Master's Thesis

Principles of Set-Based Concurrent Engineering within Modern Product Development Models

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April 2013

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Deutsche Fassung:
Beschluss der Curricula-Kommission für Bachelor-, Master- und Diplomstudien vom 10.11.2008
Genehmigung des Senates am 1.12.2008

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Für meine Eltern,

Univ. Prof. Dr. Wolfgang Petritsch & Veronika Petritsch B.Sc. M.Sc.

Danksagung

Ich möchte mich bei all jenen, die in direkter oder indirekter Weise zur Erstellung dieser Masterarbeit beigetragen haben, für die fachliche, persönliche oder organisatorische Unterstützung bedanken.

Ein besonderer Dank gilt meinen beiden Eltern, die es mir durch persönliche und finanzielle Unterstützung ermöglicht haben mein Studium anzutreten und abzuschließen.

Des Weiteren möchte ich mich an dieser Stelle bei Hr. Univ.-Prof. Dipl.-Ing. Dr.techn. Stefan Vorbach für die Aufsicht meiner Masterarbeit bedanken. Dieser Dank gilt auch Fr. Dipl.-Ing. Christiana Müller, die sich von Anfang bis zur Fertigstellung der Arbeit viel Zeit genommen hat und durch ihre aktive Betreuung eine große Unterstützung war.

Abschließend möchte ich mich noch bei meinen langjährigen Studienkollegen Jochen, Martin und Philipp bedanken. Sie haben mich während der gesamten Studiendauer mit ihrer Freundschaft gestützt und mir eine erlebenswerte Studienzeit bereitet.

Abstract

Product development is an integral part of every manufacturing company. Process models provide guidelines and serve as control mechanisms to assist with this task. One of these approaches is Set-Based Concurrent Engineering and was popularised and developed by Toyota. By adapting more and more ideas from the Toyota Production System, the Toyota Product Development System evolved into a product development model which is often viewed as the prime example of lean product development.

Set-Based Concurrent Engineering separates itself from more traditional approaches by developing multiple sets of ideas until very late in the design process and therefore intentionally delays decisions. The reason behind this is an increased flexibility of product design and an increased understanding of the system, leading to an overall better product.

The aim of this thesis was to compare the defining nine principles of Set-Based Concurrent Engineering to five modern product development models. The discussed models are the W-Model as described by Eversheim, Networked Product Development characterised by Gausemeier et al., Systematic Development as described by Pahl et al., Lindemann's MVM and the Stage-Gate process introduced by Cooper. The goal was to determine which principles remain exclusive to Set-Based Concurrent Engineering and which have established themselves independently in those models.

The five product development models were studied individually to find evidence of the principles of Set-Based Concurrent Engineering. The findings were then compared directly to the key concepts of each principle. Results for all models were assessed collectively to create an overall picture.

While the level of representation of the ideas of Set-Based Concurrent Engineering varied for each model and principle, none of them stood out in a way of showing strong evidence of similarities to Set-Based Concurrent Engineering. On the other hand, two principles were represented poorly across all discussed models.

Kurzfassung

Die Produktentwicklung ist ein essentieller Teil jedes Produktionsbetriebes. Prozessmodelle unterstützen und leiten die Entwicklung von Produkten und sind auch als Kontrollmechanismen einsetzbar. Einer von vielen möglichen Ansätzen ist das von Toyota stammende Set-Based Concurrent Engineering (Set-basierte simultane Entwicklung). Das Entwicklungssystem von Toyota wurde stark von deren schlankem Produktionssystem beeinflusst und gilt heute als das Parademodel für schlanke Produktentwicklung.

Set-Based Concurrent Engineering unterscheidet sich von traditionellen Ansätzen dadurch, dass immer mehrere Ideensets bis in die späten Phasen des Entwicklungsprozesses betrachtet werden. Somit werden wichtige Entscheidungen absichtlich hinausgezögert. Der Grundgedanke dahinter ist, dass sich dadurch die Flexibilität des Produktentwurfs erhöht und ein besseres Verständnis des Gesamtsystems zu Stande kommt. All das soll die Entwicklung eines besseren Produkts fördern.

Die Idee dieser Arbeit war es, die neun definierenden Prinzipien von Set-Based Concurrent Engineering mit fünf modernen Produktentwicklungsmodellen zu vergleichen. Die behandelten Modelle waren: das von Eversheim beschriebene W-Model, die Vernetzte Produktentwicklung von Gausemeier et al., die Konstruktionslehre von Pahl et al., Lindemann's Münchener Vorgehens Model und der Stage-Gate Prozess von Cooper. Ziel war es herauszufinden welche der Prinzipien exklusiv in Set-Based Concurrent Engineering zu finden sind und welche sich auch in anderen Modellen unabhängig davon behauptet haben.

Die fünf Produktentwicklungsmodelle wurden unabhängig voneinander auf Präsenz der Prinzipien von Set-Based Concurrent Engineering untersucht. Die Ergebnisse wurden dann direkt mit den definierenden Kernkonzepten eines jeden Prinzips verglichen. Danach wurden die Resultate aller Modelle gemeinsam bewertet um ein Gesamtbild zu schaffen.

Obwohl die Ideen von Set-Based Concurrent Engineering in allen Modellen und Prinzipien unterschiedlich präsent waren, gab es einerseits kein Prinzip, das starke Ähnlichkeiten mit Set-Based Concurrent Engineering über alle betrachteten Modelle hinweg aufwies, andererseits aber zwei Prinzipien, die in allen Modellen schlecht abgeschnitten haben.

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Abbreviations

AIM	Aachener Innovationsmanagement-Model
CAD	Computer-Aided Design
CM	Content Management
CMP	Cross Media Publishing
EDM	Engineering Data Management
FEM	Finite Element Method
FMEA	Failure Mode and Effects Analysis
GEN	Global Engineering Networking
IRM	InnovationRoadMap
LAMDA	Look-Ask-Model-Discuss-Act
LeanPD	Lean Product Development
LeanPPD	Lean Product and Process Development
MKM	Münchener Produktkonkretisierungsmodell
MVM	Münchener Vorgehens Modell
PD	Product Development
PDCA	Plan-Do-Check-Act
PLM	Product Lifecycle Management
QFD	Quality Function Deployment
SBCE	Set-Based Concurrent Engineering
STEP	Standard for the Exchange of Product Model Data
SWOT	Strengths, Weaknesses, Opportunities, Threats
TPDS	Toyota Product Development System

TPS Toyota Production System

TRIZ Theory of inventive problem solving (*Teoriya Resheniya Izobretatelskikh Zadatch)*

XML Extensible Markup Language

1 Introduction

Product development (PD) and innovation are essential parts of every manufacturing company. Cooper (2010, p. 8-10) lists the following four factors as the main drivers for the need of innovation: technological advances, changing customer demands, shorted product life spans and increased global competition. The process of designing and engineering a new product is a complex process involving a wide range of different teams, each with their own expertise. A structured coordination and communication between those functional teams is necessary to create a successful product. Process models in general are often used and viewed as a management tool to standardise operational processes (Verworn & Herstatt, 2000, p. 1). Product development models are process models which aim to provide a guide and a structured approach to idea generation and subsequently the development of a new product.

The product development model of Toyota, the Toyota Product Development System (TPDS) features an approach that differentiates itself from traditional product development. This approach was described as Set-Based Concurrent Engineering (SBCE) by Ward et al. (1995). The reason it distinguished itself from typical American or European models is the intentional delay of decisions between alternative ideas or concepts. Nevertheless, this approach is proven to be very effective and even surpasses the traditional point-based approaches, if applied correctly. (Ward et al., 1995, p. 44, 46, 58-59)

Set-Based Concurrent Engineering was characterised by a number of principles by Sobek et al. (1999, p. 73-81) enabling participating teams to use this approach beneficially. The aim of this thesis is to find evidence of the essence and core ideas of these principles within other modern product development models not explicitly featuring Set-Based Concurrent Engineering. Furthermore this created an opportunity to investigate which principles are not exclusive to Set-Based Concurrent Engineering and have established themselves independently from it.

1.1 Objectives of this thesis

This thesis had the following objectives which resulted from the above stated aim.

1. The first objective was to establish the necessary background knowledge of Set-Based Concurrent Engineering.
2. The second objective was to give examples of current product development models that explicitly feature Set-Based Concurrent Engineering.
3. Another objective was to create a baseline for the principles to compare them with five selected product development models not featuring Set-Based Concurrent Engineering.
4. The fourth objective was to comprehend the five selected product development models and their characteristics to gain the required understanding for the subsequent analysis against the principles.
5. The last objective was to look for evidence of elements of the principles of Set-Based Concurrent Engineering in these models and compare the individual results.

1.2 Research approach

The methodology followed to reach the stated objectives comprised of five main steps: a key word search, an extended research and a presentation of the principles of Set-Based Concurrent Engineering, the identification of other product development models and their understanding, the comparison and analysis of these models against the principles of Set-Based Concurrent Engineering and an evaluation and conclusion.

1. **Keyword search:** The first step to reach the objectives was to conduct an extensive literature research and review to establish the necessary background knowledge. To find relevant articles and research paper online libraries such as *IEEE Xplore*, *Scopus*, or search functions like *Google Scholar*were used. Keywords and terms searched for included: "lean product development", "Toyota product development", "Toyota product development model", "set-based concurrent engineering", "principles of set-based concurrent engineering", or "set-based design". Furthermore the literature review included reoccurring references and sources of key papers, or related articles from important authors of the topic of Set-Based Concurrent Engineering.

2. **Extended research and presentation of the principles:** The collected literature was then used to summarise and present information relevant to the reader to comprehend the origin, advantages, as well as the content of the principles

of Set-Based Concurrent Engineering. The thereby gained understanding of the principles allowed the author to chose one of the multiple definitions of principles as a baseline for the subsequent comparison to other product development models.

3. **Identify other models and discuss their characteristics:** Following the literature review five product development models were selected to have a good variation of product development approaches, each with different characteristics. This was to obtain multiple different results which allow to meet the intended research aim. The characteristics and structure of each model were summarised and presented to create the foundation for the subsequent comparison.

4. **Comparison to SBCE and analysis of other models:** Each model was reviewed for evidence of the elements from principles of Set-Based Concurrent Engineering. This initial review was followed by a more concrete analysis against the principles and their core aspects. It compared if the models consider these aspects, and if so whether they do it similar as the principle suggest it, or in a different way.

5. **Draw an overall picture:** Finally, the results of all models were collected and results combined and analysed. Multiple aspects of the principles of Set-Based Concurrent Engineering were discussed across all models. Lastly, a conclusion compared the initial research aim and objectives to the outcome.

1.3 Structure of this thesis

The remainder of this thesis is structured as follows. Chapter 2 established the background knowledge necessary for this thesis by covering Lean Product Development and the role and concept of Set-Based Concurrent Engineering. Chapter 2.6 presents two product development models of recent years which actively use elements of Set-Based Concurrent Engineering in their approach. The principles of Set-Based Concurrent Engineering themselves are explained in chapter 3. Chapter 4 to 8 feature the comparison of the principles against the selected product development models. Lastly, chapter 9 discusses the findings of all models, while chapter 10 concludes this thesis.

2 Set-Based Concurrent Engineering within lean product development

This chapter describes the origin and evolution of Lean Product Development along with the formation of Set-Based Concurrent Engineering. Furthermore it presents it's concept and the differences traditional approaches, as well as applications in literature and research areas. The final part of this chapter summarises the advantages and benefits of Set-Based Concurrent Engineering on the development process.

2.1 Lean product development

Product development evolved because of an increased need for more efficient developments of new products, in cheaper and better ways. Over the past years researchers from different areas have tried to develop practices and techniques to improve the development of new products. Since 1987 there have been a rising number of publications in this field. (León & Farris, 2011, p. 1, 29-30, 33-34)

The term "lean" evolved from manufacturing, or to be specific from the Toyota Production System (TPS), which was well documented by Ohno (1988). The connection of lean and product development was not made until later (Sobek & Ward, 1996, p. 1).

One approach towards lean product development was described in the book *The Machine That Changed the World* by Womack et al. (1991), which showed a way to develop products quicker and more cost efficient than their competition, while still delivering higher quality products. It described the basic idea of the chief engineer role, the importance of communication efforts and the principle of simultaneous development (designing the product and the process to manufacture the product at the same time). (Womack et al., 1991, p. 71-282)

The success was made up out of the focus on key elements, such as value, knowledge, or improvement. These allowed Toyota to optimise the design, while minimising rework. This results in low re-evaluation and alteration costs leading to higher profits. (Khan et al., 2011a, p. 2)

Despite it's origin, the application of lean product development was not restricted to the automotive industry. For example, the aerospace industry was interested in this concept as well. (Haque, 2003, p. 1409)

Over the time researchers have developed multiple frameworks and models based on lean product development for industrial use (Baines et al., 2007, p. 1593). However, this increase in popularity does not necessarily mean that the topic is fully explored. Most of the research is very theoretical, supported by investigatory rather than affirmative studies within a narrow study field. This would make the realisation of a lean product development model, along with its implementation, feasible. (León & Farris, 2011, p. 34, 45)

In addition to the Toyota Product Development System, LeanPD was influenced by multiple other improvement methods (Karlsson & Ahlström, 1996, p. 294-295). Nevertheless, the core and most popularly discussed lean product development technique is simultaneous or concurrent engineering (Womack et al., 1991). It's advantage was described by Terwiesch et al. (2002 in León & Farris, 2011, p. 29) as that it can help speed up the development process by creating value through parallel processing. Kennedy (2003) states that this specific technique proves to be very difficult to implement as the concurrent nature creates a complex implementation approach .

Others argue that the main complexity from implementing a lean product development model is that uncertainty is involved (Finch & Ward, 1997, p. 1, 11), or the increased number of process elements and their individual relationships, rather than a specific LeanPD technique (Browning, 2002, p. 131-132, 140).

Over the past years many lean product development frameworks were introduced in literature with slightly different approaches and focus areas (León & Farris, 2011, p. 31). Examples for this are the following:

Womack et al. (1991) wanted to introduce a model that would allow the development teams to perform better, in shorter time frames, with less effort. Their framework was based on four core elements of lean design, namely leadership, team work, communication and simultaneous development.

Karlsson & Ahlström (1996) believed that the key elements for a successful and true LeanPD process were cross-functional teams in connection with simultaneous engineering, supported by an overall strategy, as well as an extension of these concepts to the suppliers. Their main target for this concept was to reduce required resources, mainly time and effort, while focusing on an increased effectiveness and efficiency of the guiding processes, rather than creating value streams.

A different approach was taken by Liker & Morgan (2006). They described the Toyota Product Development System and focused on management principles and emphasised the need for an overall system integration of all participating elements. Their framework consisted of a total of thirteen principles divided into three categories: people, process and tools and techniques.

Ward (2007) presented a model that would focus on the generation of functional value streams through creating knowledge by living and adapting the process. He based his work on five key concepts: A strong value focus, an entrepreneurial system designer, teams of responsible experts, Set-Based Concurrent Engineering and cadence of the development process.

2.2 SBCE as the main enabler of lean product development

Set-Based Concurrent Engineering offers an evolution over the traditional point based product development approaches, where engineers typically first come up with a lot of different options, and then choose the most promising one (Sobek et al., 1999, p. 69). It is viewed as the core enabler of lean product development, along with other supporting enablers (Khan et al., 2011b, p. 5-6).

2.2.1 Point-based serial engineering

When facing decisions and alternatives it is common to quickly decide on one solution. This solution is then modified to address upcoming problems, such as manufacturing related difficulties. (Iansiti, 1995, p. 38) This process is refereed to as Point-Based Serial Engineering and is illustrated in Figure 2.1.

