contradictions and interactions create the means which stimulate creativity with the exploration for new solutions. However, creativity is not enough, there is a need to provide guidance or focus on what in the solution space can be changed. A problem’s definition and analysis provide a deep technical context and this has to be able to be utilized for a more systematic approach than just relying on intuition.

Human creativity played an important role in this case, because multi-disciplinary workgroups, brainstorming or other creativity techniques were not used. However, the inventor has deep and broad experience within engineering and specifically in the mechanical discipline. Therefore, the question is; how did the inventor end up with an invention from another discipline? The focus of this study is technical and is not extended to the human brain, even if it is the key element for the result. By focusing on the information and the problem and the eventual solution an approach for determining the seeds for the idea was developed and is presented below.

The inventor understood that the earlier development had led to the current situation and due to the static design a totally new product development would be very difficult. The new solution introduces a new way of transferring the control commands to the hydraulic valve block, enabling the construction and operation of the valve system with reliable commercial components. Accordingly, the new solution involves an additional discipline into the system, control logics and with this the operation principle of the power train system was changed.

The problem solving logic applies the multi-disciplinary approach which enables the opportunity identification to change the operating principle.

Even though there is no documented systematic exploration within and between disciplines in this case, it is feasible, with logical reasoning, that this is what took place. In developing this approach further, a path from problem to solution may be presented [Figure 7.4]

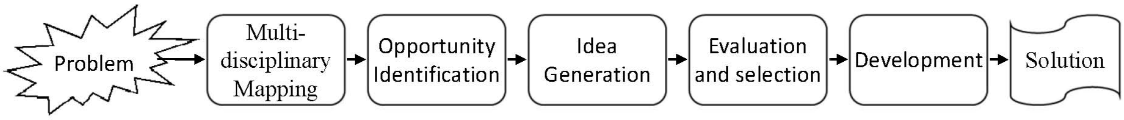


Figure 7.4 Transformation process from problem to solution utilizing multi-disciplinary mapping as opportunity identification and idea generation.

It is proposed that the information processing and multi-disciplinary mapping takes place prior to the opportunity identification and idea generation phases. This mapping includes the recognition of the function activity chain, which actually describes the operating principle of the system. The mapping identifies the interactions among and between each technological discipline in the system and as a consequence enables the recognition of opportunities and seeds for ideas in a more systematic way.

7.4 Conclusions

In this Chapter, the focus is on the opportunity identification phase and a review of the methods proposed for incremental product development is summarized. Specifically, the viewpoint comes from the practical working sphere of a development engineer bounded inside the triangle of "design - incremental innovation - concept" as presented in Figure 6.1 in Chapter 6. Additionally, a retrospective case study is presented to describe a birth of an inventive solution.

The focus of this study has been on that specific area of design that searches for incremental innovation theories and methods, which is addressed with the design context and may be favourable to the working practices of industrial engineers. Specifically, the reviewed design processes and their support for the opportunity identification were contrasted with the engineering and technical context of the product.

Generic design processes and product development methods do not sufficiently provide systematic, context sensitive support for opportunity identification. Methods during conceptual design in literature show that intuitive or discursive methods are preferred for the creation of new solutions. However, these methods are too generic and more applicable to new product development.

Opportunity identification is an essential phase in the product development process. Without an identified opportunity, the creation of ideas relies only on intuition and is just a lucky coincidence. Accordingly, the opportunity identification shall be understood in wider context to consider value improvement and/or decrease the cost of value creation, of which a problem or failure is an indication.

The retrospective case study is presented to create an understanding and basis for searching for opportunities in a more systematic way. The synthesis showed that the mental process of the innovator follows more of a problem solving theory than a design theory. In the case study, the development of the solution was fostered with the multi-disciplinary approach within the design context. Although the innovation consists of an application from the control and electrical disciplines, a mechanical engineer produced it. No explicit method was consciously used, but the capability of a global view on the system was the prerequisite for the inventor's intuition. This confirms that, as presented in the literature, creative solutions are more likely to be introduced by individuals who have multi-disciplinary knowledge and experience.

The analysis of the case provides a lot of information that can be used for creating a basis for a context sensitive approach. The approach identified in the case study, particularly the multi-disciplinary view of the modern technical systems, is essential for describing the operating principle of the system. Hence, the opportunity identification phase is presented as a phase where gathering the activity chain of the functions can be arranged in a way that supports the more systematic identification of opportunity.

However, even though the innovation in integration was the result of individual intuition, it was found to be a very attractive and promising means to generating seeds for innovative solutions. This means is further studied and developed in the following chapter.

The situation described above refers to cases where a product developer in industry typically calls for more applicable tools for the development of existing products or concepts.

8 The Incremental Innovation Method

Much discussion on innovations and their importance for enterprises has been published. The general approach currently remains in the business or organizational level and seldom penetrates deep into concrete actions with artefacts. A visit to a successful enterprise may show that innovations or inventions arise in the organization with the aid of a known talented individual, "the inventor". This person is usually one of the most experienced employees, maybe somewhat extraordinary, but is recognized with awarded patents or designs named after him/her. Naturally the organization may assist their innovativeness, but does the inventor consciously follow any systematic methodology while producing their creative work? Probably not, apparently their logic is naturally formed to sensitively identify multiple leads from the surrounding environment and combine them with product experience and knowledge that enables intuitive opportunity recognition.

Innovativeness has been highlighted in business literature as a pre-requisite for competitiveness and the survival of enterprises. Numerous publications introduce industry, product and organizational views on innovations. These views have an important role for managerial purposes regarding strategic planning and target setting. However, often the examples in literature introduce great success stories that are the result of a radical innovation, which has changed the marketplace.

Fewer acknowledgements have been given to companies, which year by year grow and maintain their competitiveness through incremental product development. Naturally these examples are less attractive to headline writers. However, engineering practitioners struggle daily with the search for better product functions and properties that can be realized with lower costs. In the business environment, the engineering challenges are divided into two; (i) the products shall appeal to customers and (ii) be cost conscious to maximize profitability. The first one directly aims to serve customer value and the latter one aims at product cost and production efficiency, but both call for innovativeness.

The development work on enterprises which is directed towards existing concepts has specifically influenced on the cost and quality feedback information utilization with well-developed analytical tools. However, product development methods that support new product development viewpoints emphasize scenario and creative techniques. Unfortunately, these techniques do not provide much value for development engineers working with static concepts, instead striving for incremental development and innovations what are required by business drivers.

8.1 Introduction

Various changes and developments are made to a product's technical concept during its life cycle. On the way to a static design stage, numerous different solutions may be introduced by many manufacturers, but finally differentiation on the main function level is reduced to only a few or one. However, competition in the marketplace requires continual efforts to improve product properties that provide greater value to customers and simultaneously decrease manufacturing costs and maintain profitability during price degradation.

A product's technical system changes when approaching and reaching the static design stage are incremental; that is the improvements take place within a few sub-systems or even one technological discipline, mostly initiated by cost drivers. When reviewing product development actions and results from an industrial point of view, several ideas may be introduced that have been generated by the impact of the development methodology on product conceptualization:

- Radical innovations, specifically with investment products, are exceptions and their time to market is long, development costs and business risks are high.
- Product concept life time is extended with incremental improvements. Results are gained through developments within technological disciplines, thus the steps become smaller.
- At the static design stage, when the functional properties of a product cannot be further improved by optimization within one technological discipline, advanced material or manufacturing technology, consequently unexpected and dissatisfied product behaviour may appear due to partial optimization.
- Application of generic product development processes in a linear way ignores the integrations and impacts between the sub-functions and different disciplines of the technical system. Linearity in development processes exists at different levels and is depended from the viewpoint, e.g. propagation from requirements – specification – properties – characteristics to detailed design assume that the product behaviour automatically follows.
- The functional structures of the technical systems are derived as a collection and interrelationship of functions. Ideally, it includes functions in a hierarchical order with material, energy and information flows needed to fulfil the purpose. However, converting the combination and relationship of organs (functions carriers) defining the operational principle into part structure in multi-disciplinary products is not well supported.
- Functional structures ignore the functional event chain during the transformation process (the time and action sequences during the mode of action from initiation to the end of the physical execution).
- The quality and the consequences of the purposeful behaviour are not defined, except as desired ability to perform a set of actions. The transformation process is assumed to be ideal and gained explicitly by the product properties.

In industries where product lifecycles are years or even tens of years, there is a quest to continuously develop existing concepts. This is a natural consequence of business economics because new product development involves significantly higher capital investment and risk, even if it may provide a better market position and/or profitability.

An industry prefers to maintain and strengthen its capability and competence within the technology of its business rather than expanding beyond it. Development activities focus on the key areas and rarely spread their efforts and resources to the search for radical innovations beyond their core competence and business (Christensen et al. 2004).

The development of existing products and technical concepts aims for product value improvements, which affects quality, function and properties. According to two viewpoints on value, the users' and the manufacturer's, opportunity identification is essential in the search for development items. Hence, much knowledge and experience of existing concepts may need to be utilized to direct idea generation beyond the application of generic product development methods.

Industrial development actions are executed through projects, which have adopted the results of studies and literature on how to establish tasks, schedule and budget control. These project management methods are also applied to product development, which has enabled industrialists to overcome many management problems. However, this has not solved the engineering challenge of creating ideas, even though their further development may be managed and controlled.

Generic product development processes have familiarities with project management methods; e.g. task clarification, target setting, dividing execution into manageable stages, analysis and verification with tools for each phase. However, even if the process descriptions provide the visualization of needed activities for the product development, the main approach is managerial and is to handle complex tasks rather than innovative ones. This is the consequence of the new product development approach, in which needs are interpreted into requirements and specifications at an early process phase. This directs the following process phases to develop according to the specifications given.

Incremental product development has a different nature; it is more like a transformation process from problem or opportunity identification to solution. The problem lies within the existing concept, which is utilized in the search for value improvements. This process requires a new approach and method for generating seeds for incremental innovations, specifically among modern multi-disciplinary products.

8.2 Purposeful behaviour of the product

Technical systems are often classified according to their functions, which enable designers' to address the constructional part structures of products more easily. A function or a combination of functions is designed to fulfil the purposeful mode of action, transforming the operand state (Hubka & Eder 1988).

Here, the purposeful behaviour of a product, function, is defined to include all necessary and relevant functions that fulfil a user's need with regard to the transformation process. Function in this context has a meaning in two dimensions; primarily it defines the realization of a transformation process by means of properties, but it also defines how the state change of the operand is performed and meets the user values.