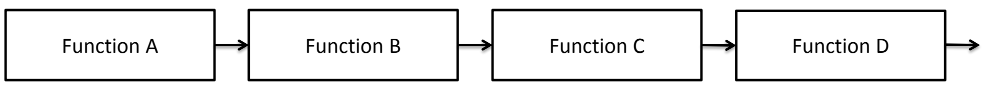

Figure 2.1: Traditional point-based serial approach to product development, according to (Sobek et al., 1999, p. 69)

If the first iteration is chosen badly, subsequent iterations and steps are prone to require a lot of rework, resulting in a project delay. This ultimately leads to a suboptimal system. Therefore decision making during product development is of great importance, especially in early project phases. (Sobek et al., 1999, p. 69)

Set-Based Concurrent Engineering suggests a method to face these challenges by considering not individual options, but sets of solutions. During the development process these sets are narrowed down, based on objective data to ultimately merge into the best overall product. (Sobek et al., 1999, p. 68-69)

This does suggest that more time is spent in the concept and early stages of product development. However, in total these increased effort leads to a shorter overall product development cycle. (Ward et al., 1995, p. 48)

2.2.2 Point-based concurrent engineering

In serial engineering each functional team works with the input it received from the upstream team. Each team works his expertise into the product with their own idea of a best solution. The result is then handed to the next functional team downstream, which possibly encounters a flaw in the chosen design. Therefore the upstream teams need to be informed and alterations need to be made to the existing design. This can go back up all the way to the initial concept or first project stage. (Sobek et al., 1999, p. 69)

With concurrent engineering all functions have a chance to input before major or final decisions are made. This concept this is illustrated in Figure 2.2. Therefore changes in early phases of a project are still rather cost and time efficient to alter and it is expected that the resulting final solution will be consistent with the input from all functions. (Sobek et al., 1999, p. 69)

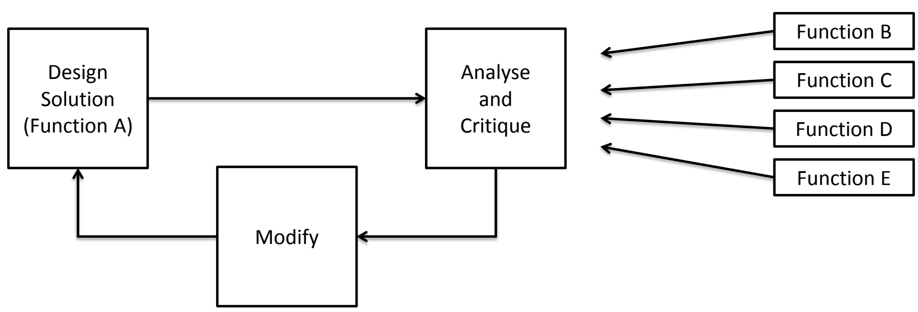

Figure 2.2: Traditional point-based concurrent approach to product development, according to (Sobek et al., 1999, p. 69)

As a result fast iterations and upstream feedback are a key factor for a successful point based concurrent engineering (Eisenhardt & Tabrizi, 1995, p. 84, 107-108).

While this offers several improvements over the traditional point-based approach, there remain some difficulties; all functions are working on one solution. As a result all upcoming changes lead to further analysis and rework for all affected teams. In reality the design phase is simply ended when then deadline is met. The final result however is not necessarily the best one that the team would have been capable of designing. (Sobek et al., 1999, p. 69)

2.2.3 Set-Based Concurrent Engineering

With Set-Based Concurrent Engineering development teams do not work with one, but sets of solutions. Sets are autonomous collections of alternatives. These evolve independently in parallel, and their reasoning and ideas are shared amongst the engineers from different teams, therefore creating an concurrent engineering environment. (Sobek et al., 1999, p.70)

In other words, engineers collaborate in multi-disciplinary teams to pursue multiple ideas, each with its own concept and alternative subsystems. This naturally suggests an increased effort, and SBCE is in fact a front loaded process model.

At first each function defines the sets very broad within the range of their feasibility. These sets are analysed and discussed within each team. Then all the functions gather feedback from other functions to eliminate non achievable design sets. These feasible regions are illustrated in Figure 2.3 as the diamond shape for Function A and the square for Function B. (Sobek et al., 1999, p.70)

In addition with information gained from testing, prototyping, supplier and customer input, sets are gradually narrowed down by eliminating weaker solutions through evidence of data to ensure an overall optimum system. (Sobek et al., 1999, p. 73-75,79)

The ultimate decision on one set is therefore delayed as much as possible, to ensure the exploration of all possibilities before committing to one idea. (Sobek et al., 1999, p. 77)

Sobek et al. (1999, p. 80) state that as designs converge, design teams commit to stay within sets at all cost to ensure an ongoing compatibility of upcoming work from all participating disciplines and manufacturing decisions. The concept of this is illustrated in Figure 2.3 where the blacked out intersection of Function A's and Function B's capabilities gets smaller and therefore more defined as time goes on and the development comes to an end. This allows the development team to get an early start on production planning and ordering of tools (Sobek et al., 1999, p.70).

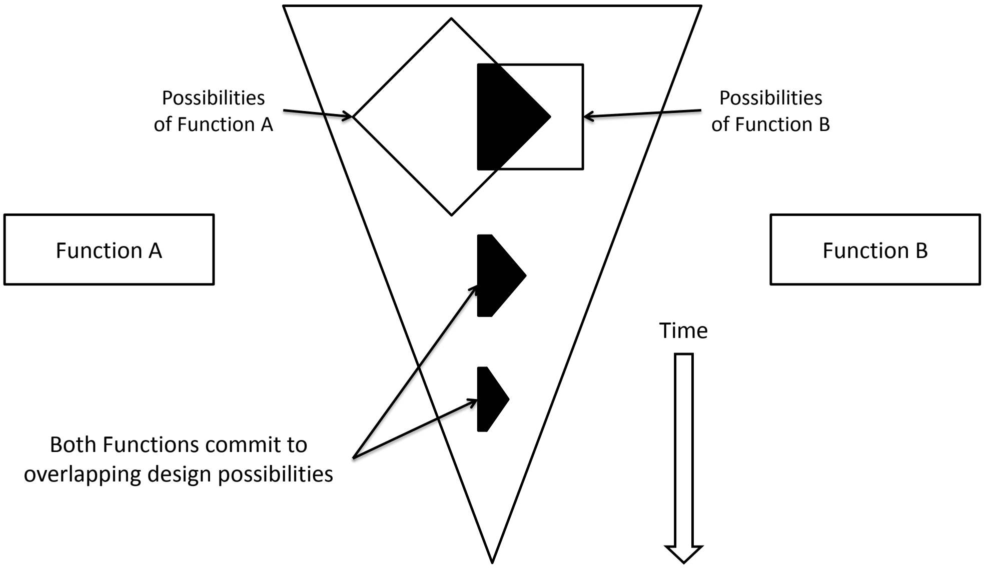

Figure 2.3: Example of Set-Based Concurrent Engineering, according to (Sobek et al., 1999, p. 70)

More details about the evolution and content of SBCE can be found in Section 2.3 and Chapter 3.

2.2.4 Other enablers of lean product development

Khan et al. (2011b, p. 5-6) identified the following core enablers of lean product development apart from the SBCE process:

- Chief engineer technical leadership
- Value-focused planning and development
- Knowledge-based environment
- Continuous improvement culture

The role of the **chief engineer** was already discussed by Sobek & Ward (1996, p. 2), when first describing the Toyota Product Development System, as an important role that is responsible for the whole product development process from concept to final production. Moreover one of his areas of responsibilities is to keep the project on schedule, therefore balancing the need to pressure for decisions or obtaining more data for objective, meaningful decisions. Khan et al. (2011b, p. 8) expanded on it and described the chief engineer technical leadership as an enabler for the successful implementation of cross-functional module development teams and manufacturing involvement.

The idea of a **value-focused planning and development** is quit obvious if talking about lean product development, which is all about the elimination of waste and generation of value (Al-Ashaab et al., 2010, p. 4). In connection with SBCE value-focus is also customer-focus. Value-stream mapping is often used to help plan the development process. Projects should be categorised according to their nature (overall new product, minor modifications, major modifications, exchange of components, etc.). The projects within each of these categories need to be standardised in terms of time requirements and process steps and activities. (Khan et al., 2011b, p. 7-8)

A **knowledge-based environment** is about creating knowledge through exploring design alternatives. This knowledge then flows to the place where and when it is needed. Assisting tools and methods for this are trade-off curves, checklists, design standards and A3 sheets. They are used as a form of knowledge representation. These act as an enabler for quick and effective communication and enhance comprehension. Another important aspect of a knowledge-based environment is the implementation of a learning organisation culture. Moreover, the development of an expert workforce has to be a focus area of management. (Khan et al., 2011b, p. 7)

Occurring problems are viewed as an opportunity to improve the product and its creating process. This represents a **continuous improvement culture**. In order to make this possible, processes, skills and design methods need to be standardised and reviewed periodically. While discussing a technical problem there is a strong emphasis on the root-cause analysis to identify the origin of the issue. This enabler is in strong connection with a knowledge-based environment, as they both support and enhance each other. (Khan et al., 2011b, p. 8)

2.3 Evolution of SBCE

Ward et al. (1995, p. 43-45) assessed the Toyota Production System (TPS) in order to explain what they called *The Second Toyota Paradox*. The paradox discussed how delaying decisions intentionally benefit the development of a new product. The outcome was that a big focus on communication and excessive prototyping lead to better products in a shorter development time, compared to Toyota's competitors (Ward et al., 1995, p. 58-59).

Ward et al. (1995, p. 44) introduced the term Set-based Concurrent Engineering to differentiate this new approach from traditional point-based engineering (see section 2.2).

Their work really established the groundwork for the Set-Based Concurrent Engineering process, as it explained the effectiveness of a front-loaded product development process. Their research summarised the Toyota Set-based Concurrent Engineering process approach into five steps (Ward et al., 1995, p. 49):

1. Development teams do not define one, but various sets of solutions at a system level.
2. Each subsystem has multiple sets of solutions.
3. These possible subsystems are then explored in parallel with detailed assessment, testing and design rules to identify a set of promising solutions.
4. The teams use the result from the exploration to progressively narrow down the sets of remaining solutions, advancing towards one single solution.
5. As soon as one single solution of any part has proven itself, engineers no longer alter it even if it could result in performance improvements.

Sobek & Ward (1996, p. 3-8) expanded the work of Ward et al. (1995) and focused on the mechanisms of the narrowing funnel of solutions, such as emphasis on communication between multidisciplinary and cross-functional teams with the help of checklists or trade-off curves, under the supervision of so called chief engineers. Their work resulted in the eleven principles of Set-Based Concurrent Engineering. These principles are presented in section 3.1.

Thereafter Liker et al. (1996, p. 176-177) explored the connection to the suppliers, which revealed that these would also use Set-Based Concurrent Engineering to explore design solutions based on the requirements of the automotive company/client.

The managerial aspect of Set-Based Concurrent Engineering were discussed in more detail by Sobek (1998, p. 36-47). They suggest six coordination mechanisms divided into two categories. Firstly, "integrative social processes", discussing the organisation from a functional perspective. Secondly, "levels of standardisation", creating the development environment that allows to quickly converge towards the optimal solution.

The first category "integrative social processes" covers the following mechanism:

1. Integrative leadership: importance of the role of the chief engineer.
2. Mutual adjustment: discusses different communication methods.
3. Direct supervision: supervisors take on the role of a mentor.

"Levels of standardisation" also comprises three focus areas:

1. Standard skills: created through job rotation and positive mentoring.
2. Standard work processes: following up uniform processes.

3. Design standards: transferred with the help of continuously updated checklists.

Later Sobek et al. (1999, p. 73) introduced a product development framework based on the five-step procedure of Ward et al. (1995, p. 49) and the previously defined eleven principles of SBCE of Sobek & Ward (1996, p. 3). A detailed summary of the framework can be found in section 3.3. The framework consists of three principles, each with three key stages representing the previous list of principles (Sobek et al., 1999, p. 37):

1. **Map the design space:** In order to fully understand the possibilities within the given design space it is necessary to "define feasible regions". Within these regions engineers "explore trade-offs by designing multiple alternatives" while they "communicate sets of possibilities" thoroughly amongst involved designers and engineers.

2. **Integrate by intersection:** Development teams "look for intersections of feasible sets" while "imposing minimum constraint" to the individual components, which allows for an optimal overall solution. Additionally the engineers "seek conceptual robustness" to create a market-ready and resistant product.

3. **Establish feasibility before commitment:** Proven "sets are narrowed gradually while increasing detail". It is important to "stay within sets once committed" to ensure ongoing compatibility between sub-systems. The product development has to be "controlled by managing uncertainty at process gates" to minimise the risk of a project failure.

In addition to this framework Sobek et al. (1999, p. 71-73) also suggest a list of methods that support and allow SBCE within product development. These include the role of a chief engineer, the value of expertise and knowledge, as well as communication and problem solving tools.

Liker & Morgan (2006) developed a conceptual lean product development model (described in section 2.6.1) based on three co-dependant systems: people, process and tools and technology. All three systems list a number of principles, thirteen in total, which define the *Toyota Way* in product development. The second of these thirteen principles stated to "front load the product development process to thoroughly explore alternative solutions while there is maximum design space" (Liker & Morgan, 2006, p. 10). This is a major aspect of Set-Based Concurrent Engineering as it allows to explore an optimal solution through delayed decisions based on facts, rather than forcing decisions and therefore missing the best solution.

Al-Ashaab et al. (2010) and Khan et al. (2011a) proposed a product development model (presented in section 2.6.2) based on lean thinking. Their model targets the whole product life cycle while focusing on three cornerstones: value, knowledge and improvement. In order to create value for the customer, Set-Based Concurrent Engineering was chosen as an approach for product development and is therefore another key component to their model in addition to the chief engineer position. The Set-Based Concurrent Engineering approach was described in five main principles which also present the five stage baseline model (Khan et al., 2011a, p. 3-4):

1. Strategic value research and alignment
2. Map the design space
3. Create and explore multiple concepts in parallel
4. Integrate by intersection
5. Establish feasibility before commitment

2.4 Studies and research of SBCE in literature

Most studies and papers on the topic of lean product development and Set-Based-Concurrent Engineering are more exploratory rather than confirmatory studies. The studies conducted were mostly theoretical evolutions on individual elements of an integrated system. (León & Farris, 2011, p. 34)

Nahm & Ishikawa (2005, p. 123) developed the computer-based framework Preference Set-based Design (PSD). This framework was intended to help implement SBCE principles and included methods to assist in the representation and modification of sets, as well as narrowing and aggregation methods.

Ford & Sobek (2005, p. 175) explained the reasoning behind delaying decisions in the product development process by mathematically proving *The Second Toyota Paradox* with the help of a formal simulation model. On the other hand they stated that converging to slowly harms the outcome and present management implications.

Kao (2006, p. 34) combined Set-Based Concurrent Engineering with Design for Logistics (DFL). DFL designs products by considering the logistics system behind the product that it needs to work correctly. The result was a decision support framework that allowed design teams to estimate logistic and financial requirements, costs, and suggests a trade-off between these two approaches.

Schäfer & Sorensen (2010, p. 721) wanted to create a generally applicable valuation model of optimal design of the product development process using Set-Based Concurrent Engineering. They discussed a methodology of finding the optimal number of alternatives which are to be developed in parallel, taking the increased costs into account.

Avigad & Moshaiov (2010, p. 619) introduced a computation approach to assist in concept selection in set-based development. It focuses mostly on the delaying of decisions between solutions as well as the concept optimality.

2.5 Benefits and advantages of SBCE

The set-based approach seemed paradox at first. How can Toyota, despite the increased effort on early design and a strong emphasis on the concept stage, deliver quality products in shorter development cycles than their competitors. Ward et al. (1995, p. 58-59) explain this with the following advantages that a set-based development method brings:

1. An efficient communication allows engineers to work more independently within clearly defined restrictions.
2. The process enables parallelism and the efficient use of independent sub-teams in all phases of product development.
3. Important decisions in early stages are based on data by exploring all potential designs.
4. The process encourages and supports engineers in documenting and updating their work and understanding in lessons-learned books as a reference for other teams.
5. The in-depth exploration of all options allows for an overall optimal solution.

Over time Set-Based Concurrent Engineering has been explored in more detail and benefits of this approach became clearer: Set-Based Concurrent Engineering works towards an overall optimum system and creates extensive knowledge for future re-use. Furthermore it helps to keep the risk of a project failure at a minimum and aims to eliminate rework, while maintaining innovation and creativity in the process. All this is supported by enhanced communication mechanisms. These benefits were explained in several literature sources as follows (Ward et al., 1995, p. 58-59) (Liker & Morgan, 2006, p. 9-16) (Raudberget, 2010, p. 690-694) (Khan et al., 2011a, p. 3):

- **Development of an optimum system:** In point-based product development the initial concept is made by one function. This concept is then modified and adapted by each upcoming function to add their requirements to the product. At the final stage the product consists of the work of individual functions and their constraints, resulting in an optimised, but sub-optimal system.

With Set-Based Concurrent Engineering all participating functions are involved from the beginning of the design process. Customer value is very important and communicated to all engineers and designers. The intersection of their different design solutions contains the optimum system, as it incorporates each functions constraints.

- **Knowledge creation and management**: The nature of Set-Based Concurrent Engineering promotes the generation of knowledge through design sets, trade-offs, or prototype test result analysis amongst other techniques. This knowledge is captured, documented and incorporated into the organisation. This can affect for example the process itself, or design constraints for components. As a result an ongoing learning cycle is formed that will benefit the current and future projects.

- **Risk minimisation:** The large number of sets that are developed at the early stages provide many alternatives. Solutions that do not redeem to be feasible can be disregarded without concern for the success of the overall system, because of the modularity of subsystems. Therefore risk is lowered by a great percentage, while maintaining flexibility. Moreover a proven and simple backup solution is available for the worst case that all new concepts turn out to be infeasible.

- **Elimination of rework:** Set-Based Concurrent Engineering rules out unpromising sets of alternatives through in-depth analysis and facts, therefore minimises the risk of rework by not pursuing those ideas. Nevertheless, there remain viable designs that can be continued to work on, without needing to rework deficient concepts.

- **Increase of innovation and creativity:** The nature of Set-Based Concurrent Engineering suggest dedicated resources to focus on innovation during the set creation phase. Engineers and designers develop multiple sets of ideas and analyse these very thoroughly. As a result, there is a strong emphasis on innovation and creativity is actively encouraged. Furthermore flexible designs and delaying decisions provide even more room for creativity, as well as the ongoing gradual convergence towards the final solution.

- **Improved communication:** During the product development all communication between different functions and teams is done in the form of sets. The number of required meetings decreases over time, because as the sets get more detailed over time weaker solutions are ruled out and therefore no longer need to be discussed. This allows more time in the meetings for the increasingly detailed specifications and understanding, which is necessary as the product development process continues. Communication with external suppliers is enhanced as the broad specifications within feasible regions allow them to work on their own terms, therefore improving the relationship.

2.6 Examples of current lean product development models featuring SBCE

This section presents two models which explicitly feature SBCE or elements of it. Morgan & Liker (2006) described the TPDS, while Al-Ashaab et al. (2010) and Khan et al. (2011a) did the same, but with an increased focus on a dedicated process model for the SBCE process.

2.6.1 The Toyota product development system

Similar to Sobek et al. (1999, p. 73), Morgan & Liker (2006) also proposed a framework in form of principles, although they explicitly mention that this is the way to go for LeanPD (Liker & Morgan, 2006, p. 5-6). Their framework is build upon three categories of principles (Liker & Morgan, 2006, p. 9):

- Process
- People
- Tools & Techniques

The approach of Morgan & Liker (2006) for a LeanPD framework based on the *Toyota Way* aimed to be suitable for both production and service industry. The TPDS itself was influenced by Toyota's own production system, the TPS. The most important ones are the customer focus and the lean aspect, or the waste elimination supported by continuous improvement. Other examples for this are: The focus on solving problems on the spot and seeing them as a chance for improvement, a strong emphasis on standardising processes as this allows for a predictable and stable work and value flow, or the importance of people and teamwork. (Liker & Morgan, 2006, p. 6-8)

Liker & Morgan (2006, p. 5) argue that a straight-forward implementation and usage of lean tools and methods will not result in a long term improvement in the expected areas. As a result they presented management principles that form a framework for a product development model together with influences from employees and managers. The principles were divided into process, people and tools and technology categories, and are explained in the following sections. (Liker & Morgan, 2006, p. 8-9)

All the below described principles interact with each other on multiple levels, and their integration into one coherent system is critical. The three subsystems, people, process and tools and technology support. They complement each other and each one depends on the remaining two. (Liker & Morgan, 2006, p. 16)

2.6.1.1 Process principles

The objective of a process principles should be to allow the people to improve and standardise the guiding process while simultaneously aiming to create a lean process environment. This includes a reduction of lead times and development costs, achieved through an identification and elimination of waste in the value chain. (Liker & Morgan, 2006, p. 9)

1. **Establish customer-defined value to separate value added from waste:** Satisfaction of the customer is always the highest priority. This can only be achieved by defining what adds value to the customer. Other activities that require resources in any form but ultimately do not add value to the customer, are considered as waste. (Liker & Morgan, 2006, p. 9-10)

2. **Front load the product development process to thoroughly explore alternative solutions while there is maximum design space:** There is an increased focus on early stages by spending additional time to understand all potential difficulties. This is to avoid expensive changes in later product development stages. Multi-disciplinary teams create multiple solutions focusing on compatibility and an optimal solution. (Liker & Morgan, 2006, p. 10-11)

3. **Create a levelled product development process flow:** It is important to stabilise the process in order to make it more manageable. This is supported by tools such as value stream mapping. Liker & Morgan (2006) mention this helps to level the workload, shorten response times to customers and coordinate functions. As an example; with more and more experience, projects can be levelled. Typically resource demands vary over the course of product development. The high need for a certain expertise is only present at specific stages. A stabilised process allows to plan these requirements and manage the employees accordingly. This can even extend to external, contract based, work force. (Liker & Morgan, 2006, p. 11)

4. **Utilise rigorous standardisation to reduce variation, and create flexibility and predictable outcomes:** Standardising the product development process in various ways enables continuous improvement. Moreover it becomes easier to develop products closer to the original concept or idea of the customer,

while still delivering high quality. Furthermore it helps lowering varying results without compromising innovation and resource demand planning.
Toyota has three main levels of standardisation. First, design standardisation of components with the help of modular systems. Second, process standardisation aims at designing in a way that already takes lean manufacturing in account. Third, standardised skill sets of engineers allow for a flexible workforce. One example for this are checklists, as first described by Ward et al. (1995, p. 44). (Liker & Morgan, 2006, p. 11-12)

2.6.1.2 People principles

People, along with their expertise and skills, are the actual enablers of any activity, process, or task. Employees are actively encouraged to point out identified problems and work towards a solution, thus improving the process on a continuous basis. The *Toyota Way* encourages the development of a strong expertise for every single engineer, while still working united towards a common goal. The following principles target the training of all people to share information amongst each other and work on improving the guiding process. (Liker & Morgan, 2006, p. 9, 12)

5. **Develop a Chief Engineer System to integrate development from start to finish:** The chief engineer ultimately serves the customer. He is responsible for the entire product development of one system. His tasks include the role of a project manager, technical leader, chief architect and system integrator. Difficult technical decisions or trade-off options are always taken to the chief engineer, because he has the authority and responsibility to make any decision within the entire project lifespan. (Liker & Morgan, 2006, p. 13)

6. **Organise to balance functional expertise and cross-functional integration:** The detailed expertise from each function requires mechanisms to make this knowledge and competence available to other functional areas. Only then the system and multi-disciplinary integration can be successful.
   Cross-functional communication and integration is achieved via an *Obeya* system, which is essentially a daily meeting between function heads and the chief engineer. Topics within these meetings are inter-dependencies and decisions concerning multiple, connected functions. The sessions are often supported by visual means such as charts or schedules, to share information and review the project status. (Liker & Morgan, 2006, p. 13-14)

7. **Develop towering technical competence in all engineers:** All design processes, but lean product development in particular, require participating engineers

and designers to have extensive technical expertise. The knowledge in specific fields relevant to the engineers job is necessary to work on modern complex systems featuring co-dependant modules.
Within Toyota engineers are required to work the first few years on shop-floor level at the production line, as well as spend considerable amounts of time with core engineering. This allows them to see directly how their design is put into practice and therefore further deepens the knowledge and understanding for a specific technical area. (Liker & Morgan, 2006, p. 14)

8. **Fully integrate suppliers into the product development system:** The involvement of a capable supplier and its integration into the product development process is one of the most important aspects of a lean design process. Selection criteria should include technical qualifications and capabilities matching the needs, as well as a comparable and therefore compatible culture.
Suppliers need to be treated with the same attention as the company's own engineering teams. This means that the expertise brought in by suppliers should be used from the first stages of the development process. One way to build a trusting relationship with one's suppliers is the invitation of guest engineers into the company. (Liker & Morgan, 2006, p. 14)

9. **Build in learning and continuous improvement:** Aiming for a continuous improvement cycle is of great importance. With every challenge or problem there are opportunities to learn and it is everyone's responsibility to make use of that chance. Short learning cycles improve the process in many aspects while also creating knowledge, benefiting future projects. This approach must be embedded into the daily routine, events and activities, and is supported by specific learning mechanisms such as mentoring. (Liker & Morgan, 2006, p. 14)

10. **Build a culture to support excellence and relentless improvement:** Organisational culture has to be shared throughout the entire hierarchy. Only then will it allow the success of all other principles. Building a corporate wide culture to create excellence is one of the responsibilities of management. All employees should cooperate towards the same goal, the satisfaction of the customer as a core value and most important factor when facing any decision related to the final outcome. (Liker & Morgan, 2006, p. 14-15)

2.6.1.3 Tools and technology principles

People are most productive if they have the right tools to deal with the surfacing problems, that allow them to contain, analyse and then create sustainable knowledge from the gained experience. Specific tools and methods are capable of providing an advantage over competitors if applied correctly. This is not restricted to software tools, but also methods that support problem solving, standardisation, or knowledge related tasks. (Liker & Morgan, 2006, p. 9, 15)

11. **Adapt technology to fit your people and process:** In order to make the most use out of available tools, they need to fit into the process and should help engineers in their daily routine. Otherwise these tools might even cloud problems rather than helping to speed up the process. Software should be optimised and adapted to the individual needs of the company. Process and People principles should be valued with a higher priority and Tools used as accelerators for a working lean product development environment. (Liker & Morgan, 2006, p. 15)

12. **Align your organisation through simple, visual communication:** To coordinate all the individual expertise towards a common goal, company wide objectives are broken down to realisable and smaller targets. These allow the engineers to understand the common goal on a working level. This management technique is called *hoshin kanri*, or policy deployment. Communication of these is done on a visual level, as this helps to display information in a simple and uniform way. Toyota uses A3 reports to enable and support communication in an easily understandable way. This is to guarantee a common understanding and develop a solution to everyone's satisfaction. These reports feature proposals, problem solving, status reporting and competitive analysis. (Liker & Morgan, 2006, p. 15-16)

13. **Use powerful tools for standardisation and organisational learning:** Continuous improvement needs standardisation on a wide level, otherwise there is no clear direction for development. Furthermore it is important to track how individual stages and activities of the product development process lead to lessons learned. This can be achieved via engineering checklists. However, the responsibilities for the standards themselves, along with their maintenance, must be done by the affected employees and not the upper management. Only this way it is ensured that the documents are ongoing and circulating. (Liker & Morgan, 2006, p. 16)

2.6.2 The LeanPPD conceptual model

As part of the Lean Product & Process Development (LeanPPD) project Al-Ashaab et al. (2010) developed a model based on the TPDS aims at challenges (e.g. market alterations, global development) current manufacturing companies are facing. Applying lean thinking to manufacturing alone is not sufficient enough , as the entire enterprise needs to be transformed into a lean environment while considering the entire product life cycle. (Al-Ashaab et al., 2010, p. 1-2)

For every manufacturing company the product design is a very critical phase in each product life cycle as it defines 80% of the production costs (Al-Ashaab et al., 2010, p. 2). Therefore the authors believe that Set-Based Concurrent Engineering is, amongst others, the main enabler of lean product development allowing an optimal product design (Khan et al., 2011b, p. 6). As a result, the LeanPPD Conceptual Model has a strong emphasis on its principles.

2.6.2.1 The LeanPPD paradigm

The conceptual LeanPPD model shifts from the traditional focus on waste elimination to value creation. This is supported by a number of tools and methods that assist the organisation during the implementation and the ongoing product development. This includes an assessment tool to measure the readiness level towards lean thinking application, value stream mapping tools, or specific tools that support SBCE. (Al-Ashaab et al., 2010, p. 4-5)

2.6.2.2 Core enablers of the LeanPPD model

The developed LeanPPD model is build around five core enablers, each with suggested tools and techniques. The enablers are as follows (Khan et al., 2011b, p. 5-6):

- Value-focus (planning and development)
- Knowledge-focus (knowledge-based environment)
- Set-based concurrent engineering
- Chief engineer technical leadership
- Continuous improvement culture

Value-focus is achieved by first identifying what activities actually do add value for the customer and which do not. If certain customer requirements are met, the activities to implement said requirements can be considered as a value adding activity. (Al-Ashaab et al., 2010, p. 6) Project classification can also assist to determine standard duration and schedules (Khan et al., 2011b, p. 7).

Al-Ashaab et al. (2010, p. 7) believe that "lean product development is product development in a knowledge-based environment". The conceptual LeanPPD model suggests two knowledge-based systems, namely a knowledge-based environment and a knowledge-based engineering system. The first system aims to provide the right knowledge at the right time to the right person in the development process. This also includes certain tools and mechanisms such as design standards, trade-off curves, A3 reports, but also digital engineering software. Moreover specific learning cycle methods are suggested (PDCA, LAMDA). The latter system captures the created knowledge, including lessons learned, and makes it easily accessible for everyone. (Khan et al., 2011b, p. 7-8)

The remaining enablers are discussed in section 2.2.4 and chapter 3.

2.6.2.3 SBCE baseline model and process

Khan et al. (2011a, p. 3-4) identified the modern principles of SBCE described in Section 3.3 and based on these, developed a baseline model.

The presented SBCE process illustrated in Figure 2.4 consists of five phases. The first phase, "Value Research", aims to classify the project type, align it with the company strategy and explore the value to the customer as well as translate this value to the engineers. In the second phase "Map Design Space" each team will choose a target for their sub-set and agree on the wanted level of innovation for each system/subsystem/component. These decisions are made within the feasible region of design space and under consideration of other functionally different teams. Phase three, "Concept Set Development" focuses on the concept set development. This is achieved by creating and performing tests for and on each subsystem. The thereby created knowledge is captured and used to assess each set. Once a set is selected, this is communicated to other teams. Phase four, "Concept Convergence", decides on the final set of subsystems by evaluating the connection of feasible sets and prospective system sets are tested. Another important activity in this phase is the determination of lean manufacturability. The final phase, "Detailed Design", covers the release of the final specifications followed by a further detailed design of the product. (Khan et al., 2011a, p. 4-5)

Khan et al. (2011a, p. 5-7) described the five phases along with their activities as follows:

1. **Value Research:**

    a) The project type is classified according to their level of innovation.
    b) Customer value needs to be identified and defined. This allows to decide on system targets and to compare the leanness of different solutions.
    c) Align the project with the company strategy to gain strategic advantages.

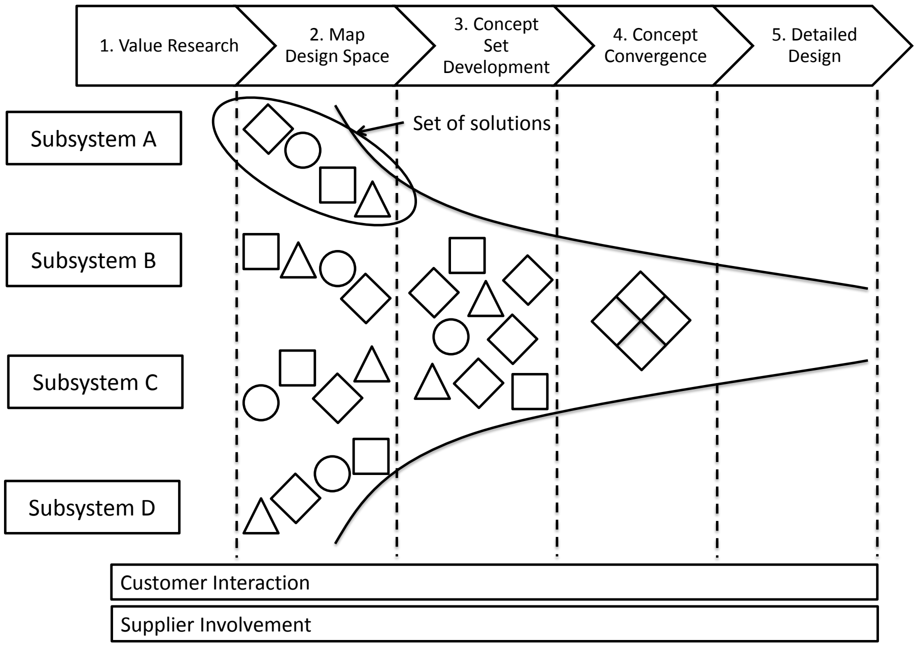

Figure 2.4: The Set-Based Concurrent Engineering baseline model (Khan et al., 2011a, p. 5)

d) Define product concepts based on customer value definitions.

2. **Map Design Space:**

a) Decide on an operational level on the degree of technical innovation for each part.
b) Analyse the architecture to identify targets for each subsystem.
c) Define the feasible regions of design space considering capabilities and constraints of functional departments.

3. **Concept Set Development:**

a) Extract innovative, fitting concepts from R&D to use them within the current project.
b) Create a set of solutions and tests for each subsystems.
c) Fully explore all sets including testing for cost, quality and performance.
d) Capture all created knowledge to assess sets effectively.
e) Present and communicate sets with others to increase the understanding of their constraints.

4. **Concept Convergence:**

a) Determine possible intersections of explored sets while considering interdependencies and compatibility.
b) Simulate sets on a system level for cost, quality and performance.
c) Seek conceptual robustness against physical, market and design variations.
d) Analyse the sets against lean production to determine costs, efficiency, or potential issues.
e) Begin to plan the manufacturing process for definitely feasible sets.
f) Eliminate sub-optimal designs and sets to converge towards a proven optimal system.

5. **Detailed Design:**

a) Release the final specifications after the last set is concluded.
b) Provide manufacturing tolerances to design teams.
c) Complete the product design with further detailed work.

2.6.3 Importance of SBCE in these models

This section discusses the importance of SBCE in these models and specifies connections to tits principles and concepts. While the framework of Liker & Morgan (2006) basically tries to describe the TPDS, Khan et al. (2011a) focused on the development of a process model for SBCE.

2.6.3.1 Describing the Toyota Way

Liker & Morgan (2006) list a number of principles divided into the categories process, people and tools and technology to present a product development model in the form of a framework. Sobek et al. (1999) also used a framework based on principles as a model while describing the essence of SBCE. The work of Sobek et al. (1999) focused on the narrowing process, while Liker & Morgan (2006) looked at a bigger picture and included managerial aspects. Both of them tried to essentially describe the *Toyota Way* or the TPDS.