The evolution and development of technology has enabled the wide utilization of programmable control systems. However, the historically strong distinction between professional disciplines has been a hindrance to true multi-disciplinary product development. Despite many exercises with multi-disciplinary teams, the consequence has been more a layered or modularized technology architecture with products.

Modern machines consist of multiple systems that interact and impact with each other. Function cannot be considered only to be delivered by the mechanical structure, because the control system plays a key role in how function is realized in bringing together product performance, and external and internal effects. The function of a technical system is strongly dependent on the integrations between technological disciplines. Consequently, function cannot be improved by changes within only one technological discipline.

Lehman (1985) presented the basic signal flow functions in micro-electronics. Regardless that this operational schema was suggested for use with modular elements in functional structure, it may also be acknowledged as illustrating the interface and interactions between the user and the technical system. Today, the operation principle of multi-disciplinary products with programmable logics may be presented in a similar way [Figure 8.1].

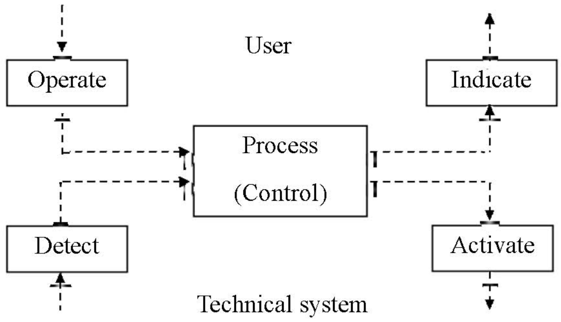


Figure 8.1 *Basic signal flow functions used in micro-electronics. Control unit processes the information and defines the further mode of action. Adopted from Lehman (1985).*

An important finding for product developers in this schema is that functions do not directly interact with the user, mechanism and environment because there is always a control unit which processes in a pre-determined way the operating commands and detects status information before activation and indication. However, the common approach of discipline-oriented product developers is to consider that the “Activate” sequence strictly follows the “Operate” command and that such function is the result of the mechanism according to the defined product requirements and specification.

The predecessors of the modern Programmable Logic Controllers (PLC) were capable of replacing hard-wired connections and relays while performing the function or mode changes in technical systems. Consequently controllers enable automatic sequences and conditional jumps, by giving the advance of autonomous operation of repetitive tasks and reducing the need for manual work by decoupling one task and dedicated resource. Today, the controllers are more like computers and capable of performing more complex calculations, functions and tasks through structured languages, state diagrams and analogue or digital I/Os.

Although machine controls have become more versatile and complex, product development can no more solely rely on conventional methods followed by functional decomposition and structure. Specifically within incremental development, the approach is focused more on understanding about the impacts and consequences of some function through the execution chain used.

The challenge with any development activity is still cross-disciplinary communication and understanding how to enable opportunities for technology integration.

A product’s function, which is physically and visually identified, is the result of a multi-disciplinary impact chain within the product. The function execution event activity of a PLC controlled machine may be described by a scheme, where the user impact is interpreted by the control system, forwarded to the power train system and finally to the mechanical part structure delivering the purposeful behaviour [Figure 8.2].

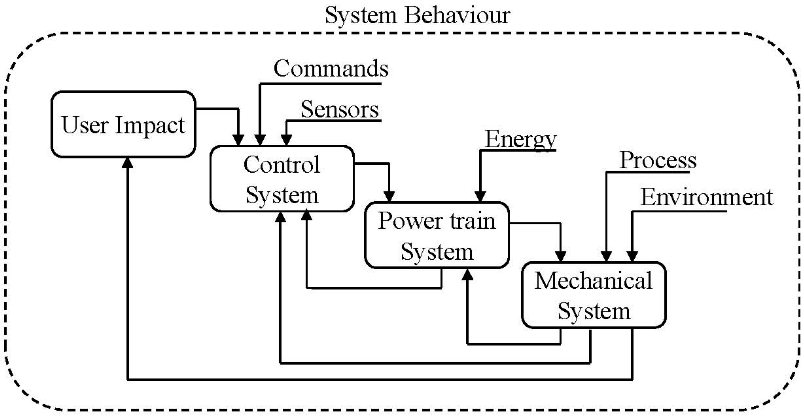


Figure 8.2 Product function is the result of the functional execution chain through different disciplines, which will be identified as system behaviour.

For a product developer, it is essential to understand that function is the result of intertwined events occurring in a technical system. Hence, it is clear that even if the different disciplines are separated, they still impact upon each other. The weak point of generic product development methods is how to model and manage the existence of this event chain and its interactions, as well as enable communication between specialists to cope with sub-systems design.

A typical industrial design process is separated into professional disciplines at early stages after the specification is defined. This may be a result of functional organizations, product specifications or unmanaged distributed design activities. The separation of professional disciplines leads to a situation where the functional requirements and characteristics of a product are mainly defined by the mechanical system. A project manager or mechanical chief engineer manages the system co-ordination. However, depending on the complexity of the system, the level of detail, which results in the behaviour of a system, cannot be adequately controlled.

Product development is typically managed as a project where the purpose is to create a product defined by a product specification. The product specification interprets customer requirements into the language of engineering i.e. functional requirements and properties. The presentation of requirements and properties may come in various formats and is typically presented by descriptions, charts, verbal lists of characteristics and attributes (Pahl & Beitz 1996).

Concerns with regard to this general approach that uses specifications for multi-disciplinary development may be raised from the following viewpoints:

- The product specification, functional structure and description define the result and realization of the transformation process, but not the qualitative.
- The transformation process of a technical system is assumed to be ideal, where the function may consist of independent consecutive sub-functions.
- A division into sub-systems leads to partial optimization within each sub-system because interfaces are defined according to ideal transformation processes.
- Sub-systems are not independent of each other, they have interactions which may not be acknowledged in the specification or appear during the functional decomposition.

From the design point of view, system behaviour is the result of a much wider interaction of the product systems than just the properties and attributes within each sub-system. During a transformation process, a technical system is in interaction with its user and environment, but this interaction is not expressed in development documents. However, it is the total system which defines how function is delivered. For this purpose, the definition of experienced behaviour is introduced.

8.2.1 Experienced behaviour

The definition of customer-experienced functionality has been introduced into software development to describe the properties of system functions apparent to the customer (Chapin et al. 2001). A similar type of approach may be used with technical systems to describe a qualitative viewpoint on transformation processes.

While the organ and parts structure focuses on what and with which kind of solutions the transformation process is realized, the experienced behaviour aims to capture how the function effects are delivered and what the activity chains involved are. Activity chains are consecutive events arising from function activation that allow the physical execution to transform an operand to the desired state. With the activity chain, the focus is on improving the understanding about the function and its consequences, specifically during the mode of action or status changes. Typically the status and mode changes introduce dissatisfying system behaviour, e.g. properties like delays, displacements and vibrations. These phenomena are easily ignored during the conceptual design phase when assuming an ideal transformation process.

The principal hindrance with functional decomposition during conceptual design is its static nature while the function is dynamic. Consequently, due to the lack of a dynamic approach, the time entity, relative dimensions, inertias, action state and its changes are not adopted into the functional structure or any conceptual model. However, describing the function and its response may thus enable an approach to a problem by introducing the realized, wanted and unwanted properties. These properties may be used to identify which integrations in and between the systems interact in the activity chain.

The prerequisite for enabling the use of an experienced behaviour approach is the feedback of the product from the real operation on its environment. This information and experience have been partly utilized for product improvements. Typically methods like value or QFD analysis have been used, whereby product improvements can be based on identified parameters that influence on the selected properties. Alternatively, dynamic simulation tools provide an efficient method of analysis to improve dedicated properties, but require accurate physical and mathematical modelling. During the conceptual design phase, these methods are too concrete and do not support innovativeness or opportunity identification.

The quest in industry is to identify opportunities for improvements and developments in products. This stage of a product development process can be identified as conceptual design, and it occurs before any division into technological disciplines has taken place. A retrospective industrial case study is presented to describe how an incremental innovation led to the creation of a new solution providing a value improvement for the user and manufacturer. The case study is then used to further develop and introduce a new methodology for the incremental innovation process.

8.3 Case study "The long travel function of a gantry crane"

A ship-to-shore container crane is an example of a static product concept, which has remained almost the same for decades. However, the dimensions, lifting capacity, operational speeds, accelerations, control systems and components have changed remarkably during the product concept life cycle. Accordingly, the structural steel frame has had different alternative shapes for creating the suspension for the load handling mechanism [Figure 8.3].

The dead weight of the crane is subject to optimization due to material usage and berth loading, which together with increased loads, speeds and dimensions have caused deflections and vibrations within the large steel frame. Apparently, these phenomena have resulted in dissatisfying operating comfort and decreased productivity.

Figure 8.3 A ship-to-shore container crane used for loading and unloading containers from/to a vessel. Static concept has variations and is tailored to meet customer specific dimensions and characteristic (Konecranes Plc).

The acceleration and deceleration movement of the crane along the rails on the berth initiates a horizontal force impulse. The massive inertia of the structure responds to acceleration and deceleration with a delay, causing a large displacement and vibration at boom level according to its natural frequency. The magnitude of the impulse and displacement is relative to the acceleration or deceleration impact. The acceleration ramp time is much longer than the natural frequency of the structure; thus the impulse from the acceleration continues over the structural oscillation amplitude and amplifies the structural displacement. The dampening of the oscillation is slow due to the great inertia, which prevents the crane driver positioning the load accurately.

The business environment with economic drivers set constraints for the solution space: the solution has to be developed quickly, its cost impact has to be kept minor and any corrective action has to be applicable to field installation.

Conventional, linear problem solving or design logics may have approached the case as follows:

- Problem cause: The displacement and horizontal oscillation are the consequences of a flexible structure with a low natural frequency, which dampens slowly after initiation.
- Solution 1: Increase the rigidity of the structural sections for more resistance against impulses. Achieving any significant improvement with this solution

requires a huge amount of additional steel resulting in a high cost impact on material and work. Consequently, the increased weight will affect the sizing of other components. Alternative solutions to increase rigidity include changing a structural section to lighter and more rigid lattice type. This solution is not preferred due to increased fatigue properties and a more demanding manufacturing process and inspection requirements.