Therefore there are multiple connections between these two frameworks. The process principle stating to "front load the product development process to thoroughly explore alternative solutions while there is maximum design space" basically describes the core idea of SBCE to delay important decisions. The idea of standardisation from the SBCE principle "seek conceptual robustness" is even mentioned in two principles: "Utilise rigorous standardisation to reduce variation [...]" and "Use powerful tools for standardisation [...]". The "full integration of suppliers into the product development system" is mentioned in both models. (Liker & Morgan, 2006, p. 14) (Sobek et al., 1999, p. 75-76, 78-80)

Continuous improvement or the chief engineer are other examples that are featured in both models (Liker & Morgan, 2006, p. 13) (Sobek et al., 1999, p. 72), although they are not listed as one of the SBCE principles, as they are not exclusively related to the narrowing process.

2.6.3.2 Developing a process model for SBCE

Khan et al. (2011a, p. 6) proposed a complete SBCE process model based on collected principles. They explicitly state SBCE is one of the main enablers of LeanPPD. Additionally, same to Liker & Morgan (2006, p. 13, 14), they list the chief engineer and continuous improvements as key factors for product development. (Khan et al., 2011a, p. 3-4)

3 Principles of Set-Based Concurrent Engineering

Chapter 3 presents three different definitions or lists of principles for Set-Based Concurrent Engineering. The first are principles defined by Sobek & Ward (1996) which were then reworked into a framework by Sobek et al. (1999), representing the second list. Khan et al. (2011a) collected the modern principles of Set-Based Concurrent Engineering from multiple literature sources and used these as a base for their process model presented in section 2.6.2. Lastly, one of the three lists was chosen to serve a base for the subsequent analysis against the other product development models.

3.1 Original principles from Toyota's product development process

Sobek & Ward (1996, p. 3) originally identified eleven principles of SBCE after studying the TPDS. Their motivation was to explain the paradox that Toyota is able to develop better products faster, by intentionally delaying decisions. The described principles attempted to create a foundation for a possible framework that would allow companies to work with solution sets in parallel. The following listing explains the eleven proposed principles (Sobek & Ward, 1996, p. 3-9):

1. **Define feasible regions:** The design teams draw the sets of options. Each function decides on the features and performance requirements and range within their responsible area of expertise. This range is defined based on experience, standards and information from other functions. Subsystems can be defined to make complex systems more manageable.

2. **Communicate sets of possibilities:** For the entire development team to understand the whole product, functions communicate their previously defined feasible regions as sets of possibilities, not as individual ideas. This allows for a best solution, as one function does not have the knowledge of other perspectives. The discussed topics are for example defined subsystems, interfaces, or restrictions.

Sets are typically presented in intervals, trade-off curves, performance charts, or tests and analysis.

3. **Look for intersections:** After teams exchanged the sets of possibilities, they look for intersection of feasible regions. The target should be to find solutions that achieve an overall optimised system. To find these intersections, engineering checklists help by describing what is possible within each function. These checklists contain information such as functionality, manufacturability, or external regulations. This allows all functions to know what everyone is capable of, while still staying within the defined regions.

4. **Explore trade-offs by designing multiple alternatives:** Making decisions between alternatives in a meaningful way can be achieved with the use of trade-off curves. These trade-offs show results from testing prototypes or simulating individual systems and present a relationship of the gained data. Consequently decisions can be made based on quantified data which ensures that the chosen solution is in fact optimal for the overall system.

5. **Impose minimum constraint:** Design specifications are kept to a minimum as this allows both development teams and external suppliers to contribute to the system in the best possible way. The specifications get more detailed as the project continues and subsystems are better defined.

6. **Narrow sets smoothly, balancing the need to learn and the need to decide:** Teams will always need to gradually remove sets from the list of possibilities. With each removal the understanding for the remaining sets should grow larger. This process is done by all functions in parallel and communicated to ensure the ongoing compatibility and ultimately choose a solution that fits best with the overall system. The gradual elimination of possibilities has to be a balanced act between spending enough time to explore and understand each option, while still staying within the given time frame and using available resources. This balancing is guided by the chief engineer.

7. **Pursue high-risk and conservative options in parallel:** This principle suggests that in addition to a solution promoting new technology a safe solution should be available as a back up. New technologies often require additional research and it is not always guaranteed that they will indeed proof superior over the current solution. Should the new solution not be functional or meet certain criteria at a specific cut-off point, the conservative solution can be chosen. In order for this principle to work, elements must be modularised to guarantee compatibility to the overall system.

8. **Establish feasibility before commitment:** With this principle the authors highlight the importance of ensuring designs are operable. This is enabled by the exploration of different designs in parallel and the slow convergence towards the final design. Additional measure to get around changes at late alterations depend on the nature of the product. Subsystems that are more likely to change due to results from testing should aim at a late production start.

9. **Stay within sets once committed:** Sets of solutions defined at early stages are only of value if teams do not stray from the communicated and agreed upon sets. When functions stay within those sets they can continue their work without worrying about possible rework due to incompatibilities. This principle depends heavily on the correct application of principle 8.

10. **Control by managing uncertainty at process gates:** Process gates should be used at key stages of the entire design process to allow managers to check the development status. These gates serve as a target for the remaining number of sets, as well as their understanding. As the projects passes more and more process gates, the number of sets must get smaller, and the understanding of each set larger, therefore reducing uncertainty. In the case that uncertainties are not resolved to the aimed level at specific process gates, the resolution of these issues must be prioritised and dealt with.

11. **Seek solutions robust to physical, market, and design variations:** Designs and solutions must function correctly regardless of physical influences such as manufacturing variations, wear, or weather condition. This concept of robust design was popularised by Taguchi (1988). To be able to deal with varying market variations short development cycles, adjust ability, and standardisation enable short development times. Therefore the market is less likely to change, which would result in rework to adapt to the latest developments. Finally, modularity and working within the range of available sets help face design uncertainties.

3.2 Framework based on SBCE principles

The original principles from Sobek & Ward (1996, p. 3) (see section 3.1) were later refined, restructured, and categorised into an overall framework by Sobek et al. (1999, p. 73). Their motivation was to gain a deeper understanding of the TPSD and confirm their previous claims (Sobek et al., 1999, p. 68).

The framework differentiates three main principles, whereas each lists three methods to implement them. The aim of the framework is to allow product development teams to work on subsystems in parallel and combine them into one overall system. (Sobek et al., 1999, p. 73)

3.2.1 Principle 1 - Map the design space

The first principle explains how the sets of possibilities are developed, defined, and communicated from all participating functions. This is done on two levels. First, for each new project design and manufacturing engineers discuss multiple options. This allows them to explore many aspects of subsystems and systems such as the feasibility or manufacturability, thus creating a deep understanding of the sets of alternatives. Second, engineers capture new information and data on alternatives, trade-offs and design standards on a continuous basis. The list below elaborates the approaches to "map the design space". (Sobek et al., 1999, p. 73)

- **Define feasible regions:** The objective of the first principle is to outline the feasible regions. All teams define their feasible regions in parallel and independently. Moreover they consider design constraints, or what is possible and what not. This is done with help from simulations and tests, as well as past experience and outside input from chief engineer or production engineering.
  A key tool for this step are the engineering checklists. They contain detailed design standards including functionality, manufacturability, regulations, as well as suggestions to improve specific aspects of individual parts (lower cost, simplify manufacturing process, improve quality, etc.) The first step for a new project, or project stage is that all teams exchange these checklists, to update each other on the current possibilities. In addition to design standards checklists also contain capabilities as understood by each designer. Experience adds in to update and further polish the possibilities.
  These lists are used to guide development teams through the process. If any part or component conforms to the checklist, it has a certain quality and functionality is guaranteed. Should this not be the case, it is a high priority of involved engineers to match the part to the checklists. (Sobek et al., 1999, p. 73-74)

- **Explore trade-offs by designing multiple alternatives:** The purpose of this principle is to help each other understand the effects of choosing one solution over another. After identifying and defining multiple alternatives, engineers need to choose between the options. The decision process is based on quantifiable data obtained from investigating trade-offs. This should show the relation between a design parameter and a performance outcome related to that parameter. During the exploration of trade-offs, knowledge and expertise are formed. Current, similar, or future projects can benefit from this. Additional resources are invested to

find the best solution and confirm it.
While exploring multiple alternatives, all involved teams and engineers share the findings and results amongst each other. Early design decisions are therefore very well thought through and result in very little rework effort in upcoming project phases.
Within this principle there is a strong emphasis on supplier involvement. The decision on the supplier should depend on his capability for the discovered alternatives. Supplier also use trade-offs to narrow down possible solutions and contribute to an optimal subsystem. All designs are not finalised until late stages in the development process, therefore creating room for full exploration and understanding of the sets. (Sobek et al., 1999, p. 74-76)

- **Communicate sets of possibilities:** Practising this principle allows different engineering teams to comprehend the capabilities and feasible regions of the other involved teams. Using only one idea can start an iterative chain of correcting associated subsystems or parts that need to be altered in order to continue to work with the whole system. Therefore all communication is done in form of sets of ideas within the defined feasible regions.
These sets must be communicated in explicit form. The consideration of subsystems or interfaces is important. Representation of sets should be simple, such as in form of matrices, lists, models, or drawings containing key criteria, and the alternatives themselves. Other useful information can be interval ranges of parameters, trade-off curves, or performance charts. (Sobek et al., 1999, p. 76)

3.2.2 Principle 2 - Integrate by intersection

The first principle "map the design space" creates a common understanding of each functions capabilities and feasible options. In order to integrate the different sets, the next step is to identify alternatives that are feasible and functionally acceptable for everyone. (Sobek et al., 1999, p. 76)

- **Look for intersections of feasible sets:** To find an alternative that is suitable to everyone's needs, the design teams look for intersections of the design spaces described by each team.
The aim of formal meetings with all involved teams should be to maximise the overall system performance. After the first team or function presents their sets, they receive comments and feedback from the other teams, who then in return incorporate the newly obtained information into their own sets. This process is done repeatedly until the best feasible solution is found. The intersection can be one single or a combination of multiple options. Nevertheless, the chosen design

must conform with the engineering checklists of all functions. (Sobek et al., 1999, p. 76-77)

- **Impose minimum constraint:** By reducing the limitations for a certain part or system, the system is not restricted too early and retains flexibility to make adjustments at later stages closer to production start. Furthermore this enables teams to fully understand and explore all set options, allows the combination of alternatives with according changes and thereby utilising the remaining flexibility and lack of constraints. Manufacturing engineers often have the expertise to decide on the final specifications what can be manufactured in a quick and cost efficient way.
  Suppliers are only provided with the minimum required information such as performance targets, needed interfaces, cost, and weight limits. They are then free to decide what detailed adjustments and fine tuning to make, as they have the expertise to create the best possible performance within the given restrictions. (Sobek et al., 1999, p. 77-78)

- **Seek conceptual robustness:** Designs and solutions must function correctly regardless of physical influences such as manufacturing variations, wear, or weather condition. This concept of robust design was popularised by Taguchi (1988).
  To be able to deal with varying market variations, short development cycles, adjustability, and standardisation enable short development times. Therefore the market is less likely to change, which would result in additional rework to adapt to the latest developments (Bhattacharya et al., 1997 in Sobek et al., 1999, p. 78). Finally, modularity and working within the range of available sets help face design uncertainties (Chang et al., 1994 in Sobek et al., 1999, p. 78-79).

3.2.3 Principle 3 - Establish feasibility before commitment

Iansiti (1995, p. 55-56) argues that designer and engineers put a lot of effort into understanding the design space along with its alternatives, for both their own and other functions' parts. This flexibility of the product development is the key criteria to allow an overall system optimisation. Both the first and second principle described in section 3.2.1 and 3.2.2 create the base and allow the third, and final principle "establish feasibility before commitment" to work. Set possibilities are gradually slimmed down to one single choice. This process is controlled by specific milestone events that set targets for each narrowing iteration. (Sobek et al., 1999, p. 79)

- **Narrow sets gradually while increasing detail:** The Set-Based Concurrent Engineering process enables product development teams to develop and commu-

nicate multiple sets of possibilities. The number of sets has to be narrowed down over the course of development. As this happens, details within sets described by drawings/models/simulations/prototypes increase. With these the development teams develop better understanding before disembarking specific sets or committing to one set. Reducing the number of sets creates more time to spend on the remaining ones.
The narrowing process is done in stages by all functions in parallel. This allows to work towards an overall system as a solution. Doing it in parallel allows the different teams to guide each other in the decision making process. This leads to meaningful decisions within the given time frame. The chief engineer must balance exploring sets in great detail and staying within the schedule. Changes become smaller and more detailed as the product development comes to an end.
This narrowing of sets can also extend to the suppliers. They are provided with general requirements and requested to generate ideas. These also get more detailed as the product development process goes on. At the point where the supplier's item needs to be specified, the client provides him with the remaining sets from the narrowing process. The supplier then takes the left over alternatives and creates test results, designs, and trade-off data. This new information helps to decide on the final design. (Sobek et al., 1999, p. 79-80)

- **Stay within sets once committed:** Development teams from different disciplines must stay within the communicated and agreed upon sets. If teams would decide to use ideas or concepts outside the committed design space, they will inevitably cause rework to other functions. However, staying within the committed sets guarantees compatibility and no future rework, allowing the product development teams to focus on next steps, instead of redesign efforts.
It is important to have a safe solution available in addition to a solution promoting new technology. New technologies often require additional research and it is not always guaranteed that they will indeed proof superior over the current solution. Should the new solution not be functional or meet certain criteria at a specific cut-off point, the conservative solution can be chosen. In order for this principle to work elements must be modularised to guarantee compatibility to the overall system. (Sobek et al., 1999, p. 80)

- **Control by managing uncertainty at process gates:** Dealing with many sets and therefore alternatives results in a lot of uncertainty. Uncertainty is determined by both the remaining number of alternatives for a set and the understanding of it. One way to address this is the introduction of process gates linked to specific stages within the product development.
With each consecutive process gate the size of the set decreases while its understanding increases, therefore managing uncertainty and allowing the project manager to keep track of the development. Every part or subsystem of the final

product has its own requirements and wanted uncertainty levels at specific gates. When the uncertainty is too high at a specific gate, the project manager must direct additional resources to resolve this problem, ensuring the product development can continue as planned.
Recurring and regular process gates also provide a number of advantages such as a report from all functions, creating an overview across all teams. As a result Eisenhardt & Tabrizi (1995, p. 108) claim that this results in an increased level of innovation and faster adjustments to possible changes.(Sobek et al., 1999, p. 80-81)

3.3 Modern SBCE principles

Khan et al. (2011a, p. 3-4) performed a literature review of the principles of SBCE amongst other things. The principles collected were obtained from different well established sources (Ward et al. (1995), Sobek et al. (1999), Morgan & Liker (2006), Ward (2007)), while adding some of their own ideas. They divided all identified principles in five categories, namely "strategic value research and alignment", "map the design space", "create and explore multiple concepts in parallel", "integrate by intersection", and "establish feasibility before commitment" (Khan et al., 2011a, p. 3-4).

3.3.1 Category 1 - Strategic value research and alignment

This new category, when compared to the framework described by Sobek et al. (1999, p. 73), takes elements from it, while Khan et al. (2011a, p. 4) added a focus on value creation by exploring the customer value for each project, and aligning projects to the overall strategic direction.

- Classify projects into a project portfolio.
- Explore customer value for project X.
- Align each project with the company value strategy.
- Translate customer value to designers.

3.3.2 Category 2 - Map the design space

The second category takes its first three principles from Ward (2007), and somewhat summarises the "define feasible regions" principle identified by Sobek et al. (1999, p. 73-74).

- Break the system down into subsystems.
- Identify essential characteristics for the system.
- Decide on what subsystem/component improvements should be made and to what level.
- Define feasible regions based on knowledge, past experience and the chief engineer, and consider the different functional groups.

3.3.3 Category 3 - Create and explore multiple concepts in parallel

This category aims at managing promising ideas from research and creative departments, and develop possible concepts for them with the help of SBCE. The eight principles listed below originated from the work of Sobek et al. (1999, p. 74-76) and Ward (2007).

- Pull innovative concepts from R&D departments.
- Explore trade-offs by designing multiple alternatives for subsystems/components.
- Schedule time for innovation and problem solving while the set of alternatives is broad.
- Ensure many possible subsystem combinations to reduce the risk of failure.
- Extensive prototyping of alternatives to test for cost, quality, and performance.
- Perform aggressive evaluation of design alternatives to increase knowledge and rule out weak alternatives.
- Information goes into a trade-off knowledge base that guides the design.
- Communicate sets of possibilities.

3.3.4 Category 4 - Integrate by intersection

The fourth category is essentially the same as the second principle described by Sobek et al. (1999, p. 76-79). However, Khan et al. (2011a, p. 4) added the importance of considerations towards concurrent engineering of product design and manufacturing in a lean environment.