- Solution 2: Decrease the force impulse by reducing the gantry travel acceleration impact. Theoretically, this solution provides an almost linear effect; doubling the acceleration ramp time will decrease the impulse to half. However, this is in conflict with the requirements and specification and will significantly decrease the performance of one product function.

The most obvious solution of single-disciplinary alternatives led to a dead-end. However, an opportunity was identified for improving structural behaviour through an innovative solution:

- Opportunity: The acceleration time of the crane movement is longer than the oscillation time of the natural frequency. The acceleration impulse increases the displacement amplitude when acting in the same direction and decreases when moving in opposite directions. Arranging the impulse in a pre-determined sequence during acceleration may be utilized to decrease the harmful effect.
- The innovative solution: The shape of the acceleration ramp value was stepped to match the structural oscillation turning points by use of a lower acceleration value when oscillation and impulse move in opposite directions and a higher value when their directions are the same. The total acceleration ramp time remains the same, but an in-built dampening effect was achieved [Figure 8.4].

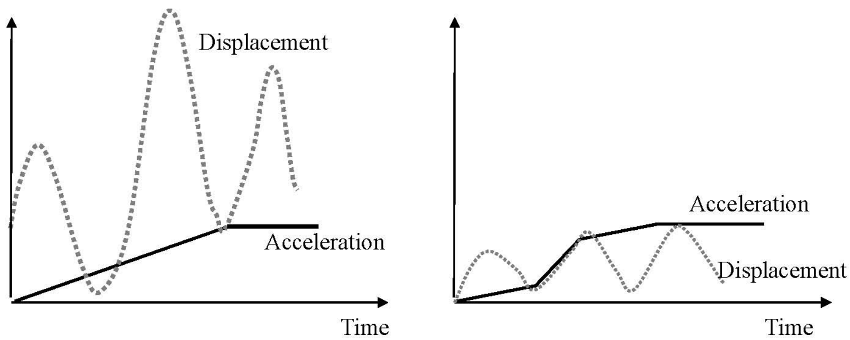


Figure 8.4 The impact of changing the acceleration ramp shape from linear (before) to stepped (after) to reduce dynamic amplification and initiated structural sway (Konecranes Plc).

The innovative solution was easy to implement with the control system, as the required sequence with ramp times and acceleration values could be calculated from the structural data. However, the solution involves three technological areas to be considered:

- Mechanical system; Steel structure and machinery. No changes required, however a possible change exists because the acceleration increase requires higher torque from the travel machinery. However, this operation mode is not the determinative loading case and the necessary margin exists.

- Electrical power train; Electric motors and their converters. No changes required, however the same possible threat as with the mechanical system.
- The control system requires the interpretation and processing of user commands and sensor information and a detailed event execution in digital format to the electrical power train. A moderate change in the sub-program of the acceleration ramp generator, instead of one linear ramp was also needed, and a three-step ramp was developed with unique parameters for each crane according to its natural frequency.

The birth of this innovative solution came purely through intuition - at least the inventor did not consciously follow any systematic method. However, retrospectively all obvious elements for the opportunity identification existed and they are evaluated to find out if any systematic method can be found. The evaluation of the case produced several observations and resulted in some conclusions:

- The technical system presented is a static multi-disciplinary concept.
- The nature of the problem or opportunity was an unspecified, dissatisfied property of the technical system, which came out in the operation and was a part of an experienced behaviour.
- The unexpected appearance of dissatisfactory properties was a consequence of partial optimization and weight minimization within one technological discipline. The original design with a linear top-down development method and its division into single functions principally aimed to match one product property to one design parameter (axiomatic principle), which then failed to be applicable within a multi-disciplinary product. The separate development of systems may provide a more controllable process but also lead to the proliferation of such functional compatibility.
- The prerequisite to identify the opportunity was to perceive the total function, and interactions and impacts between different technological systems and the functional execution chain during the action mode changes.
- The implementation of the solution took place in a sub-concept level of the product, in an activity where functional decomposition and structure do not penetrate.
- Functional structure and decomposition into sub-structures or sub-systems do not recognize impacts on other sub-structures.
- The solution was within all constraints and almost ideal, the cost impact practically zero.
- The solution was implemented within a different technological discipline to the one it appeared in.
- A creative technique, brainstorming was used for idea generation, but this failed due to lack of systematic or value creating processing in the existing concept.

Observations and question; can a generic product’s development processes and methods respond to the industrial demand for developing static multi-disciplinary concepts? Based on earlier considerations, it is claimed that:

i. *The initiation of an incremental development results from a problem or an opportunity within an existing concept and not a need as with new product development.*

ii. *Incremental development focuses on a static concept, where the sub-systems or each discipline have been thoroughly optimized during the life cycle of a product.*

iii. *With static and multi-disciplinary concepts, the potential development opportunities may be identified with sub-system or discipline integrations.*

8.4 The incremental innovation method

The main finding from the retrospective case study was that the mental processes of an inventor are more familiar with problem solving methodology than design methodology. However, the practical means for the structuring and verbalization of a multi-disciplinary view and the role of different technologies lie beyond the consideration of problem solving methods.

Based on earlier observations and conclusions, it is obvious that the development of static concepts needs to be approached by different and more specific methods. The primary objective is to capture and understand the design conditions and physical phenomena during function execution. During any innovative process, ideas may be generated and introduced in numerous formats, but sources for incremental innovations may also be identified.

A new method has been developed which is based on the approach of combining elements from the context of the technical product concept, which are recognizable from static multi-disciplinary concepts:

- Product value viewpoints from both the user and manufacturer can improve a product's value and decrease the cost of value creation.
- The experienced behaviour of a product will ultimately determine how well the transformation process is delivered.
- Concept development with multi-disciplinary integration involves evaluating the function execution chain through various disciplines.

The incremental innovation method begins from the value viewpoints. This is crucial for a business; without value improvement there is no premise for consecutive transactions, enabling the existence of enterprises.

Next, the understanding about the behaviour of a product in its operating environment is deepened. The function provides the means to transform the operand between states and act as an important measure for user satisfaction by determining how well the function is delivered to the customer, and how well a product performs. Its experienced behaviour combines the different aspects of product properties.

Finally, insights into a function execution system can be made and a context sensitive approach can be introduced to identify interactions and impacts between different technological systems in a product. Further on, opportunity identification with multi-disciplinary integration may be used as seeds for ideas [Figure 8.5].

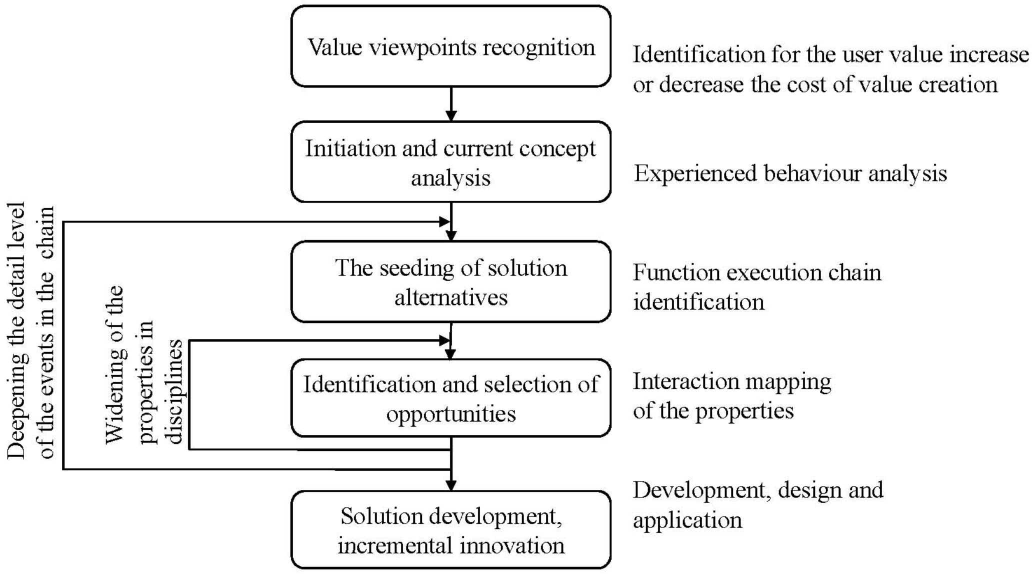


Figure 8.5 Basic stages of the incremental innovation method and the iteration loop to deepen the detail level of events and/or widening the selection of properties for interaction mapping.

The two crucial stages of the method, the function execution event chain identification and interaction mapping of the properties, are strictly application depended. Therefore these stages include feedback loops to deepen the detail level of the events and/or widening the properties along disciplines to enable developers to find potential interactions.

The different phases of the method are presented in more detail in following paragraphs.

8.4.1 Initiation, current concept analysis

Incremental development focuses on the product improvements through conceptual changes in product sub-concepts and implementation in sub- or supporting functions. Concepts, which have passed several improvement or cost reduction activities during their lifetime, may show up with various functional problems. The typical appearances of these are:

- Vibrations or displacements due to weight optimization, inertia or operating speed changes or dimensional growth.
- Increased noise, wear or temperature due to increased power utilization or component volume.
- Slow response time to the activation of a function due to increased size or inertia.
- Breakages due to high or alternating stresses caused by materials, complicated design or ignored loading cases.

Once the problem has been identified, the initiation of an incremental innovation method is directed to analyze the existing system. Rather often many of these are the consequence of partial optimization within one technology or discipline (Liedholm 1999).

The analysis begins by describing the problem with the experienced behaviour and continues by recognizing and defining all systems and technologies involved in a function execution chain. This includes the functional structure, mechanical system with mechanisms, energy and power train system and control system.

The focus of the analysis is on the status and/or mode changes of a function, which is used to identify the function execution chain in the transformation process. The modelling of this execution chain enables the development team to identify the impacts and integrations between different sub-systems and technologies, which finally, in combination, accomplish function.

The modelling of the function execution chain may be first visualized by using a modification of Function Analysis System Technique (FAST) introduced in the 1960's for the systematic organization and representation of the functional relationships in a technical system. The technique was later successfully adapted and applied with value engineering [Figure 8.6] (Bytheway 2006).

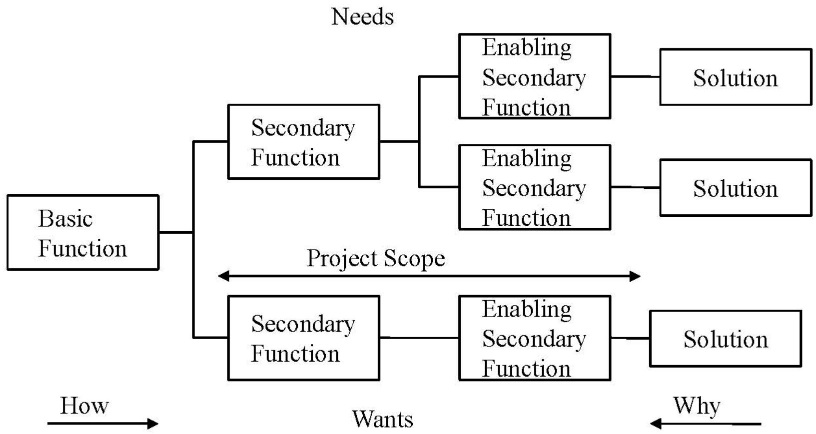


Figure 8.6 *Visualization of function execution and its decomposition into secondary and enabling functions. Adapted and modified from FAST-diagram principle (Bytheway 2006).*

With the original FAST, a logic hierarchy was introduced and provocative questions were directed to each level to better understand system function. Each logic level was challenged with questions (Bytheway & Administrator 1975):

- Critical path logic: How is the *function* actually accomplished? How is it proposed to be accomplished?
- Higher level logic: Why must the *function* perform? What is really meant to happen when the *function* is active. What higher level function caused the *function* be active?
- Support logic: When is the function performed? If the function is executed, what else must also happen?
- Basic function determination logic: If the function is not executed, would other functions perform? When a function is executed in the manner conceived and does it cause each apparent and dependent function to come into existence?

Bytheway & Administrator (1975) argue that function shall be split and distinguished into smaller sub-functions with the purpose of determining the basic function, specifically the function that caused all the other functions to come into being or existence. The principle is analogous with functional decomposition (Hubka & Eder 1988, Pahl & Beitz 1996), but the specific questions are directed more towards execution order and relationships.

The same principle may be applied first while analyzing the existing concept and functional structure, but identifying a function execution chain requires a deeper evaluation of the transformation process [Figure 8.7].

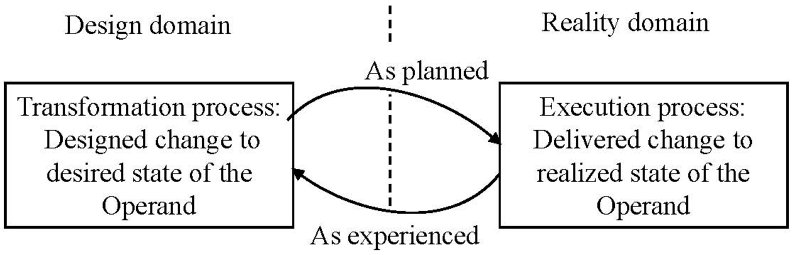


Figure 8.7 *Transformation from the design domain to the reality domain, the change of concretization from requirements and planned state towards execution and feedback.*

The transformation process model in the design domain can handle all relevant parameters to describe the execution process as long as the function can be described within a single discipline's structure.

An addition of disciplines (or technologies) into a function creates a series of events, which have consecutive and parallel impacts on a function activation process. With multi-disciplinary products, the concept analysis aims to identify:

- What initiates the function?
- How is the initiation indicated to the control system?
- What are the other indications, interlockings and events which are coupled with the function?
- How are the function status or mode changes modelled in the control system?
- How does the control system initiate the power train system?
- How does the power train system initiate the mechanism?
- What measures or consequences can be identified during the execution process, which differ from the ideal design transformation process?
- What are the physical static and dynamic characteristics of the mechanism and power train systems?

The transformation process in the design domain describes how the operand transforms from an existing state to a desired state. However, during the execution process in the reality domain, it is possible to identify how the state change is actually realized.

The function execution chain may be visualized as a consecutive event chain connected with coupled or uncoupled effects [Figure 8.8].

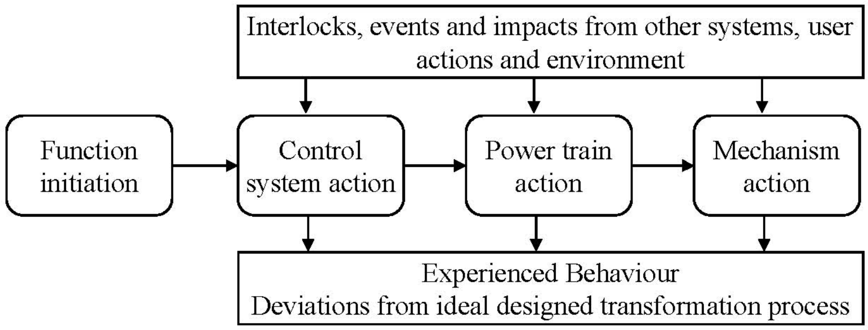


Figure 8.8 Function execution chain from initiation to the concrete mode of action with interactions between disciplines, effects and active environment.

A specialist, dedicated to design within one technological discipline according to specification, often ignores the modes of execution and focuses only on the design properties and characteristics. The visualization of a consecutive function execution chain provides an extended view for the development team of what systems actually influence the function. An example of partial function execution chain during gantry acceleration in the case study presented in Chapter 8.3 is presented in Table 8.1.

Table 8.1 Example of the function execution chain events and their correspondent disciplines during gantry acceleration.

	Gantry acceleration	**Discipline**
1	Driver indicates the desired speed with joystick	User
2	PLC reads speed reference signal and filters unintended fluctuation	Control
3	PLC sends the speed direction reference to inverter	Control
4	Inverter magnetizes the motor and generates the torque	Power train
5	Inverter energizes the brake	Power train
6	Brake opens	Mechanism
7	PLC checks brake open and interlocks free	Control
8	PLC sends to inverter speed reference according to the ramp shape	Control
9	Inverter raise supply frequency to motor	Power train
10	Motor generates the torque and accelerates the rotating inertia	Power train
11	Speed and torque are directed to wheel through a reduction gear	Mechanism
12	Wheel - rail friction converts the torque to horizontal force	Mechanism
13	Gantry (crane) accelerates to desired direction	Mechanism
14	Structural sway appear	Mechanism

The presented event listing of the function execution chain includes at this stage the main events which are in interaction to or with other disciplines. Further detailing of these events penetrates deeper into each discipline thus enabling the development and optimization within the discipline.

The listing of the events enables communication between practitioners and allows them to acknowledge interactions that cross the borders of the disciplines. The concretization of the isolation between disciplines and the need for communication may be described with the practical work scopes of different specialists; the mechanists follow the specification derived from requirements as “gantry travel speed is 45 m/min and acceleration time from zero to full speed is 5 seconds”. Once the required acceleration force has been defined and converted to motor torque, the electricians choose the correct sizing for the power supply and inverter. Finally, the automation specialist programs the PLC code for particular function and related interactions.

8.4.2 The seeding of solution alternatives

The deviations in various forms from the ideal transformation process are obvious development issues. The consequences when applying development processes in a linear way with partial optimization within one discipline lead to the exploration of the root causes of a problem. However, a threat exists in that the analysis is limited to the discipline in which the problem appears.

Each discipline has its own design environment, including phenomenon, design rules, criteria and parameters to address. Without guidance, this leads an individual engineer trying to overcome a problem within his/her knowledge and experience. While a mechanist is familiar with assemblies, parts, forces, stresses, etc., an electrician’s design world consists of circuits, connectors, voltage, current, frequency etc. An automation engineer who programs the control system software focuses on signal processing, event handling and function sequencing.

In literature the analysis and development methods for multi-disciplinary products are rather immature. Also the problem solving and development methods are not known among all disciplines. Therefore engineers prefer to remain within their professional area when a problem solving situation appears. Accordingly, in the worst case, the problem solving process may imitate the decomposition and divide into disciplines [Figure 8.9].

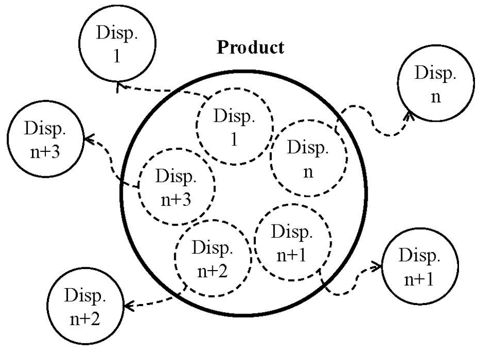


Figure 8.9 Problem solving distinguished into disciplines (Disp. n) imitating linear design method and decomposition.

The analysis and suggestions for improvements within one discipline are naturally important, but they ignore the influence and impact of other systems. With multi-disciplinary products the search for the seeds of solution alternatives has two dimensions: one along the disciplines and the other across disciplines following the function execution chain [Figure 8.10].

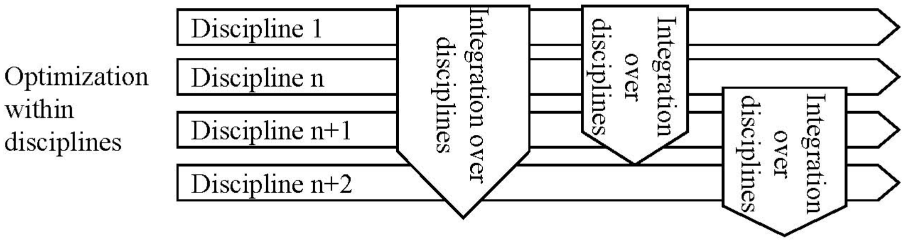


Figure 8.10 Two problem solving dimensions; linear optimization within a discipline and integration over disciplines.

The dimension along a discipline provides the traditional development route, resulting in a linear process and sub-optimization. As stated earlier, with static concepts the development has gone through optimization within disciplines and obviously reached its limits. The other dimension across disciplines provides a platform for identifying seeds for alternative solutions. The integration across disciplines follows the function execution chain and enables developers to escape from a linear axiomatic design strategy.

The integration dimension also illustrates the root cause path for identified deviations from the ideal (designed) transformation process. Accordingly, it can be concluded that the integration dimension across different disciplines with multi-disciplinary products presents a path for a functional response including interactions and impacts. Through this event chain the experienced behaviour is performed in the reality domain.