- Look for intersections of feasible sets, including compatibility and interdependencies between components.
- Impose minimum constraints: Deliberate use of ranges in specifications and initial dimensions should be nominal without tolerances unless necessary.
- Seek conceptual robustness against physical, market, and design variations.
- Concurrent consideration of lean product design and lean manufacturing.

3.3.5 Category 5 - Establish feasibility before commitment

The final category draws strongly from Sobek et al. (1999, p. 76-77, 80-81) and also from some elements of the work of Ward (2007). Multiple principles within this category highlight the importance and advantages of delaying decisions in the product development process.

- Narrow sets gradually while increasing detail: Functions narrow their respective sets based on knowledge gained from analysis.
- Delay decisions so that they are not made too early or with insufficient knowledge.
- Design decisions should be valid for the different sets and should not be effected by other subsystems.
- Stay within sets once committed and avoid changes that expand the set.
- Control by managing uncertainty at process gates.
- Manufacturing evaluates the final sets and dictates part tolerances.
- Manufacturing begins process planning before a final concept has been chosen and thus act on incomplete information.
- Delay releasing the final hard specifications to major suppliers until late in the design process.

3.4 Chosen principles

The modern principles collected by Khan et al. (2011a, p. 3-4) were in fact just a byproduct while developing the SBCE baseline model. Moreover they were heavily influenced by Sobek et al. (1999) and Ward (2007). The work of Ward (2007) proposed the *Conceptual LeanPPD Model* which focused more on the whole product development, rather than on SBCE specifically.

The original principles described by Sobek & Ward (1996, p. 3-8) received a lot of scepticism (Sobek et al., 1999, p. 68), and were therefore reworked and elaborated later by Sobek et al. (1999, p. 73) into a framework. This indicates that the nine principles described in the framework are more mature than the initial eleven. Therefore the principles that will serve as a comparison baseline for the product development models will be those described by Sobek et al. (1999, p. 73-81):

1. Define feasible regions.
2. Explore trade-offs by designing multiple alternatives.
3. Communicate sets of possibilities.
4. Look for intersections of feasible sets.

5. Impose minimum constraint.
6. Seek conceptual robustness.
7. Narrow sets gradually while increasing detail.
8. Stay within sets once committed.
9. Control by managing uncertainty at process gates.

The assessment of the level of presence of these principles within the examined models will be on a scale from one to four. The four scores describing these levels are defined as follows:

1. **"+" :** No evidence of the core idea and/or strong contradictions to core elements of the principle itself.
2. **"++" :** There are a few similarities to the SBCE principle, however the core essence is not grappled. Some contradictions can still occur.
3. **"+++":** Many correlations and no contradictions. There are still important elements from the SBCE principles missing.
4. **"++++" :** Strong resemblance of the concept of the principle. The model achieves the same aspects as the SBCE principle, via the same or a different way, but ultimately aim for the same thing.

4 Innovation management for technical products

This chapter analyses and compares the W-Model as described by Eversheim (2003) to the principles of SBCE. The W-Model lies within a framework which is explained in section 4.1 along with the seven steps of the model. Section 4.2 discusses identified concepts of the principles of SBCE within the W-Model and analyses them against these principles.

4.1 Characteristics of innovation management for technical products

The W-Model lies within the strategic management layer of the Aachener Innovation Management (AIM) model (*Aachener Innovationsmanagement-Model*) which serves as a framework for it. Section 4.1.2 presents the supporting InnovationRoadMap (IRM)-methodology, listing requirements for an effective innovation process.

4.1.1 Aachener Innovation Management model

The AIM model shown in Figure 4.1 was created to provide a reference framework for all kinds of innovation management by aiming to increase the innovative capabilities of a company and identify gaps and core areas of the innovation process. (Eversheim, 2003, p. 5-7)

The management philosophy comprises the general attitudes, believes and ideals which influence the doings and actions of executives in a company (Ulrich & Fluri, 1992 in Eversheim, 2003, p. 8). The normative and strategic management layers build the framework in which the operative management is acting. Additionally the three pillars structures, activities and behaviour cross the three layers and represent the core mechanism for each of these layers. (Eversheim, 2003, p. 8)

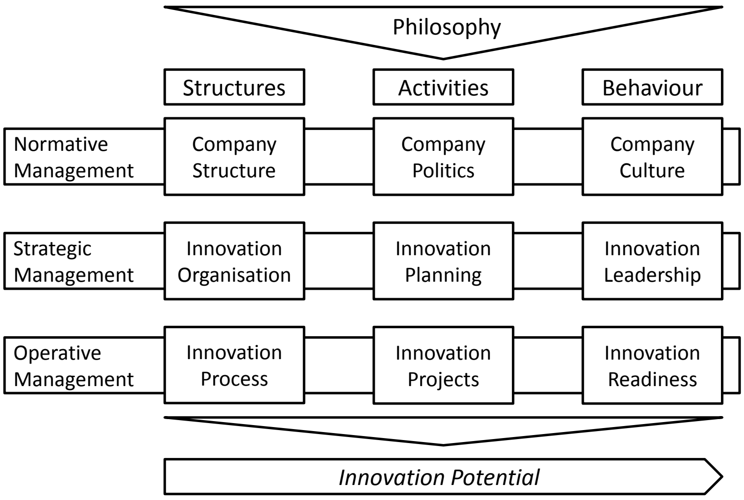

Figure 4.1: The Aachener Innovation Management model, according to (Bleicher, 1999 in Eversheim, 2003, p. 7)

- **Innovation Organisation** (*Innovationsorganisation*): The target of this aspect is to create structures that guide the organisation strategically and reach an ideal innovation capability. Covered areas are task positioning in terms of people or case orientation, the level of publicity of information exchange, the lifetime of proposed budgets and the distribution of resource inputs. (Eversheim, 2003, p. 17-18)

- **Innovation Planning** (*Innovationplanung*): Innovation planning indicates the direction for the type of innovation and is characterised by four concepts. There has to be a chronological direction of an innovation, meaning whether it is more urgent and a lot of information already exists, or more future oriented where the details still have to be worked out. Another concept describes the level of competence the company has and its relation to the state of market. Furthermore, management must address the degree of relationship towards both suppliers and customers and balance the need for flexibility with the complexity of modern products. (Eversheim, 2003, p. 8-12)
These four concepts are combined into one overall picture to determine the as-is position in terms of innovation planning for a company, as well as the future wanted to-be position. The gap between those two positions shows the required work to point out the direction for future product and process innovation. (Eversheim, 2003, p. 13, 15-16)

- **Innovation Leadership** (*Innovationsführung*): The purpose of innovation leadership is to encourage a positive, innovation supportive and friendly employee climate. This is achieved by balancing the facilitation of employees on either

specialisation or generalisation, dictating decisions either by hierarchy or perform them on an operational level and evaluating the performance results- or development-oriented. Furthermore, communication can be holistically or task specific. (Eversheim, 2003, p. 19)
Innovation leadership is a very delicate component of the AIM model, as it adds particular requirements to the employees. Any changes here need to be well thought out and given time to take effect. (Eversheim, 2003, p. 20)

Normative and strategic management are transcribed operatively in form of innovation projects, or product development projects. The purpose of the operative management is to translate the normative and strategic intentions into operations (Bleicher, 1999 in Eversheim, 2003, p. 20). The IRM-methodology (see section 4.1.2) provides a number of methods and tools to support this, especially for the innovation process and innovation projects. (Eversheim, 2003, p. 20)

Eversheim (2003, p. 21-23) discusses the categorisation of products according to their position on the market and from the viewpoint of the developing company. The market differentiates between newly developed products featuring a rich level of innovation, and improvements or adaptations of existing ideas. On the other hand the company has to decide between using the existing expertise or creating additional competence by risking innovation. It is often recommended that each company should aim to strike a balance between these four types, although depending on the industry specialisations can be more beneficial (Gassmann et al., 2001 in Eversheim, 2003, p. 23).

4.1.2 InnovationRoadMap-methodology

The IRM-methodology enables the systematic planning of product innovation or product development in a successful matter. This is achieved with bringing the strategic and operative layers of the AIM model to the praxis. The base for this methodology is the W-Model (explained in section 4.1.3). It is divided into seven main phases and is complemented with specific tools and methods that support these process steps. (Eversheim, 2003, p. 27)

There are multiple important requirements which are needed for an effective innovation process. They originate from the product innovation and innovation process elements from the AIM model as well as from experience and industrial studies. According to Brandenburg (2002, in Eversheim, 2003, p. 27-28) the nine requirements are:

1. Be geared towards clear targets (*An klaren Zielen orientieren*).
2. Idea quality before idea quantity (*Ideenqualität vor Ideenquantität*).

3. Design for the future (*Für die Zukunft gestalten*).
4. Make use of existing strengths (*Vorhandene Stärken nutzen*).
5. Create transparent and standardised processes (*Transparente und standardisierte Prozesse schaffen*).
6. Objective and comprehensive idea selection (*Objektive, nachvollziehbare Ideenauswahl*).
7. Manage uncertainties (*Mit Unsicherheiten umgehen*).
8. Synchronise market and technology development (*Markt- und Technologientwicklung synchronisieren*).
9. Remain candidness and stimulate creativity (*Offenheit bewahren und Kreativität stimulieren*).

4.1.3 W-Model

The W-Model illustrated in Figure 4.2 is a core element of the IRM-methodology and consists of seven main phases where each phase presents a confined planning element (Eversheim, 2003, p. 32). Because of the irregularities of market, fast technological evolution, or company dynamics phases 1, 2 and 7 need to be repeated periodically. The remaining phases 3, 4, 5 and 6 need to be included into the product development planning. (Brandenburg, 2002 in Eversheim, 2003, p. 32)

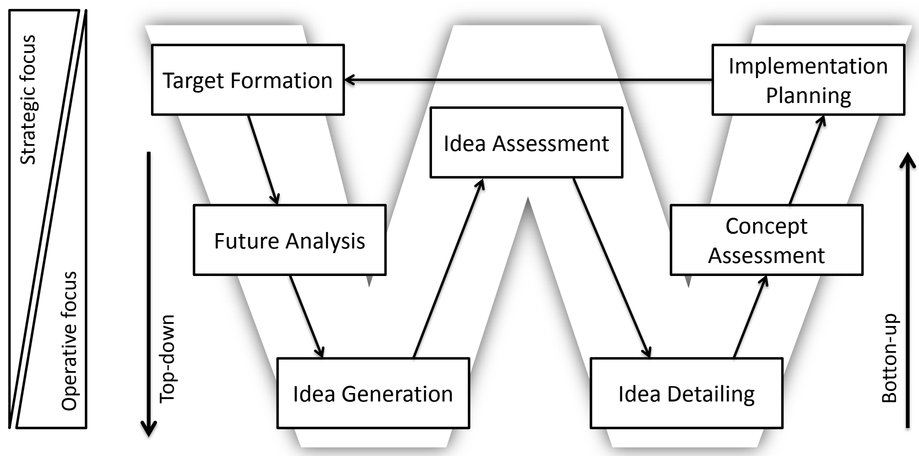

Figure 4.2: The W-Model, according to (Brandenburg, 2002 in Eversheim, 2003, p. 39)

Eversheim (2003, p. 32) mentions that the seven main phases cannot be separated entirely as they have interdependencies and fluid change overs. Moreover it is possible, or sometimes even encouraged, that certain phases are executed in parallel. Depending on the product and the type of project which is being developed, it might not be necessary to execute all of them. The seven main phases are (Brandenburg, 2002 in Eversheim, 2003, p. 33-35):

1. **Target Formation (*Zielbildung*):** The purpose of the first phase is to define strategic guidelines and innovation targets, or to identify the innovation potential. These guidelines and targets can emerge from the overall business strategy. The input of this phase can be from both internal and external sources. Additional outputs are the innovation strategy and a specified configuration space (*Gestaltungsfelder*).

2. **Future Analysis (*Zukunftsanalyse*):** Targets of the second phase is the revelation of business related innovation potentials and duties. Another aspect of this phase is the analysis of trends and future market and/or technology progress. This results in a future prospect analysis as another target.

3. **Idea Generation (*Ideenfindung*):** As the name suggests, the emphasis in this phase is the generation of creative product ideas. These should adhere to the identified innovation potential. It is encouraged that a multitude of ideas are generated. In a second step, solutions have to be proposed for each of the ideas. They have to be documented in preparation for the next phase.

4. **Idea Assessment (*Ideenbewertung*):** The objective of the fourth phase is to assess the ideas based on market, technological and strategic criteria. This process creates information which is used to allocate the idea into the InnovationRoadMap.

5. **Idea Detailing (*Ideendetaillierung*):** This phase aims to create product concepts with the help of further market and technology considerations. An important activity is the definition of product requirements, which in return are used to produce detailed solutions. The final output should be specific product concepts for each product idea, ideally validated and tested through prototyping.

6. **Concept Assessment (*Konzeptbewertung*):** The goal of the sixth phase is the quantitative assessment of the specific product concepts from the previous phase. In addition to the steps already performed in the fourth stage, idea assessment, the economic feasibility is evaluated. These results are then used to describe the planned InnovationRoadMap in more detail.

7. **Implementation Planning (*Umsetzungsplanung*):** The purpose of the final phase is to use all the generated data and information to create a thorough program for the InnovationRoadMap. While doing this, it is important to consider

the whole product life cycle.

4.2 Comparison of the W-Model to the principles of SBCE

This section presents the identified concepts of SBCE principles found within the seven phases of the W-model and analyses them against these principles.

4.2.1 Map the design space

The overall configuration space (*Gestaltungsfeld*) for possible products that can be developed can for example be determined with the help of a Gap or SWOT analysis. (Eversheim, 2003, p. 45)

In addition to the collection of trends and their analysis, engineers make projections of the future (*Zukunftsprojektionen*). These two elements are combined into the future analysis (*Zukunftsanalyse*) and assessed based on their correlation. This enables a company to create a targeted future preview tailored to the configuration space (*Gestaltungsfeld-spezifisches Zukunftsbild*). (Eversheim, 2003, p. 57-62)

4.2.1.1 Define feasible regions

Concepts of this SBCE principle within the W-Model

The definition of the feasible regions and wanted product attributes are achieved in the phases "idea generation" and "idea detailing". The activities within these two stages result in product concepts. Additionally "concept assessment" and the conjoint-analysis mention prototyping as a form of testing.

In the early phases of idea generation, an ideal product is defined. It is purely theoretical and can be used as a point of reference, as well as to help improve creativity. (Eversheim, 2003, p. 77)

Another important step is the translation of customer requirements into technical parameters. These need to be measurable in an objective way to correlate them to the product features. Customer requirements can be determined from market research or with the help of Kano models. Latter categorise customer requirements into either basic, demand, or enthusiasm attributes. From these customer requirements the product attributes are generated. (Eversheim, 2003, p. 101-102, 144)

Prototypes and simulation can be used to verify and test product concepts. Product features should be reviewed by marketing experts, engineers, as well as potential byers. (Eversheim, 2003, p. 111-112, 125, 212)

Analysis and rating

Eversheim (2003, p. 212) encourages the involvement of other parties, other than designers to be involved in the generation of product features. This includes marketing and potential buyers. However, unlike explained in the SBCE principles, the different functions do not do this independently.

There are no explicit checklists until later in the process when generated ideas are being assessed. In contrast to SBCE, where the engineering checklists are used to confirm the manufacturability and capabilities of involved engineering teams, these checklists are more focused towards product features and attributes as well as their assessment. (Eversheim, 2003, p. 87)

Simulation or prototyping is suggested as a method to verify the functionality of a product.

Rating: +++

4.2.1.2 Explore trade-offs by designing multiple alternatives

Concepts of this SBCE principle within the W-Model

The development and decision making spans across all of the seven phases. Additionally multiple concepts of this principle were found in several suggested methods (e.g. TRIZ methodology and technology-roadmapping) which assist in multiple phases.

Idea generation can be supported by a multitude of methods and instruments such as abstraction, combination and variation (Brandenburg, 2002 in Eversheim, 2003, p. 39). The assessments of product ideas can be based on the following criteria: increased profit, market growth, capacity utilisation and distribution of risk (Haberfellner et al., 1999 in Eversheim, 2003, p .42). The importance and favour of one point over the other depends on the company and/or industry. Assessment criteria for idea selection can be assigned to one of the following three categories: beneficial to the company, seminal and technological potential (Brandenburg, 2002 in Eversheim, 2003, p. 40). The information from the first category can be used to determine the value of benefit for each product idea. (Eversheim, 2003, p. 39-42, 93).