Experienced behaviour is the qualitative aspect of how function is delivered and received during the execution process. In other words, it is the response to the system, its sub-systems, user and environment when the mode of action is being performed. However, the measurement of this aspect is challenging – often the deviation from the designed ideal process can be recognized, but the measuring is either relative or indirect. For example, an increase in a vibration level can be measured, but the perception is relative to the situation, location or person and impacts on performance indirectly.

Experienced behaviour, the response, has a dynamic nature. A function in a transformation process expresses the change in an operand's state and obviously is a time related activity. However, this is not well considered by functional and process structures or other conceptual approaches. With incremental development, the dynamic relationship during a function execution can be identified when:

- The timescale or time aspect is included with the function mode and changes in state.
- The time related impacts (deviations from the ideal transformation process) within and between the sub-systems are identified.

The time dependent interactions expand the complexity of the functional modelling. However, it is obvious to add this dimension to the general interface logic between subsystems. The time dependency represents and visualizes different views on the design and reality domains [Figure 8.11].

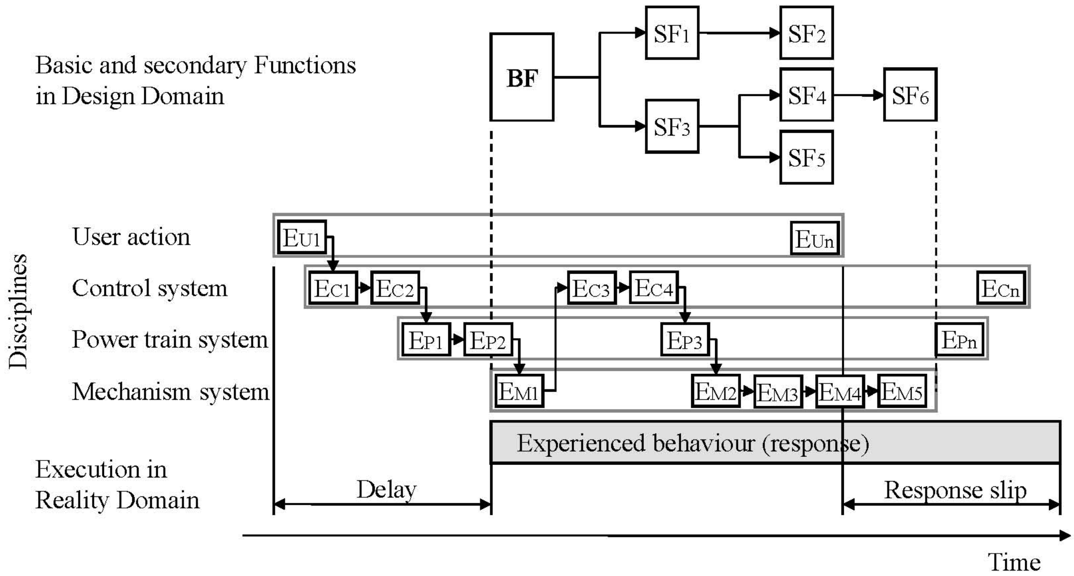


Figure 8.11 Time dependency of different systems through functional execution chain. Differences in Design and Reality Domains when multiple events occur before the physical function activation and response.

The time dependency chart, even on a very rough level widens the understanding about the system behaviour within the design team. The sub-system interactions are not sequential, because depending on the type of transformation process, the activity and response period of each sub-system varies. More specifically, this is concretized by the difference between the internal functions and external effects. On the basis of the case studies, typically ignored differences between the design and reality domains during the conceptual design phase are those where:

- The function activation input reference is assumed to be linear and continuous and can be used as such for control purposes. Cases which involve human controlled equipment or analogical sensors, the reference signal includes a lot of noise and requires programmed filtering.
- The activation reference signal transmission to give a reference for a power train system consists of several sequences; status check, function initiation and start-up, function acceleration, constant function mode, function deceleration, function stop and deactivation. During each sequence various interlocks and interruptions from other sub-systems are active and may influence the sequence.
- Each power train system has its own capability to respond to the reference signal. Depending on the type of energy conversion necessary for the function mechanism, the activation delay and form of force and speed varies. This causes a differentiation between the reference and actual status of the mechanism. At this stage of a function activation event chain, a physical movement in the function exists.
- The mechanical system carries the physical functions and is designed for external and internal requirements. However, when the design parameters and criteria are derived from the functional requirements and specification, all earlier mentioned events in other sub-systems are ignored. Accordingly the functional

response and experienced behaviour in the reality domain differ from the ideal in the design domain.

Each technical transformation process is unique and two-dimensional search for seeds for solution alternatives and possible innovative solutions are strongly dependent on the system configuration. However, even different maturity levels within products in companies can be identified. Therefore, a similar type of approach can be utilized with various multi-disciplinary products.

8.4.3 Identification and selection of opportunities

The analysis of the current concepts and seeding of solution alternatives within and between subsystems provides much detailed information and data on how function is delivered. The next challenge is to organize information into a format, which supports intuitive and creative thinking that provides ideas for further improvements in an existing concept. For that, a visualization of the interactions within a concept provides a context sensitive platform for identifying potential ideas that can be generated from seeds through systems integration.

A chart in two dimensions is created in order to organize the function activation event chain shown on the timeline on the lower part of Figure 8.11 consecutively over disciplines in a vertical direction and the function properties influencing in each event in disciplines in a horizontal direction [Table 8.2].

Table 8.2 Interaction mapping graph, a hypothetical example to show interactions within(S) and between disciplines (M).

Function	Discipline 1		Discipline 2			Discipline n
Property in discipline Execution chain event	Property 1	Property 1	Property 2	Property 3	Property 4	Property m
Initiation	0/0	S/0	S/M	0/0	./.	./.
Event n	S/M	S/M	0/0	0/M	./.	./.
Event n+1	S/0	0/M	S/0	0/M	./.	./.
Event n+2	S/0	0/M	S/M	./.	./.	./.
Deactivation	0/0	S/M	S/M	./.	./.	./.

The function execution chain and specifically the events present the key role while defining the properties for each discipline. Properties evaluated from the execution viewpoint and exposed for the specialist of other disciplines introduce the framework for interaction recognition.

The mapping and interaction identification is executed in two stages. First, within each discipline the design properties are gone through along the function execution chain in a vertical direction and the existence of a correlation is recognized; yes (S as Single-discipline), no (0). The second stage involves a similar routine along each horizontal activation event, recognizing the correlation with other properties over disciplines; yes (M as multi-discipline), no (0).

Mapping the interactions within each discipline and property introduces the discipline-centred view for improvements, or the linear optimization design path. Depending on the concept maturity in its life cycle, the opportunities for improvements along that path may already be used. The more interesting direction with mapping is across disciplines; i.e. the cases where correlation exists in both directions indicate a potential opportunity to influence the delivered function.

The intention of the mapping is to visualize opportunities and indicate interactive properties between two or more disciplines. These interactions may be used to indicate possible deviations from ideal function that have occurred as a result of ignorance during the design process. Static concepts, where a multi-disciplinary method has been applied, are good candidates for improvements, because recognized interactions may lead to the identification of possible concept modifications through a change in design conditions, operation sequence, product architecture or organs.

A detailed example of the interaction mapping from the case in Chapter 8.3 is presented in Table 8.3. The list of properties in each discipline is not comprehensive at once, it is more the framework for practitioners to acknowledge, discuss and complement or remove subjects as the result of interactions.

Table 8.3 Interaction mapping of gantry acceleration showing interactions within and between disciplines. First character (S) indicates single-disciplinary interaction and second (M) multi-disciplinary interaction.

	Horizontal Oscillation of the boom	**User**	**Control**			**Power train**			**Mechanism**			
	Property in discipline Execution chain event	Reference stability	Sequence speed	Filtered response	Ramp shape	Output current	Output torque	Moment of inertia	Accelerative force	Mass	Stiffness	Sway amplitude
1	Driver indicates the desired speed with joystick	S/0	0/0	0/M	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/M
2	PLC reads speed reference signal and filters unintended fluctuation	0/0	S/M	S/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
3	PLC sends the speed direction reference to inverter	0/0	S/M	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
4	Inverter magnetizes the motor and generates the torque	0/0	0/M	0/0	0/0	S/M	S/M	0/0	0/0	0/0	0/0	0/0
5	Inverter energizes the brake	0/0	0/M	0/0	0/0	0/0	0/M	0/0	0/0	0/0	0/0	0/0
6	Brake opens	0/0	0/M	0/0	0/0	0/0	S/M	0/0	S/M	0/0	0/0	0/0
7	PLC checks brake open and interlocks free	0/0	S/M	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
8	PLC sends to inverter speed reference according to the defined ramp	0/0	S/M	0/M	S/M	0/0	0/0	0/0	0/0	0/0	0/0	0/0
9	Inverter raise supply frequency to motor	0/0	0/M	0/M	0/M	S/M	0/M	0/0	0/M	0/0	0/0	0/M
10	Motor generates the torque and accelerates the rotating inertia	0/0	0/0	0/0	0/M	0/M	S/M	S/M	S/M	0/M	0/M	0/M
11	Speed and torque are directed to wheel through a reduction gear	0/0	0/0	0/0	0/0	0/0	0/M	0/M	S/M	0/M	0/0	0/M
12	Wheel - rail friction converts the torque to horizontal force	0/0	0/0	0/0	0/0	0/0	0/M	0/M	S/M	S/M	0/M	0/M
13	Gantry (crane) accelerates to desired direction	0/0	0/0	0/0	0/M	0/0	0/M	S/M	S/M	S/M	S/M	S/M
14	...	./.	./.	./.	./.	./.	./.	./.	./.	./.	./.	./.

The practical detail level in both dimensions of the graph varies from case to case; the first approach should be made on the main events which be identified as clear state changes during the function execution. Similarly, the properties of each discipline are numerous and they should be chosen from top view affecting on each event. The different discipline specialists in the development team may utilize their experience and viewpoints while communicating and creating items on both dimensions of the graph.

The interaction mapping may be used to the identification of opportunities in two ways; within one discipline by following each vertical column and its first character (S) identifying the events where the property acts. This presents the more general optimization path within one discipline.

Second application may be used as the multidisciplinary approach; choosing the second character (M) with the selected property and following horizontally along properties in each discipline showing interaction with the second character (M). As an example for property "sway amplitude" M is shown in rows 1, 9 – 13. Accordingly for each row which relates with the sway amplitude (ignoring the user intervention) may be identified.