Product design is diverted from the technical aspects, which in return are derived from the customer requirements. Therefore should the requirements change the product design will be influenced. Scenario management can help to predict these customer driven changes. Apart from multiple creativity techniques, the W-Model suggests the use of the TRIZ methodology to deal with complex contradictions during product detailing. This includes the target of an ideal final solution. (Eversheim, 2003, p. 138-139, 151, 158)

The assessment of possible solutions is done with quantitative data and supported by checklists (Eversheim, 2003, p. 87). Because of the lack of detailed information in early stages of development, business and cost related calculations have to be made with adjusted methods. (Staudt et al., 1991 in Eversheim, 2003, p. 88)

If the product development is expected to be very complex and demanding, or newly available technology is used in the development or manufacturing phase, a cooperation with suppliers is recommended. (Brandenburg, 2002 in Eversheim, 2003, p. 125, Schmitz, 1996 in Eversheim, 2003, p. 227)

Analysis and rating

Trade-offs are made in the form of evaluating and assessing concept alternatives. Unlike in SBCE, there is a lack of information in early decision stages which lead to the elimination of solutions that have not been fully explored yet. (Eversheim, 2003, p. 87-88) On the other hand, one of the requirements for the IRM methodology is the consideration of new technologies from outside the company (Pfeiffer & Weiß, 1995 in Eversheim, 2003, p. 30).

The active involvement of the supplier into the product development process is encouraged only for complex products. (Brandenburg, 2002 in Eversheim, 2003, p. 125, Schmitz, 1996 in Eversheim, 2003, p. 227)

Targeting the optimum system is attempted with the use of the TRIZ methodology (Eversheim, 2003, p. 158). SBCE does not suggest a methodology to ensure the overall best possible system, but rather focuses on exploring trade-offs and simulations.

Rating: ++

4.2.1.3 Communicate sets of possibilities

Concepts of this SBCE principle within the W-Model

The introduction of an information model (*Informationsmodell*) is recommended in the phase "idea generation".

In praxis the correct documentation of product ideas is not always present. Moreover a lot of company expertise is in form of implicit knowledge of individual employees. During the whole development process information is often missing. It requires a lot of resources to find this missing data. (Eversheim, 2003, p. 79)

An information model attempts to eliminate these difficulties by offering an effective and efficient planning based on existing application-oriented information, briefing all involved engineers, supports and enhances cross-functional and interdisciplinary communication, providing guidelines for data gathering and creating a knowledge-basis usable for future projects. (Brandenburg, 2002 in Eversheim, 2003, p. 80)

With the help of an information model ideas are communicated with product idea data sheets (*Produktdatenblatt*). Apart from the description of the idea, these data sheets also hold information about the target market, technology and organisation. (Brandenburg, 2002 in Eversheim, 2003, p. 80) This unified representation of ideas makes the upcoming evaluations easier. (Eversheim, 2003, p. 82)

Analysis and rating

Eversheim (2003, p. 79) discusses the introduction of an information model. The purpose of an information model is very similar to the elements of this SBCE principle; to comprehend the capabilities of all participating teams. This is achieved with offering interdisciplinary communication and planning. Additionally communication of alternatives can be done with product idea data sheets, holding clear descriptions of the product idea, as well as information about the target market or underlying technology. (Brandenburg, 2002 in Eversheim, 2003, p. 80)

The consideration of interfaces between parts or models is not discussed or highlighted explicitly, but it is featured in the phases "idea generation" and "idea detailing". (Eversheim, 2003, p. 74, 100)

Rating: +++

4.2.2 Integrate by intersection

The intersection of possible solutions takes place in form of assessment. This is mostly done in the stages four, "idea assessment", and six, "concept assessment". (Eversheim, 2003, p. 86, 108)

4.2.2.1 Look for intersections of feasible sets

Concepts of this SBCE principle within the W-Model

There are various relations to this principle in the W-Model. They are covered in phases three to six, namely "idea generation", "idea assessment", "idea detailing", and "concept assessment".

The combination of problem and solution ideas into overall solutions can be done with the help of a morphological analysis (Eversheim, 2003, p. 78). This can result in many possible solutions which encourages unusual concepts and increases the number of alternatives. (Haberfellner et al., 1999 in Eversheim, 2003, p. 78)

The chosen ideas should be those that match the initial target, defined in the "target formation" phase, best. (Brandenburg, 2002 in Eversheim, 2003, p. 90)

After grading all product attributes it is necessary to consider the interaction between them to determine synergies and conflicts early on. The suggested method for this is the House of Quality. (Eversheim, 2003, p. 102) Solutions for each of the described product attributes are combined (Brandenburg, 2002 in Eversheim, 2003, p. 103). This offers a wide range of solutions. With the help of morphological analysis, the overall best solution is turned into a product concept. (Eversheim, 2003, p. 103)

It is important that a product concept meets the adapted and detailed product specifications and requirements (Brandenburg, 2002 in Eversheim, 2003, p. 111). In the phase of "concept assessment", these specifications can be compared to the likewise evolved technical criteria. (Eversheim, 2003, p. 111)

Analysis and rating

Unlike stated in the SBCE principle, there is no declared focus to base the selection of ideas or concepts on the capabilities of individual disciplines. The phase "target definition" although aims at identifying the actual abilities of the company and therefore including all different disciplines. (Eversheim, 2003, p. 40)

While in SBCE the chosen solutions have to conform with the engineering checklist to safeguard the conformance to initial product expectations and requirements, the W-Model favours ideas that best match the initial target definition of the "target formation" phase. (Brandenburg, 2002 in Eversheim, 2003, p. 90)

Even though Eversheim (2003) does not discuss the incorporation of newly gained information from one team into the development of other teams, the information model provides the capability to access this data. (Brandenburg, 2002 in Eversheim, 2003, p. 808)

Rating: +++

4.2.2.2 Impose minimum constraint

Concepts of this SBCE principle within the W-Model

There are only a few references to the idea of delaying decisions and allowing flexibility in the design process. These are made in the phase "concept assessment" within the conjoint-analysis. Manufacturing considerations are made in the "concept assessment phase".

In line with the conjoint analysis, customer requirements are translated to solution neutral product features (Geisinger, 1999 in Eversheim, 2003, p. 210). Furthermore, all product features derived from customer expectations must have a certain freedom of change. (Backhaus et al., 1996 in Eversheim, 2003, p. 212)

The manufacturing process has to be designed with attributes such as production number, variants, quality features, or geometrics. (Eversheim, 2003, p. 112)

Analysis and rating

The suggested conjoint-analysis method recommends to convert customer requirements to neutral product features (Geisinger, 1999 in Eversheim, 2003, p. 210) with a certain freedom of change (Backhaus et al., 1996 in Eversheim, 2003, p. 212). However, it is not mentioned or noted if this freedom of change is intended to allow for an overall optimum system, or if it is simply to avoid costly rework with minor adaptations to certain parts.

Decisions in form of assessments and selection of and between alternatives are not delayed intentionally. Eversheim (2003, p. 36-37) even states that the sustained effort would become too high if many concepts would reach later stages of the development process.

Manufacturing engineers are involved in the development process as this helps the planning of the production stage and tailors the product to the company's manufacturing capabilities (Eversheim, 2003, p. 112). There are no references to using elements of this principle with involved suppliers.

Rating: ++

4.2.2.3 Seek conceptual robustness

Concepts of this SBCE principle within the W-Model

In order to achieve an effective working environment that allows complex problems to be solved in a continuous way, standardised software tools, processes and information storage can be used. (Schmidt, 1996 in Eversheim, 2003, p. 29)

Additionally, product robustness is covered briefly in the phase "idea generation".

Scenario management can be used as a tool to develop robust product ideas in terms of future reliability. (Eversheim, 2003, p. 138)

Analysis and rating

The idea of robust design is considered. Scenario management is used as a method to devise ideas that have a strong degree of future reliability (Eversheim, 2003, p. 138). SBCE encourages the use of robust design according to Taguchi (1988) which additionally aims to create mechanical and market related robustness.

Transparent and standardised processes are one of the requirements for the IRM methodology (Schmidt, 1996 in Eversheim, 2003, p. 29) which serves as a supporting guideline for the W-model (Eversheim, 2003, p. 27). Both of these models do not focus on a short development cycle, but rather make use of the company's potential to come up with innovative products for a successful market entry. The usage of a modular development and product system is mentioned throughout the model.

Rating: ++

4.2.3 Establish feasibility before commitment

During the phase "idea assessment" one of the criteria categories is technological potential. This criteria covers aspects such as technical feasibility, manufacturing capabilities, availability of required resources, or other factors. (Brandenburg, 2002 in Eversheim, 2003, p. 94) After further refinement of the criteria, the product concept can be verified with the help of prototypes and/or simulation. (Eversheim, 2003, p. 111-112)

4.2.3.1 Narrow sets gradually while increasing detail

Concepts of this SBCE principle within the W-Model

The elimination of non-promising ideas and concepts is described with the idea funnel, as well as somewhat within the phase "concept assessment".

The number of ideas is constantly reduced. First within the future projections and then continuing up to the stages of product concept selection. This process is referred to as an idea funnel. While the effort for each idea increases as the process continues, the agility and flexibility decreases, allowing the idea to get more detailed. (Eversheim, 2003, p. 36-37)

All product concepts are assessed in terms of conformity towards the requirements and technical and economical feasibility. The increased detail of the product concepts allow engineers to use more specific benchmarking tools. (Eversheim, 2003, p. 108)

Analysis and rating

Both of the main elements from this principle are present in the W-Model. The sets, or in this case ideas and later concepts, are reduced in a process that is referred to as an idea funnel. So the number or remaining ideas are reduced along with it the flexibility, meaning an increase in detail and an increased working effort per idea. (Eversheim, 2003, p. 36-37)

Nevertheless, there are no references whether the elimination or assessment is done in collaboration or independently in parallel by participating disciplines. Furthermore, an extension of this principle to the suppliers is not mentioned.

Rating: +++

4.2.3.2 Stay within sets once committed

Concepts of this SBCE principle within the W-Model

The importance of a modular system is mentioned within the laws of technical evolution and technology-roadmapping.

Eversheim (2003, p. 171) refers to the laws of technical evolution. One of these highlights the importance of a parallel development of the subsystems. Not doing so would slow down the development process and prohibit the improvement of the overall system. (Eversheim, 2003, p. 177)

Eversheim (2003, p. 224-225) implicitly suggests the use of a modular parts systemwhile mentioning that it should be decided early on whether each modular part is to be altered in the process of finalising the product or not. This also includes the option of introducing new manufacturing processes or machinery. These tasks can be supported with a technology calender (*Technologiekalender*).

Analysis and rating

As the W-Model follows the idea of assessing and eliminating ideas (Eversheim, 2003, p. 36), it is only logical that engineers stick to one concept once it has been chosen.

There are no references of having a safe solution as a backup if the currently worked on idea or concept is redeemed to be impractical. However, as this model aims at pure innovation (Eversheim, 2003, p. 5, 27, 31), safe solutions are not within the scope of purpose.

Eversheim (2003, p. 177, 224) mentions the use of modularised elements and subsystems multiple times, even though not in direct connection to the W-Model or its phases.

Rating: ++

4.2.3.3 Control by managing uncertainty at process gates

Concepts of this SBCE principle within the W-Model

In the early phases of the product innovation process engineers make a lot of assumptions as they discuss product ideas that are completely theoretical at this point. This creates uncertainty in terms of manufacturability or market acceptance, resulting in the need for applying only methods which are fitting to the situation. (Eversheim & Schuh, 1996, p. 4-6 to 4-14,) The methods that support the narrowing of alternatives depend on the level of concretion and remaining number of ideas. (Eversheim, 2003, p. 36)

Additional elements of this principle are found in the phase "idea assessment".

While assessing ideas and determining a promising solution there are certain uncertainties that can arise concerning the information of these ideas. Firstly, the uncertainty if while ignoring cost and time aspects, the sought-after solution can be reached. Secondly, whether the remaining time frame is enough to obtain the wanted information. Thirdly, how much effort is actually required to reach the wanted level of information at a certain point. Lastly, if the results of product innovation are actually economically feasible. (Brandenburg, 2002 in Eversheim, 2003, p. 88)

Analysis and rating

While the number of remaining alternatives is not suggested, the outputs for each end of the seven phases of the W-Model is clearly defined. Although the pre-defined outputs are not technically process gates, they essentially describe the required level of understanding and the targeted uncertainty level at specific stages in the development process.

Uncertainty is discussed in the early phases in connection with manufacturability and market success of a new innovation. (Staudt, 1996 in Eversheim, 2003, p. 30)

Rating: +++

4.3 Summarised results of the W-Model

The W-Model has many correlations with the SBCE principles spread over all nine of them. Nevertheless, the model of Eversheim (2003) does not even have one strong resemblance to a particular principle. The overall ratings collected in Table 4.1 are therefore quite balanced.

No.	Principle	Rating
Map the design space		
1	Define feasible regions	+++
2	Explore trade-offs by designing multiple alternatives	++
3	Communicate sets of possibilities	+++
Integrate by intersection		
4	Look for intersection of feasible sets	+++
5	Impose minimum constraint	++
6	Seek conceptual robustness	++
Establish feasibility before commitment		
7	Narrow sets gradually while increasing detail	+++
8	Stay within sets once committed	++
9	Control by managing uncertainty at process gates	+++

Table 4.1: Overall results of the comparison between the W-Model and SBCE's principles

5 Networked Product Development

This chapter describes and compares the Networked Product Development model of Gausemeier et al. (2006) to the principles of SBCE as defined by Sobek et al. (1999). Gausemeier et al. (2006) proposes a unique approach as he suggests to make heavy use of products, components and parts from supplying companies with the help of a so called Global Engineering Network (GEN).

5.1 Characteristics of Networked Product Development

This section discusses the increased complexity of products which Gausemeier et al. (2006) refers to as self-optimising systems (*Selbstoptimierende Systeme*) and the underlying consequences in the product development process. Furthermore, the proposed product development process consisting of three connected development cycles and the enabling GEN are presented in section 5.1.3.

5.1.1 Self-optimising systems

Typical problems during modern product development result from the increased complexity of systems. The problems occur mostly in development praxis. The interaction between different disciplines of engineering in product development do not work as intended. This is because of the isolated view of each team. The final combination of each teams individual work results in rework and additional iterations of tasks and activities. Because of these factors predictions and planning for cost, as well as testing in general, are not always reliable and dependable. (Gausemeier et al., 2006, p. 18-19)

Recent trends in technological advancement go towards the development of intelligent autonomous systems (*Selbstoptimierende Systeme*) that adapt dynamically due to their surroundings. This is achieved with sensors obtaining information, analysing them and responding to them in real time. The responses can be in form of changing parameters, behaviour and structural alignment. The self improvement process itself consists of three consecutive steps. It begins with the analysis of the as-is situation, followed by the appointment of system targets and finally the alignment of the system behaviour. (Gausemeier et al., 2006, p. 19-22)

In addition to mechanical working principles and their solutions, engineers need to take solutions and the integration of modern information processing into account. Gausemeier claims that with the help of networked product development it is possible to make use of existing solutions over the internet and use them effectively for ones own need. (Gausemeier et al., 2006, p. 25)

5.1.2 Product development process

During the product development the design takes place inside a three dimensional development space. The actual position of each development project within this space depends on the product. (Gausemeier et al., 2006, p. 26-27) The three dimensions are:

- Abstract towards concrete
- General to detailed
- Viewpoint (structure, behaviour and design)

These points are targeted in the product development process, ranging from product or business idea up to market entry. It is an interplay of tasks divided into three cycles, where all cycles are linked with each other. This interrelation is shown in Figure 5.1. (Gausemeier et al., 2006, p. 28, 31)

- **First cycle: From the potential of future to a promising product concept (*Von den Erfolgspotentialen der Zukunft zur erfolgsversprechenden Produktkonzenption*)**

  In the first cycle there are three tasks or fields of activity. The first is "Potential Finding" (*Potentialfindung*) and is about identifying the capability of future technology, their application, as well as an appropriate course of action. After recognising potential ideas, the "Product Finding" (*Produktfindung*) task is all about the search and selection of ideas to make use of this potential. Moreover engineers must also consider requirements. Important tools in this step are creativity techniques such as TRIZ. The last field of activity in the first cycle is "Business Planning" (*Geschäftsplanung*). It is about the definition of business strategy to determine a market for the possible product. Thereafter the product planning takes place, with a focus on variety of options and used technology. Lastly, the business plan is developed to determine the financial feasibility of the new product. (Gausemeier et al., 2006, p. 28-29)

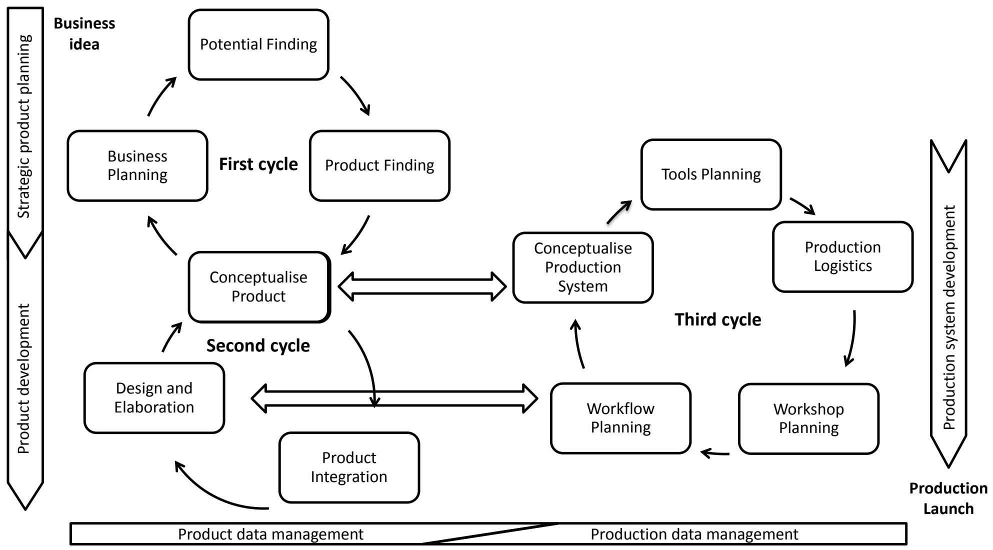

Figure 5.1: Three-cycle model of product development, according to (Gausemeier et al., 2006, p. 31)

- **Second cycle: Product development/virtual product (*Produktentwicklung/ Virtuelles Produkt*)**

  The second cycle is all about the generation of a product concept and relevant solutions, as well as the elaboration and combination of all domains to one overall solution. Because of the rising importance of computer assisted design, the term virtual prototyping became increasingly popular. (Spur & Krause, 1997 in Gausemeier et al., 2006, p. 29)

- **Third cycle: Process development/digital factory (Prozessentwicklung/ Digitale Fabrik)**

  This cycle's focus includes the process itself, location, times, limitations and cost calculations amongst others. The most important steps for the process development are the tools planning, production logistics, workshop planning and workflow planning. (Gausemeier et al., 2006, p. 30)

5.1.3 Cooperative product engineering & Global Engineering Network

Cooperative product engineering (*Kooperatives Produktengineering*) attempts to convert a product idea into a market ready entry (Gausemeier et al., 2000 in Gausemeier et al., 2006, p. 36). Gausemeier et al. (2006, p. 36) emphasis the importance of task- and discipline-overlapping cooperation and suggest a model that aims to tackle these challenges.