However, even at this stage it shows that in total all other properties are in interaction with the chosen property, it is new to practitioners to acknowledge that there are interactions or impacts between disciplines in such extend. As such, the first target of having the framework for multidisciplinary discussion has provided to analyze in detail how these interactions relate to each other.

8.4.4 Solution development, incremental innovation

The delivered function in a multi-disciplinary product is a combination of various interactive sub-systems or disciplines. The activated subject in the transformation process creates an event, which can be presented by using structured analysis design technique (SA/DT) schematics, mainly used in software development [Figure 8.12] (Marca & McGowan 1987).

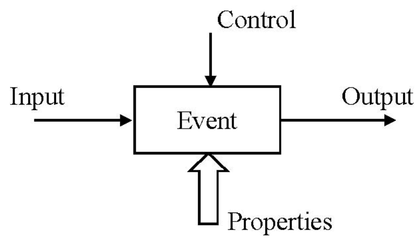


Figure 8.12 Modified SA/DT box describing the basic system element (event) interactions with input, control and properties which results the output. Adopted and modified from Marca & McGowan (1987).

With the modified SA/DT box, the event meets the interactions between different disciplines (properties) under control while changing the state from input (existing) to output (desired). In the search for innovative solutions, a different operating principle may be found in two different ways; either by changing the function execution chain itself (properties) or by changing the control of the events.

The change in the function execution chain may be so significant that a new product class is created. This concept change can be recognized as a radical innovation. If the change in the function execution chain alters one or a few function organs (properties), or the control, then the change creates a new variation in a product class. Accordingly this change is a type of incremental innovation. A change in organs or in control initiates a change in the operating principle of the concept, which in the case of organs may be a result of a new technology implementation, and in the case of control, a new sequence.

With interaction mapping, the primary aim is to identify opportunities to change the operating principle. For each identified event in the interaction chart, where the interaction is positive in both directions, the SA/DT type approach is used to further explore the root causes of the function activation.

Each event forms a SA/DT box and the affected or affecting other events in the same or other sub-systems or disciplines can be seen. Corresponding connections shall be indicated as found in the interaction chart [Figure 8.13].

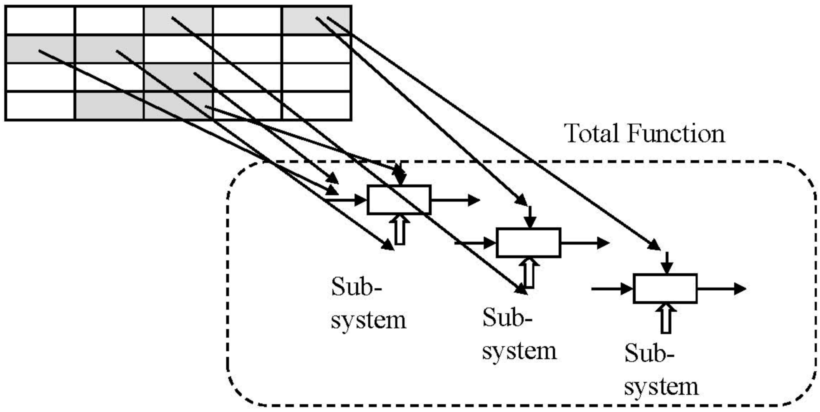


Figure 8.13 Innovation opportunities identification from the interaction mapping chart to sub-system input and/or control sections. New opportunities may be identified with interactions between disciplines.

The interaction chart visualizes the experienced behaviour environment, where the correlations to system (product) behaviour can be identified and used for further idea processing with the development team. The team may use the chart to foster idea processing or development, but also to generate different what-if scenarios to test and communicate how the changes affect – or even generate new ideas to change the operating principle. As the opportunities have been identified, the development tools can then be directed towards concrete items instead of free associations on a conceptual or functional level.

The identified interactions with the properties in the case study are analyzed in more detail for further processing:

- Sequence speed; control property by the hardware characteristic. Consequences: reaction time, the delay of the feedback loop.
- Filtered response; control property to the output signal by the pre-determined data algorithm characteristic. Consequences: smoothing and compensating user command, the delay with the response.
- Ramp shape; control property to the output signal by the pre-determined characteristic. Consequence: actual governor of the speed.
- Output current; electrical characteristic according to the control signal. Consequence: sizing of the hardware according to the required torque. Subjected to optimization due to cost.
- Output torque; mechanical characteristic according to the power train output current. Consequence: sizing of the hardware according to the required accelerative force. Subjected to optimization due to cost.
- Moment of inertia; mechanical characteristic according to the power train installation. Consequence: sizing of the hardware. Subjected to optimization due to torque minimization.

- Accelerative force; mechanical characteristic according to the power train torque. Consequence: original demand according to the specification and initiator of the sway.
- Mass, mechanical characteristic according to the selected concept and specification. Consequence: the requirement for the accelerative force. Subjected to optimization due to cost and stiffness.
- Stiffness, mechanical characteristic according to structural properties. Consequence: the combination of the mass and the moment of inertia. Subjected to optimization due to weight and manufacturing complexity.

With the presented case, the solution was developed by modifying the ramp shape according to the structural properties, which resulted in the variable acceleration force path eliminating the amplification of the sway. However, each of the identified interactions may have been taken for further processing with different concept development methods applied with new product development. Suitable approaches like 40 inventive principles (Altshuller 1998) or other systematic methods presented in engineering literature (Pahl & Beitz 1996) may be used. Once the best potential change items are selected, the continuation of the incremental innovation method follows a general development process. Thus, it develops a new operating principle to provide a solution, comparison and evaluation, as well as testing, validation and finally implementation.

8.5 Conclusions

In this Chapter, the new method was developed to enable the identification of ideas to change the operating principle of a technical system. The method is based on the visualization of interactions between systems disciplines and function events. A specific phase, multi-disciplinary mapping, is presented to provide a system view for a development team that enables their communication and a context sensitive approach to enabling the generation of seeds for ideas.

The method was developed starting from the purposeful behaviour of the technical system and deepening the understanding about the multi-disciplinary product function execution. The contrast between the design and reality domains is presented and the definition of experienced behaviour is presented. Further on, the functional and structured analysis methods are utilized while developing the time dependency approach to function execution event chain.

The key characteristic of the method is the evaluation of the function execution event chain, which across the discipline borders. Further, the properties affecting the events in each discipline are evaluated and their interactions are acknowledged.

The application area of the presented method is best suitable for static multi-disciplinary products, with which the integrative approach over disciplines may provide better concepts, specifically when numerous optimization efforts have been experienced.

The role of the new method is to foster the seeding of ideas in a more focused and systematic way compared with creative techniques. However, the use of creative techniques has an application once the seeds have been identified and creativity and intuition may then be directed to the technical context of the transformation system.

The method also has another role among the development team, because information sharing in a hierarchical team and between specialists with complex products is challenging. When the development tasks are divided into smaller teams or individuals, the understanding about the purposeful function of the total system becomes essential. Specifically, the experienced behaviour is the combination and interaction of numerous sub-systems. However, ignorance of a discipline may result in a supposed solution negatively affecting a function in that discipline and destroying the design intention.

The method was developed based on experiences with industrial development projects and a retrospective study was presented as an example of incremental innovations of the kind that may be developed after the successful seeding of ideas. However, it is acknowledged that the method itself does not generate and guarantee results in the search for ideas as ultimately human creativity enables inventions.

9 Method Application

The developed method is applied in an industrial case to demonstrate its application and outcome in more detail. The case considers one subsystem of a Ship-to-Shore crane, similar type as presented in the earlier case. The crane is used to load and unload containers to and from container vessels, which holds are equipped with cell guide bars to maintain container positions during the voyage [Figure 9.1].

Figure 9.1 The ship hold and vertical cell guide bars for containers. Snag load may occur when a container is jammed into guide bars during lifting (Konecranes Plc).

While unloading, a container jam and stop into the cell guide bars during lifting cause a very high dynamic load peak to the lifting machinery and supporting structure. During past years, several mishaps have occurred when no additional measures have taken to reduce excessive load cases. Earlier, when lifting speeds were lower, the sudden stop of a container could be accommodated by rope stretch and additional safety margin with supporting structure. However, while the performance requirements increase, the higher lifting speeds were reduced while operating in vessel hold. A snag is a mechanical issue and additional devices have been developed to avoid the lifting speed reduction and one typical example of a snag load system which smoothens the load peak [Figure 9.2].

Figure 9.2 An example of a snag load system preventing excessive load peaks to lifting machinery and supporting structure. The operating principle of the system is based either on collapsible friction or hydraulic cylinders (Konecranes Plc).

The additional equipment to protect the supporting structure of the crane has been an obvious solution. However, this equipment requires continual inspections and maintenance. Additionally, the operations personnel are not in favour of the type of triggering systems due they need manual recovery after a snag, which increases the down-time of the crane.

9.1 Initiation and current concept analysis

The value approaches to the case showed opportunities for the user and the manufacturer. The user may be attracted by removing the speed limitation in vessel hold and both by avoiding additional equipment.

The analysis begins from the consequence of the sudden load stop; the high dynamic load peak due to the rapid stop of the load. The lifting system consists of the loading device, which is suspended with the rope reeving system. The ropes are directed to machinery, which have a drum, driven by a reduction gear and electric motor.

The snag event, the sudden load stop during lifting causes rapid load increase in the rope system. This increase is caused as the lifting machinery continues to rotate for a while due to inertia in the system, even the stop is initiated by the overload limiter. The snag event is presented with a time-force graph [Figure 9.3].

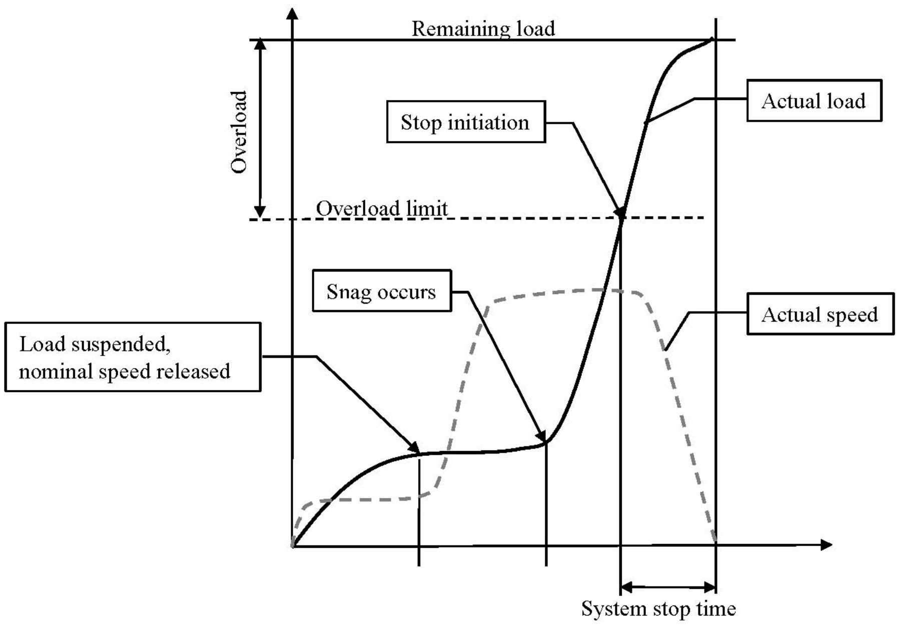


Figure 9.3 Snag event presented with a force-time graph which shows the overload caused by the lifting machinery rotation due to inertia after overload triggering.

The root causes which create the problem of snag consequences are the lifting speed and relatively long stopping time of the machinery. The speed problem may be explained partly by the increased power during the concept evolution, but also with applied “constant power drive system”, whereby the lifting speed is increased with partial load to maximally utilize the machinery power. Even the speed with nominal load could be withstood without additional protection equipment; the utilized double lifting speed without load is far beyond that the structure can accommodate itself.

9.2 The seeding of solution alternatives

The function execution chain is evaluated as shown earlier by collecting the main events during the lifting function when a snag occurs. The event path is followed from the point where the user activates the lifting movement. Notable is, that this captures only partially the whole work cycle needed for a container move [Table 9.1].

Table 9.1 Function execution chain events of the lifting function while a snag occurs and stops the lifting machinery.

	Container lifting	Discipline
1	Driver activates the lifting movement with joystick	User
2	PLC sends the speed direction reference to inverter	Control
3	Inverter magnetizes the motor and generates the torque	Power train
4	Inverter energizes the brake	Power train
5	Brake opens	Mechanism
6	PLC sends to inverter creep speed reference	Control
7	Inverter raise supply frequency to motor	Power train
8	Motor generates the torque and rotates the lifting machinery with creep speed	Power train
9	PLC waits untill censor signal stabilized, mesures the weight and calculates the maximum speed reference to inverter	Control
10	PLC sends to inverter maximum speed reference	Control
11	Inverter raise supply frequency to motor	Power train
12	Motor generates the torque and rotates the lifting machinery with maximum speed	Power train
13	Container moves between guide bars and jams	Mechanism
14	PLC detects overload from load censor signal	Control
15	PLC initiates stop command and sends ramp down reference to inverter	Control
16	Inverter closes the brake	Power train
17	Inverter decrease supply frequency to motor	Power train
18	Lifting machinery stops at extreme load state	Mechanism

The evaluated function execution chain shows at least for the mechanists that the function includes many events before the lifting motion reaches its maximum constant state.

9.3 Identification and selection of opportunities

The event chain list is then complemented in the horizontal direction with properties. As acknowledged form the event chain, the user does not have any involvement during the lifting as the control system masters the function execution. The problem in the system includes also numerous application specific features which are not dealt or explained in detail with this chapter. However, the events and properties are explained providing adequate understanding about the method application.

The first five events may be ignored for this snag analysis, as they take place before any movement. The properties in different disciplines are collected in the interaction graph and their interactions are analyzed within the development team by single- (S) and multi-disciplinary (M) directions [Table 9.2].

Table 9.2 Interaction mapping (partial) of lifting function while the snag occurs and lifting machinery stops at extreme load state.

	Snag load during lifting	**Control**				**Powetrain**			**Mechanism**		
	Property in discipline / Execution chain event	Sequence speed	Speed limit	Triggering limit	Stop mode	Output torque	Moment of inertia		Braking distance	Rope stretch	Snag force
	…	-/-	-/-	-/-	-/-	-/-	-/-	-/-	-/-	-/-	-/-
6	PLC sends to inverter creep speed reference	S/0	S/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
7	Inverter raise supply frequency to motor	0/M	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
8	Motor generates the torque and rotates the lifting machinery with creep speed	0/0	0/M	0/0	0/0	S/M	0/M	0/0	0/0	0/0	0/0
9	PLC waits until load censor signal stabilized, measures the weight and calculates the maximum speed reference to inverter	S/0	S/M	S/0	0/0	0/M	0/M	0/0	0/0	0/M	0/0
10	PLC sends to inverter maximum speed reference	S/0	S/M	0/M	0/0	0/M	0/M	0/0	0/0	0/0	0/0
11	Inverter raise supply frequency to motor	0/M	0/M	0/0	0/0	0/M	0/M	0/0	0/0	0/0	0/0
12	Motor generates the torque and rotates the lifting machinery with maximum speed	0/0	0/M	0/0	0/0	S/M	S/M	0/0	0/0	0/0	0/M
13	Container moves between guide bars and jams	0/M	0/M	0/M	0/M	0/M	0/M	0/0	0/M	S/M	S/M
14	PLC detects overload from load censor signal	S/M	0/0	S/M	0/M	0/0	0/0	0/0	0/0	0/0	0/M
15	PLC initiates stop command and sends ramp down reference to inverter	S/M	0/M	0/M	0/M	0/M	0/M	0/0	0/M	0/M	0/M
16	Inverter closes the brake	0/M	0/0	0/0	0/M	S/M	0/M	0/0	S/M	0/M	0/M
17	Inverter decreases supply frequency to motor	0/M	0/M	0/M	0/M	S/M	0/M	0/0	0/M	0/M	0/M
18	Lifting machinery stops at extreme load state	0/0	0/0	0/0	0/M	0/0	S/M	0/0	S/M	S/M	S/M

The considered problem was the high dynamic and residual loading of the crane after the container jam into guide bars. The interaction mapping indicates that the mechanical snag event may have consequences also from other disciplines. Properties which can be identified as multi-disciplinary interactions with the snag force are:

- Sequence speed; control property by the hardware characteristic. Consequences: reaction time, the delay of the feedback loop which has the impact how fast the stop mode can be activated.
- Speed limit; the essential mechanical characteristic which affects the dynamic energy in the system to be stopped. Consequences: sizing the means for energy absorption and stopping time of the lifting machinery.
- Triggering limit; the crane structure is protected with an overload device, which prevents to lift a load in excess of the rated capacity. The exceeding of the overload limit activates the stop mode of the lifting machinery. Consequences: the trigger to activate the stop mode.
- Stop mode; the controlled stop mode of a motion is made with a ramp generator based on the acceleration and deceleration times in the product specification. Consequence: the motion slowdown follows the ramp and the brake closes when the speed is zero. Due to snag the stopping time is significantly shorter than with the controlled stop mode.
- Moment of inertia; the mechanical characteristic of the lifting systems, which causes the load increase. Consequence: the lifting machinery continues to rotate and tighten the hoisting rope even the container is stopped.
- Braking time; mechanical character to stop the hoisting machinery. Consequence: time to stop the motion affects the hoisting rope tension and the force level.

- Rope stretch; the mechanical character of the hoisting rope which defines the force level resulting of the rope elongation. Consequence: the rope accommodates the dynamic load impact partly.

From the identified interactions, the properties of sequence speed, speed limit and rope stretch may be considered at first as given characteristics of the system and not primary seeds for further evaluation.

9.4 Solution development, incremental innovation

The remaining seeds are further developed on with more familiar methodology by questioning and aiming for modifications:

Triggering limit

The time from snag identification to stop initiation has an essential role of how high the residual load will raise. From the force-time graph [Figure 9.3] it can be identified that the snag indication could be made significantly earlier. However, the lifted load may vary from zero to full and a fixed triggering limit cannot be set. An idea of setting a dynamic triggering limit for each container lifting was made while acknowledging that the actual load is measured for every lifting during the creep speed. The dynamic triggering limit enables to initiate the stop mode earlier and decreasing the residual load after the stop. This idea could be implemented in the control system.

Stop mode

The controlled stop mode is too slow to react on container jam and practically the hoisting machinery stops by “stalling” due to increased secondary torque caused by rope force. An idea of a faster stop mode after triggering was made; the motor of the hoisting machinery may be stopped actively by reversed torque as the direction of the torque could be changed by the inverter in the power train in a few milliseconds. The whole maximum torque can be directed to stop the rotating system only; the slow-down ramp time is significantly shorter which also decreases the residual load. This idea relates directly with the braking time property. This idea could be implemented in the control system.

Moment of inertia

The moment of inertia in the hoisting system is the root cause for the high residual load. The used additional equipment tackles this problem by providing energy absorption by means of collapsible cylinders. The quantity of the moment of inertia is difficult to reduce; it is the result of the physical motor size and the rotation speed. An idea of decoupling the moment of inertia after triggering was made; implementing a break-away type coupling to detach the motor from the lifting system after triggering will remove the root cause creating the high residual load. This idea affects directly on the primary force flow and requires additional development; a high speed coupling with pre-determined break-away torque, means to stop and hold the hoisting machinery after detaching the coupling.

9.5 Conclusions

The problem in the case was the result of numerous performance improvements, the increase of the lifting speed, during the concept life cycle. The implemented mechanical snag load protection system is an example of the single-disciplinary approach while the problem of acknowledged mechanical force impact is solved with a mechanical device.

The current concept analysis shows the physical event and its occurrence on the time axes. Accordingly, after the function execution chain events creation, it was identified that the control system has the dominant. This and further on the interaction mapping provides the identification of seeds, on which ideas may be developed more systematically.

Two first ideas could be implemented only in the control system and were very promising. The characteristics of the dynamic triggering limit according to measured load and stop mode were simulated and results showed that the speed reduction in vessel hold could be removed and safe operation could be provided for typical crane configurations without any additional snag load prevention systems. These properties were further developed and implemented into the control system, resulting in the change of the operating principle in the lifting system and accordingly creating incremental innovations.

The third idea, decoupling the moment of inertia, was forwarded for further development aside of delivery projects due to the development need for the special components.

The applied method required very in-depth understanding about the operation of the lifting system and required the involvement of professionals from different disciplines. The communication between specialists was enabled with the method, specifically while developing the function execution chain events. Accordingly, the seeds for ideas were context sensitive and useful for further development.