The reference model illustrated in Figure 5.2 covers the three task strategic product planning (*Strategische Produktplanung*), product development (Produktentwicklung), and process development (*Prozessentwicklung*). It is very important to consider the relationships and their dependencies. Their overlapping areas are strategic product development *(Strategische Produktentwicklung*), strategic process development (*Strategische Prozessentwicklung*), and integrated product and process development (*Integrierte Produkt- und Prozessentwicklung*). (Gausemeier et al., 2006, p. 37)

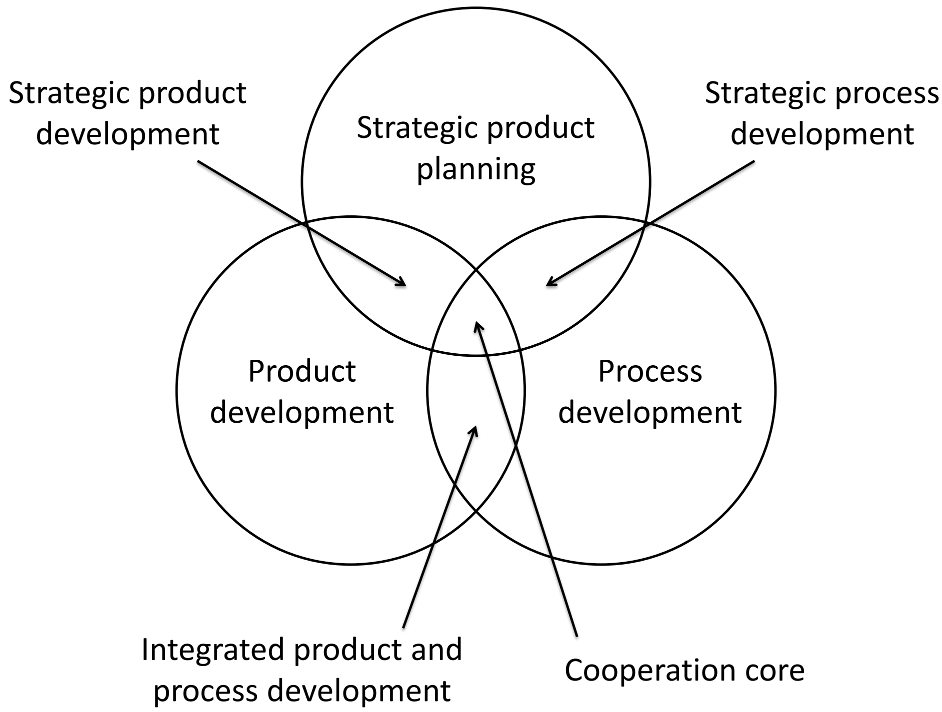

Figure 5.2: Reference model of cooperative product engineering, according to (Gausemeier et al., 2000 in Gausemeier et al., 2006, p. 37)

To adapt and deal with the quickly changing market, companies cannot rely on market analysis alone and must realise/find/identify its own potential in product and manufacturing planning. Teams cooperate on three aspects: field of activity, interdisciplinary and location wise (meaning between different locations or between different companies). This is called Global Engineering Networking (GEN). The purpose of the GEN is to make the lessons learned, solution elements, methods, or services of one company accessible to others. In other words, the GEN is an electronic marketplace for knowledge and solutions. Users can use the GEN to search in categorised search registers for a particular field of expertise, where they will be able to find the solution best suited for their needs. (Gausemeier et al., 2006, p. 36, 39)

5.2 Comparison of Networked Product Development to the principles of SBCE

This section identifies the concepts for each of the principles of SBCE and compares them directly. Gausemeier et al. (2006, p. 40) claim that most components or subsystems are bought from other companies , therefore the focus of networked product development is on the possibilities of finding the best possible solution from a GEN database with the help of modern technologies which are described in his book. The actual product development is only covered lightly, nevertheless some pointers can be found.

5.2.1 Map the design space

The initial strategic planning already has to involve all departments with considerations to their interdependencies. When a development team searches a marketplace for suitable components, the usability of the results depends heavily on the classification and provided data from the suppliers. The more detailed this information is, the likelier it is that the development teams find what they are looking for. (Gausemeier et al., 2006, p. 37, 297)

Methods such as Quality Function Deployment (QFD) or Failure Mode and Effects Analysis (FMEA) can provide information which can be the starting point of new product or process innovations. (Gausemeier et al., 2006, p. 307)

5.2.1.1 Define feasible regions

Concepts of this SBCE principle within Networked Product Development

The type and kind of product that will be developed depends heavily on the potential of the company. Therefore the potential determines the business plan. The product development is in close connection to process development, especially for complex systems. Both of them have to be developed in parallel and interplay. This is to be supported by a suiting data management system. (Gausemeier et al., 2006, p. 30, 37)

In relation to knowledge management, the idea generation is the first step of product development. It is supported by market analysis and creativity techniques. (Gausemeier et al., 2001 inGausemeier et al., 2006, p. 354) Based on the requirements, the concept and target solution are defined. Furthermore, they provide the basic structure of the system and help create the necessary foundations of cooperative work. (Gausemeier et al., 2006, p. 377)

Design reviews involving development engineers from multiple locations can be made with the help of remote presentations. Manufacturability needs to be taken into consideration early, as it already has an influence on the concept. (Gausemeier et al., 2006, p. 30, 111)

Analysis and rating

The feasible regions are defined by identifying the potential of the company. In SBCE the technical feasibility of an idea plays a very important role. Gausemeier et al. (2006) suggest the involvement of manufacturing from as early as the concept phase, which is covered by the potential assessment. (Gausemeier et al., 2006, p. 30, 37)

The design or idea generation process does not only involve engineers from the own product development, but can extend to and include those working at cooperating firms or partners. There is, however, no mentioning of an independent definition of all teams.

Gausemeier et al. (2006, p. 233-235) suggest that PLM systems should take the role of SBCE's engineering checklists and keep track of requirements, progress, as well as recent findings and experiences from teams. Nevertheless, PLM systems are rather complex and the simplicity of the engineering checklists can be advantageous in day-to-day business.

Rating: +++

5.2.1.2 Explore trade-offs by designing multiple alternatives

Concepts of this SBCE principle within Networked Product Development

Even when new products are developed, many of their components and subsystems are bought from suppliers. Most components are bought from suppliers already fully developed. With modern technology, these components are selected from online catalogues. Example catalogue systems are Content Management (CM) and Cross Media Publishing (CMP). However, these systems are of the same interest to the supplier, as they use them to sell their products. (Gausemeier et al., 2006, p. 40, 271-272)

Initially generated ideas need to be documented to establish a common understanding for everyone who will be involved in the development process. This documentation covers topics such as market performance, positioning or success factors. Promising ideas are assessed based on previously defined criteria, possibly with the help of checklists (Vahs & Burmester, 1999 inGausemeier et al., 2006, p. 355). Test data can be obtained from external tools with the help of Web Services. Furthermore, the reuse of explicit knowledge is an important factor in product development. (Gausemeier et al., 2006, p. 102, 128, 354)

Personnel from product planning, development and manufacturing have to cooperate in interdisciplinary teams. This is essential to create a successful product. There is a constant exchange of information between project teams about product and manufacturing system technologies. (Gausemeier et al., 2006, p. 36, 38)

A software development environment can only support the product development successfully if it has the necessary features. Firstly, the methods should match the product specifically. Secondly, the current state of the development must be tracked. Moreover, different kinds of representation have to be unified into a comparable format. Lastly, the resulting data needs to be able to be communicated. An additional important point is the consideration of interfaces between different companies. (Gausemeier et al., 2006, p. 116-117, 119)

Virtual prototyping is used to reduce cost and time requirements on possibly not feasible or functional solutions. Because of the extensive computational effort, grid computing is often used to achieve the required results in a reasonable time. (Gausemeier et al., 2006, p. 104)

Analysis and rating

The GEN makes optimal solutions available for the individual needs of each product

(Gausemeier et al., 2006, p. 39). Nevertheless, it is the engineers job to identify and find this best solution. This creates the opportunity to achieve an optimum system, but it is not guaranteed that the chosen combinations actually do result in the best possible system.

Virtual prototyping is used to obtain quantifiable data to make meaningful and sound decisions. The purpose of this is to reduce the number of solutions before spending too many resources and test runs on them. (Gausemeier et al., 2006, p. 104) SBCE also suggest to use extensive testing such as prototyping to make supported decisions.

Gausemeier et al. (2006, p. 36, 38, 354-355) encourage the communication and cooperation of multi-disciplinary teams, extending to a constant exchange of information. Additionally, they mention the concept of knowledge management systems as an important part of product development. This includes the documentation of existing solutions bought from suppliers and their incorporation into the product. These software assisted systems provide the necessary tools to share the findings amongst all teams.

SBCE suggests to ask suppliers for multiple designs of the potential component. Gausemeier et al. (2006, p. 40) claim that most components are already developed and do not need to be re-invented. Therefore he does not suggest to ask suppliers for multiple concepts, but rather makes use of the GEN and online catalogues to find a wide range of alternatives and select the most fitting one. This is a different approach compared to SBCE, but when considering his argument, it ultimately yields the same result.

Rating: ++++

5.2.1.3 Communicate sets of possibilities

Concepts of this SBCE principle within Networked Product Development

A lot of product related information is exchanged throughout the entire product life cycle. There are specific applications and standards that allow an easy communication between partners within an industrial sector. The most used standard is the STEP (Standard for the Exchange of Product Model Data). STEP is in continuous adaptation to suit and meet the latest requirements of the industry. (Gausemeier et al., 2006, p. 169)

Communication is mostly done via an intranet inside the company, an extranet for alliances or close cooperation with other firms and with the internet as the universal network. Exchange and transfer of technical data (e.g. CAD models) can be done with the help of file transfer protocol (FTP). (Gausemeier et al., 2006, p. 46, 52)

Nowadays, the development of most technical products involve mechanical, electrical and software engineering. Simultaneous cooperation between these areas is encouraged and has to be long-term and actively encouraged. System elements get more detailed and are ultimately combined to modules, components, or subsystems. (Gausemeier et al., 2006, p. 37, 221, 376)

Analysis and rating

Similar to the SBCE process, the individual capabilities of participating teams are very important in networked product development. The technical capabilities of the company and its functional areas define what products will be developed. (Gausemeier et al., 2006, p. 40)

Gausemeier et al. (2006, p. 40) describe systems as a cascade of solution elements. This ranges from the overall system down to component level. This structure of the products is the core enabler that makes the use of GEN possible and effective. The partial elements are combined to modules which are ultimately combined into one system.

With consideration to the heavy use of modern information technology, Gausemeier et al. (2006, p. 223-226) suggest Engineering Data Management systems to represent, store, manage and exchange CAD or simulation models, as well as other product related technical information.

Rating: ++++

5.2.2 Integrate by intersection

Different types of Product Lifecycle Management (PLM) systems can provide the needed tools to maintain a complete overview of the product progress. Furthermore, they allow the engineers to keep track of the progress of other teams or suppliers. (Gausemeier et al., 2006, p. 223)

5.2.2.1 Look for intersections of feasible sets

Concepts of this SBCE principle within Networked Product Development

An crucial step during the development process is the integration of different available solutions from suppliers into the company's own product. Modern information and communication technologies are replacing printed catalogues of available components and systems, thus creating a lot of potential. On the other hand, it also brings a lot of challenges, as there are different interfaces that need to be brought together, and matching solutions need to be found first. This multitude of interfaces is managed by the GEN by promoting standardised interfaces for industry specific classes. (Gausemeier et al., 2006, p. 40, 261-262, 385)

Analysis and rating

The individual capabilities of each technical department is determined before product development begins (Gausemeier et al., 2006, p. 29, 38). This covers the SBCE's recommendation that the solutions must be within everyone's defined design space.

Gausemeier et al. (2006) do not suggest to confirm that chosen solutions match the initial requirements directly, or to aim at maximising overall system performance. Neither is there any description of team meetings, their participants, schedule, or immediate actions.

Rating: ++

5.2.2.2 Impose minimum constraint

Concepts of this SBCE principle within Networked Product Development

Product ideas that made it through the initial screening are analysed in a much more detailed fashion, including feasibility studies. However, it is important that the number of ideas is reduced to a fraction (10%) of the initial number of ideas. This is because the effort at this stage increases dramatically. (Gausemeier et al., 2006, p. 355)

Analysis and rating

Gausemeier et al. (2006, p. 355) rate the increased effort and costs of multiple possible solutions until very late in the development process as not feasible. This is a strong contradiction to the SBCE process, as this denies engineers to study several alternatives in more detail.

Suppliers are seen as providers of available components to choose from (Gausemeier et al., 2006, p. 37). So no newly developed components or subsystems are considered. The SBCE process focuses more on the non-standard parts of a product that need to be customised in order to optimise the overall system, which can only be achieved with providing the suppliers with room for compromises. There is no suggested level of detail for the requirements.

Rating: +

5.2.2.3 Seek conceptual robustness

Concepts of this SBCE principle within Networked Product Development

The standardisation of components is encouraged and Extensible Markup Language (XML) schemata can help with this, as each company typically present the attributes of their products differently. XML offers a way to structure data. (Gausemeier et al., 2006, p. 79-80)

Knowledge-based engineering can assist engineers in connecting product components and product features. This results in the use of common parts or similar system structures. (Gausemeier et al., 2006, p. 348)

Analysis and rating

As in SBCE, Gausemeier et al. (2006, p. 348) advocate an accentuation on standardisation of both components and their interfaces. Networked product development proposes the use of knowledge based engineering to keep track of connected components. Furthermore, the representation of the available solutions from suppliers within the GEN are standardised with the XML schemata (Gausemeier et al., 2006, p. 79).

The concept of robust design or a focus on short development cycles are not mentioned.

Rating: ++

5.2.3 Establish feasibility before commitment

Before products receive their final specifications they undergo technical feasibility and market attractiveness studies (Gausemeier et al., 2006, p. 355). Proof of the functionality of components is determined with analysis tools such as finite element methods (FEM) and Digital Mock-Up (DMU) tools (Gausemeier, 2004 inGausemeier et al., 2006, p. 162).

5.2.3.1 Narrow sets gradually while increasing detail

Concepts of this SBCE principle within Networked Product Development

Concrete solutions are typically reviewed on an abstract level to enable generalisation and therefore produce better solutions. The concretion of designs is supported by modelling or composition tools. An example for this are CAD systems. Not only the product but also the process development steps get more concrete over time. (Gausemeier et al., 2006, p. 30, 32, 103)

Analysis and rating

In relation to knowledge management, the systematic management of ideas is handled with the help of an idea cone. As in the SBCE process, ideas are gradually reduced and their level of detail increases all the way to technical and economical specifications. Nevertheless, the idea cone aims to reduce the number of solutions very early and only to roughly 10% at the concretion stage. (Gausemeier et al., 2006, p. 353-355)

On the other hand, the remaining solutions are first reviewed on an abstract level. They are analysed and developed in more detail with the help of computer assisted tools . Further, at the same time the process steps get more detailed as well. (Gausemeier et al., 2006, p. 30, 32, 40, 103)

Gausemeier et al. (2006) do not discuss that the elimination of ideas or solutions ought to be performed by all functional departments in parallel and independently. Again, there is no reference to extending this principle to the suppliers, except that provide a list of their produced components for the engineers to choose from.