The application of the method with the case validated that the seeding of ideas may be done context sensitively and systematically with multi-disciplinary concepts in an incremental way. However, the particular case application is one type of concept and wider applicability of the method with different products is required. Accordingly, the method itself does not guarantee innovations, human creativity involvement is necessity.

10 Discussion

In this study, a constructive research towards a new incremental innovation method for developing multi-disciplinary technical concepts was presented. The approach is strongly based on product development and engineering in industry and has its viewpoint presented according to the practical tasks and challenges of a development engineer.

Product development processes, technical systems and innovation theories and methods were studied and discussed, especially with regard to how they assist and/or guide the ideation of solutions, innovations and the development of better concepts during development projects in an incremental way. The practical experience and case studies have emphasized the further development of existing methods and specifically focused on static, complex and multi-disciplinary concepts.

10.1 Research approach

The nature and behaviour of complex technical systems has been acknowledged in literature to be an integrated combination of several sub-systems and technologies, where the internal interactions have a significant role when performing a total transformation process. However, even the behaviour of a technical transformation system has an analogy with systems theory, the application of design methodologies among product development processes in industry has a linear nature because they are based on frozen specifications with strict project management. Even the processes in literature include formal feedback loops enabling iteration between different phases, the industrial application prevents to return and change predetermined concepts with alternative solutions which may cause a delay on schedule or risk in the realization.

This raises a practical problem for product development. As the preliminary technical solution and specification are defined by means of the functional decomposition approach and are hierarchical, where each function or group of functions is defined, they act as a definition for the transformation process at the next (higher) level of complexity (Eder & Hosnedl 2007). However, the purposeful behaviour of the whole technical system, the mode of action and produced effects are produced through embedded systems or integration; within those the linear functional decomposition cannot be explicitly defined.

The generic product development processes provide systematic approaches for new product development. In such, approaches the process initiation is triggered from opportunity identification from market need or technology push. The nature of these processes is to create a new technical system or concept from scratch. In industry, the practice for product development is more focused on existing concepts due to financial business continuation constraints. However, the experience of the development of static concepts has shown that the existing methods do not provide adequate support for development in an incremental way.

10.2 Contribution

The basis for the study and the research question has been approached from three aspects and answered as follows:

i. *What are the differences between a manufacturer and a user when evaluating product properties?*

The nature of value is studied in various contexts in business and engineering design. In design context, value is qualified by the degree to which how well somebody's needs are fulfilled. Value is determined by properties, which can be divided into various categories and the goodness of a technical system is measured by its deviation from an ideal solution.

In business a product shall provide greater value and benefit to a stakeholder than the required investment. This reveals that the value content is different depending on the viewpoints of a technical system, user or producer. Accordingly, value is relative and dependent on the viewpoint, time and context. Customers and manufacturers make their decisions and judgement based on benefit analysis. Benefits, consisting of the different elements of value, are evaluated case by case and are dependent on time and context.

Value is not an absolute measure as a product requires evaluation by stakeholders in order to be given a value and a concept itself does not have a value until a transaction is conducted. Accordingly, during a development process, benefits and value are assumed to a virtual stakeholder.

An approach of *two value viewpoints* is presented. This consists of value elements, which may be used by development engineers for the better exploration, evaluation and analysis of product innovations in order to fulfil two business drivers: decrease the cost of producing a product (the internal pressure of an enterprise for profitability) and the improvement of a product's value (the market's external pressure to maintain competitiveness)

ii. How does product function differ between design and reality?

The focus of the development methods is functions and how the purposeful behaviour may be designed. Less emphasis is laid on the functional response, e.g. how the behaviour realize in reality and how the technical transformation process operates the operand to the desired state. The behavioural consequences in a reality domain are seldom completely acknowledged or determined during the development stage, as the behaviour fulfilment is assumed to be gained through properties.

The understanding gained with retrospective case studies has shown that the product development methods are applied in a linear discipline oriented approach during conceptualization. This leads to the separation of the functional structure into independent sub-systems and/or disciplines and directs design activities to partial optimization within the borderlines of each discipline. With multi-disciplinary technical systems the behaviour of a product in its real operating environment is the result of system interactions and impacts, which need to be addressed during the conceptual design phase. An approach of *experienced behaviour* is presented to extend the understanding about the system behaviour in real life within multi-disciplinary products. This was utilized to overcome the conceptual development challenges in today's industry and provide a basis for developing an incremental innovation method for technical concept development.

iii. How do product development processes support incremental conceptual design?

Within product development, idea generation and conceptualization is dependent on the task assignment as different approaches between new product (dynamic) and incremental (static) development may be acknowledged. Methods for dynamic concept development are varied and their purpose is to provide a wide range of ideas - starting from abstraction. Incremental development has a different origination because it already has a concrete concept, which enables the use of systematic context sensitive analysis and synthesis methods.

The weak point of the available analysis methods in literature is their linear nature because each of them aims for the decomposition of a product's functional structure, and the simplification and isolation of the impact of multiple design parameters. The methods are capable of presenting relationships and interactions to some extent, but it is questionable how well these methods assist development engineers in their search for ideas.

The synthesis from the case studies showed that the new incremental development method enable multi-disciplinary integration, the understanding about the system interactions with the creation of the functional execution chain. The functional execution chain is determined according to the operational principle of the system, which enables a distinction between dynamic and static concepts and opens up to accept more context sensitive idea generation and conception opportunities for incremental development.

10.3 Results

The research question of this study was formulated as:

What kind of incremental innovation method is applicable for finding innovation opportunities that aid the development of multi-disciplinary technical concepts?

The research question builds a hypothesis that a context sensitive method in a more systematic way to support idea generation for static concepts may be developed. As a result, one approach was identified with the case studies and understanding was further developed for a method. The new method focuses on improving the technical systems by means of refining incrementally existing concepts that carry the "idea in" aspects, by means of utilization of the multi-disciplinary integration approach and the change of the operating principle of the technical system.

The new method was developed based on existing theories and methods and by using a constructive research method and logical reasoning. Based on the different aspects, a new method was developed to find incremental innovation opportunities for the development of multi-disciplinary technical concepts. The goal of the method was to enable the identification and understanding about the design problem challenges and encourage cross-disciplinary communication as the case studies have shown that potential innovation opportunities were found through multi-disciplinary integration. The new method focuses on:

- The product development problematic in industry with regard to the development of static concepts, and value appreciation from the viewpoints of user and manufacturer, as well as the conceptualization of multi-disciplinary products.
- The distinction of technical systems according to operating principles and the identification of the experienced behaviour, e.g. how and with what consequences the technical transformation process is performed.

- The identification of the functional execution chain which activates the technical transformation system from function initiation to the end state.
- The description, definition, mapping and analysis of functional interfaces, interdependences and impacts between technologies and disciplines in order to provide opportunity identification for incremental innovation seeds.

The new approach enables an integrative development process, which fosters opportunity identification for static concepts. The method includes four specific phases which form the core of it:

1. Initiation and current concept analysis:

   The recognition and analysis of the experienced behaviour of the function in the reality domain. Identification of the different disciplines in the transformation process.

2. The seeding of solution alternatives:

   Identification of the function execution chain through different disciplines. With this the consecutive events on the timeline are developed within the development team enabling the communication between specialists and understanding the function response in the reality domain.

3. The identification and selection of opportunities:

   The exploration and identification of interactions by means of the multi-disciplinary mapping between function execution events and properties in each discipline. The selection of the events which are affected by properties from several disciplines.

4. Solution development and incremental innovation:

   Identification of the properties and control which affect on the selected events and developing solution alternatives which change the operating principle of the function.

The presented method enables a context sensitive approach to generate seeds for ideas which has resulted in incremental innovations in multi-disciplinary technical concepts. The method application is presented in Chapter 9 as a practical example and validation for the purpose.

The research question is answered by the developed method which differs from the presented methodology in the literature for new product development.

10.4 Conclusions

The new method focuses on improving the technical system by providing better alternative concepts in an incremental way. Evidently, when discussing idea generation and concept development, the impact of the method is in the early stage of its development process. This approach provides an alternative initiation path for a product development process, which complements the generic methodology specifically aimed at static concepts.

The distinction into two by separating radical and incremental innovation as the main streams of product development was based on the concept of the operating principle. With this approach, the pure technical system of a product has been taken as the viewpoint, and other business, product originating process and use viewpoints were excluded. This distinction has enabled the building of a more solid understanding about the engineering approach to incremental product development. Accordingly, the concept of an operating principle enables the identification of opportunities within modern multi-disciplinary products and highly integrated systems by approaching development from sub-systems and their interactions.

The identification and utilization of the function execution chain provided a tool for sharing information within a development group and expanding design team knowledge according to the chief engineer's competence and viewpoint. The overall function and purposeful behaviour of technical systems are interpreted according to user and manufacturer requirements.

The search of seeds for incremental innovations is fostered by the means of the multi-disciplinary mapping. With the mapping, the interactions and impacts of the properties of different disciplines affecting on function execution chain events are identified. The events which are affected by several disciplines are subjected under development to change the operating principle of the function.

The applicability of the method has been explored retrospectively with case studies and validated with the method application. The environment and products studied are applications of investment products, e.g. working machines which operate in a value adding process. Accordingly, the function of these machines has the particular purpose as they are the means by which users run their businesses. Therefore all issues and aspects experienced and found with this study are not applicable to products of all kind, especially those which are more dedicated to consumers.

Methods, specifically for idea generation and innovation, are not implicit processes that guarantee successful results. Thus, it is recognized that it is individual human creativity which explores and identifies opportunities. This viewpoint was excluded from this study as the focus here is on a technical approach. However the new method may be used to assist navigation within a problem's parameters and provide idea seeds for human creativity to grasp, use and process.

10.5 Suggestion for further studies

The case studies which were used for developing the method present specific applications with working machines, which reduces the direct application on other types of technical systems. However, the method responses to the research question by providing at least one applicable method for the specific problem of opportunity identification with the incremental development of static multi-disciplinary concepts.

The wider applicability of the development of different technical systems requires further studies that can validate a more general use of the method. In addition to the method validation, wider understanding in industrial applications may be studied as:

- What and how many disciplines are needed for multi-disciplinary mapping to enable the identification of seeds?
- Would an addition or change of a discipline to the technical system increase the probability of opportunity of finding seeds?
- The formulation and format of the communication tool among and between different disciplines by means of the system interactions.

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