Rating: ++

5.2.3.2 Stay within sets once committed

Concepts of this SBCE principle within Networked Product Development

Standard part components can be identified with the help of the ISO PartLib, a standard that tries to unify all complex information into a structured and categorised system. Keeping the own product module based allows the development teams to have a broad range of solutions available from other suppliers. (Gausemeier et al., 2006, p. 40, 177-179)

Knowledge management integration into PLM systems creates the advantage of an automated check of interdependencies. This means that if an alteration to one component is entered into the system, it elaborates which other components are affected and need to be adapted as well. (Gausemeier et al., 2006, p. 254)

Analysis and rating

Rework is identified and reduced, but not eliminated with the help of PLM systems. This is because necessary changes are pointed out as soon as any changes are required, preventing a massive rework effort at a later checkpoint/stage in product development. (Gausemeier et al., 2006, p. 254) On the other hand the interplay between the three cycles (see Section 5.1.2) is repeating itself, although this is intentional as Gausemeier et al. (2006, p. 28-29) try to consider the whole product lifecycle.

There are a number of safe solutions available as a backup, as most of the components will be bought from suppliers either way. Depending on their range of products and standard interfaces, safe solutions will be available. (Gausemeier et al., 2006, p. 40)

Rating: ++

5.2.3.3 Control by managing uncertainty at process gates

Concepts of this SBCE principle within Networked Product Development

To apprehend minus development, the strategic position of the company on the market is determined by the current manufacturing capabilities and engineering skills. (Gausemeier et al., 2006, p. 38)

Analysis and rating

Gausemeier et al. (2006) do not discuss process gates or regularly scheduled checkpoints during the product development process, which should control the remaining number of alternatives and their level of concretion.

Rating: +

5.2.4 Other observations

Gausemeier et al. (2006, p. 223-224) mention that simultaneous development is widely used amongst companies. The increased amount of information generated because of this approach the company has to fulfil the following requirements: a consequent Engineering Data Management (EDM), a systematic approach to product development, an aligned company structure and the necessary attitude and willingness of engineers.

The creation, identification, development and usage of knowledge within a business on both the operational and strategic level is of great importance to the product development. (Gausemeier et al., 2006, p. 311-312, 347)

GEN enables to provide the right information, at the right time, at the right place. Therefore it does not only include the necessary capabilities to manage, but also to searches for the required information. (Gausemeier et al., 2006, p. 385)

5.3 Summarised results of Networked Product Development

While all the principles of "mapping the design space" were rated with very high scores, all six remaining principles showed little to no elements of SBCE, resulting in poor ratings. "Impose minimum constraint" and "control by managing uncertainty at process gates" were assessed to have no representation within networked product development or contradicted to the idea of SBCE. Table 5.1 shows the rating of all principles for this chapter.

No.	Principle	Rating
Map the design space		
1	Define feasible regions	+++
2	Explore trade-offs by designing multiple alternatives	++++
3	Communicate sets of possibilities	++++
Integrate by intersection		
4	Look for intersection of feasible sets	++
5	Impose minimum constraint	+
6	Seek conceptual robustness	++
Establish feasibility before commitment		
7	Narrow sets gradually while increasing detail	++
8	Stay within sets once committed	++
9	Control by managing uncertainty at process gates	+

Table 5.1: Overall results of the comparison between Networked Product Development and SBCE's principles

6 Systematic Development

This chapter describes the Systematic Development model of Pahl et al. (2007) and compares it's product development process to the principles of Set-Based Concurrent Engineering. The model is aimed at the operational level which is supported by the suggestion and explanation of multiple methods and techniques to support the presented product development process.

6.1 Characteristics of Systematic Development

The development process of Pahl et al. (2007) is divided into four main phases which are presented in section 6.1.2 and preceded by a production planning stage described in section 6.1.1.

6.1.1 Decision characteristics and production planning

Psychology as well as philosophy represent insight and recommendations of the systematic approach (Pahl, 1994 in Pahl et al., 2007, p. 59]. These two domains suggest that in order to solve a problem there has to be access to the required knowledge in an eligible form. Moreover, abstract and concrete aspects need to be balanced as well as a flexible progress without loosing sight of the target. (Pahl et al., 2007, p. 66)

The following list presents good characteristics of engineers (Pahl et al., 2007, p. 66-67):

- A detailed analysis of the objective at the beginning of a project. This extends to sub-ordinate targets during the development process.
- A concept phase to determine a favourable solution and a detailed design in a dedicated design stage.
- The search for solutions should start broad and converge quickly as the project continues. Decision approaches should alter, i.e. abstract-concrete, overall-partial problem.
- Reoccurring objective evaluation of solutions based on comprehensive criteria.

- Continuous reflection on performed methods and, if required, adaptation to current and future situations.

Pahl et al. (2007) describe production planning as an important part of product development. Production planning consists of seven steps and should integrate seamlessly into the development process (eighth step) (Pahl et al., 2007, p. 103-105):

1. Analyse situation
2. Align retrieval strategy
3. Look for solutions
4. Selection of solutions
5. Define products
6. Plan implementation
7. Clarify and specify product
8. Development and manufacture

6.1.2 Product development process

Pahl et al. (2007, p. 194-199) separate the development process into four main phases:

1. **Plan and clarify the assignment (*Planen und Klären der Aufgabe)*:** The purpose of the first phase is to clarify the target. This yields the necessary information to decide the wanted requirements of the future product. The end result is a descriptive requirements list, which is updated continuously as the product evolves.

2. **Conceptualize (*Konzipieren*):** The second phase focuses on the root problem statement, definition of functional structures and searching for solutions. The technological possibilities have to be taken into consideration. The development of more than one solution is conceivable. Developed solutions have to be assessed and compared to the requirements list. Based on this assessment, the most promising concept is chosen and continued to work with. There is the possibility, that multiple solutions get conceptualized and need to be analysed further in the next phase.

3. **Design (*Entwerfen*):** The first step in this phase is to come up with multiple designs for each concept. This creates a better understanding of the problem and enables design teams to obtain quantifiable data, which in return allows them to assess all designs. Subsystems are then combined into the overall system. This system is then analysed in terms of overall feasibility before it is finalised in the

last phase.

4. **Finalise (*Ausarbeiten*):** As the name suggests, this phase is about finalising all technical regulations, in addition to cost and manufacturing planning. The emphasis is the optimisation of the functionality, design and production. Prototypes and their testing are also an important step in this stage.

With the proposed product development approach Pahl et al. (2007) aim to reduce the number of required iterations, or working steps and activities within one main phase. Obviously, backtracking from one main phase to a previous has to be avoided. (Pahl et al., 2007, p. 205)

Ideally there is a parallel handling of working tasks as this creates the biggest opportunity to shorten the development cycle. This requires specific planning concerning modular product design, clearly defined interfaces between process steps and autonomous process steps. The presented methods and instructions present more a guideline which need to be adapted individually for each company and development project. (Pahl et al., 2007, p. 104, 205, 190)

6.2 Comparison of Systematic Development to the principles of SBCE

Pahl et al. (2007, p. 513) revisit most of the SBCE principles within each of his four main phases. The principles are discussed in detail, analysed and rated according to their level of representation of the principles of SBCE.

6.2.1 Map the design space

Concept development starts with the abstraction of the requirements list. Thereafter the function structure is established, followed by the development of working structures. As one way of generating ideas, the aesthetics of a product can be taken into account from the very beginning. The design does not need to be very detailed. However, it should give an outlook of things to come. (Pahl et al., 2007, p. 116, 232,)

6.2.1.1 Define feasible regions

Concepts of this SBCE principle within Systematic Development

Most of the ideas of this first principle can be found in the description of recommended methods with additional comments from the first main phase, "plan and clarify the assignment".

The technical feasibility of ideas is checked in the planning stage, which Pahl et al. (2007) do not consider as part of the product development and therefore happens before "planning and clarifying the assignment". (Pahl et al., 2007, p. 103-104)

Pahl et al. (2007) describe requirements lists in great detail. They represent the starting point and must be kept up to date at all times. The list can be categorised according to the products subsystems. Furthermore, they are needed for later evaluation and grading of solutions. When developing a product from scratch, requirements lists are the basis for early concepts. The generation of requirements lists should involve all participating parties, such as designers or manufacturing engineers. (Pahl et al., 2007, p. 94, 117, 215-217, 226)

Before the actual product development can begin, it is necessary to clarify on properties that define the core idea of the concept, influence the basic structure and define the basic design. (Pahl et al., 2007, p. 226)

Analysis and rating

There is a check for the technical feasibility of early concepts. However, there are no prototypes and very little testing, as these early concepts are described on a very abstract level. Additionally, there is no explicit recommendation of parallel and independent feasibility checks from different functional groups. (Pahl et al., 2007, p. 103-104).

As in SBCE, the core idea of each concept is communicated between involved teams. The requirements list has a different purpose as the engineering checklists in SBCE. In early stages the requirements list is used to verify functionality and serves as a starting point, while in later stages it is often used as baseline for assessing alternatives. Engineering checklists on the other hand are a communication tool to keep all engineering teams up to date with each others latest intentions and activities. This ensures that everyone stays within the "defined feasible regions". (Pahl et al., 2007, p. 117, 215, 226).

Pahl et al. (2007, p. 94) state that each idea should be based on the requirements list, whereas in SBCE the engineering checklists grow and evolve from the development process.

Rating: ++

6.2.1.2 Explore trade-offs by designing multiple alternatives

Concepts of this SBCE principle within Systematic Development

Pahl et al. (2007) discuss the idea of developing more than one concept mostly indirectly within the proposed methods for product planning and determining solutions, as well as their assessment. Additionally there are references to this principle in the phases "plan and clarify the assignment", "conceptualise", and "design".

To come up with a satisfying result, multiple concepts need to be developed. The search for working principles to complete all desired subfunctions results ideally in multiple solutions, referred to as the solution space. The design of multiple alternatives should be done in collaboration of all participating teams, especially with input from manufacturing. (Pahl et al., 2007, p. 117, 256, 305, 308)

The aim is always to generate an optimal system. An optimal solution is defined by meeting all mandatory and most optional requirements as well as stay within budget, delivery schedules and manufacturing possibilities. Complex problems are divided into their partial functions and solved separately, as this makes the process more approachable. (Pahl et al., 2007, p. 121, 156)

After obtaining enough reasonable data from testing or analysis, all product ideas can be graded. For an initial screening of the ideas simple yes or no decisions can be used. Detailed analysis during the concept phase can be very difficult as abstract concepts are not detailed enough to provide objective and usable data. (Pahl et al., 2007, p. 118, 161, 166)

There is no grading of ideas in the concept phase as there are not enough details available. Assessment of developed alternatives typically happens after the concept or design stage. The requirements list typically supports these assessments and gradings of alternatives. (Pahl et al., 2007, p. 166, 215, 270)

Analysis and rating

Pahl et al. (2007, p. 117, 256, 305, 308) also recommend the design of multiple ideas and concepts with the help of all relevant teams. This should include manufacturing to allow an early start on production planning.

In contrast to SBCE there is no discussion of trade-offs, and quantifiable data cannot be obtained as ideas are not developed to greater detail until later. As with SBCE, decisions are explicitly made to aim for an overall optimum solution. (Pahl et al., 2007, p. 121, 161, 166, 270)

The concept of involving the supplier into decisions, or requesting multiple possible solutions is not discussed.

Rating: ++

6.2.1.3 Communicate sets of possibilities

Concepts of this SBCE principle within Systematic Development

The representation of ideas, concepts and designs is outlined in the proposed methods and extended with minor elements from the "conceptualise" and "design" phases.

A Product Lifecycle Management (PLM) system assists in the control and regulation of information flow between both internal teams and external suppliers. This happens throughout the entire development process starting from concept stages, up to product support and beyond. All changes to products are managed and documented in an Engineering Data Management system (EDM). (Pahl et al., 2007, p. 89, 100)

All developed proposals must have a description of the intended functionality as well as a requirements list, representing the same features that engineers would use during the actual development. If future changes or alterations of the product or some of its components are intended from the beginning, they have to be communicated. (Pahl et al., 2007, p. 119)

While working on the functional structure it is reasonable to present both, all the wanted functions and their relevant solutions in a matrix. After concept selection Pahl recommends to work on subsystems first and then combine these to possible design. (Pahl et al., 2007, p. 256-257, 309)

Analysis and rating

Participating teams communicate with the help of Product Lifecycle Management and Engineering Data Management systems. Similar to SBCE, the communication between engineers contains possible solutions, as well as their alternatives for each component.

The actual capabilities of each department are considered implicitly, as the working structure represents both all the wanted product functions and their relevant solutions. (Pahl et al., 2007, p. 89, 100, 256-257).

Nevertheless there are no sets of ideas and there is no communication method targeting optimal exchange between individual functional groups.

Rating: ++

6.2.2 Integrate by intersection

After defining the working structure and functional structures, the teams select suitable combinations of ideas. These are then analysed and described in more detail. (Pahl et al., 2007, p. 119, 232)

6.2.2.1 Look for intersections of feasible sets

Concepts of this SBCE principle within Systematic Development

Pahl et al. (2007) discuss the identification of acceptable and feasible alternatives acceptable to everyone within both the recommended methods and the "conceptualise" phase.

The different solutions generated through the previously independently tackled problems must be combined to one overall solution. One of the main issues for intersecting ideas is the compatibility between partial solutions. Furthermore, the following considerations must be made when combining possible alternatives: only pursue ideas that meet the requirements list and the expected expenses and to highlight attractive combinations and analyse their advantages towards other combinations. (Pahl et al., 2007, p. 159-160, 166)

All working principles, each fulfilling partial functions of the overall system, are combined with their neighbouring working principles to create a system solution, while considering their compatibility. Pahl et al. (2007) state that the physical and technical restrictions and tolerance of partial solutions pose the greatest challenge when combining partial solutions. It is important to compare the chosen solution with the requirements list before committing to it. (Pahl et al., 2007, p. 259-260, 265)

When trying to determine the optimum overall system, each component has to be assigned a certain weight. The weight of each idea can be based on one of three options. Firstly, based on the requirements. Secondly, with the help of a value-benefit analysis. Lastly, Pahl et al. (2007, p. 170) suggest an approach based on the VDI2225 (VDI (1977)), which assigns different weights only if there is a significant difference between options. To reach the optimal design it is necessary to make use of modern computational capabilities, as the number of possible combinations, in connection with their interdependencies, create a very complex problem. (Pahl et al., 2007, p. 162, 168-171)

Analysis and rating

Pahl et al. (2007, p. 159-160, 166, 259) highly emphasise the combination of partial solutions and the complexity of this matter. The SBCE process attends to this matter already with the "exploration of trade-offs". In the concept stage, SBCE focuses more on the exchange of new information from meetings, their incorporation into each teams set of ideas, as well as ensuring the chosen solutions are within the defined design space. Latter is achieved with the help of the engineering checklists.

As with engineering checklists in SBCE, chosen solutions have to be conform with the initial requirements lists.(Pahl et al., 2007, p. 260, 265).

The idea of maximising the entire system performance is highlighted and Pahl et al. (2007, p. 168-171) propose three different methods to approach this matter. While Sobek et al. (1999, p. 76-77) do not propose specific methods, they encourage engineers to maximise the system performance as well.

Rating: +++

6.2.2.2 Impose minimum constraint

Concepts of this SBCE principle within Systematic Development

Pahl et al. (2007) mention only a few pointers about loose regulations in early stages. These can be found in the general section and while "planning and clarifying the assignment".

To ensure that product development engineers are not affected by suggestions, requirements must be presented without implementation suggestions or hints. The requirements lists can evolve gradually, nevertheless the requirements and specifications have to be finalised as soon as possible. On the other hand, Pahl et al. (2007) mention that if the final specifications for a product are defined too early, it hinders innovation. (Pahl et al., 2007, p. 104, 119, 229)

Development teams start with a very broad definition of the problem description to allow engineers to take non traditional approaches and therefore enhance innovation. (Pahl et al., 2007, p. 233, 236)

Analysis and rating

In early stages, requirements lists, present the requirements without implementation suggestions, while their level of detail evolves gradually as the process continues (Pahl et al., 2007, p. 119, 236). Nonetheless, Pahl et al. (2007, p. 229) recommend that they need to be finalised as soon as possible. This is in contradiction to the essence of SBCE, where delaying decisions intentionally allows for a full exploration of all possible options.

Manufacturing engineers are involved in important decisions, but there is no extension of this principle to suppliers. (Pahl et al., 2007, p. 117)

Rating: ++

6.2.2.3 Seek conceptual robustness

Concepts of this SBCE principle within Systematic Development

The notion of robust design is described partially within the basic guidelines, the advocated methods for product planning and the last of the four main phases "finalise".

Pahl et al. (2007, p. 313) propose a checklist for embodiment design. It features elements such as durability and deformation, which come close to the concept of robust design.

Detailed design must take manufacturability, assembly and transport into consideration. Apart from the interrelationship of subsystems, other factors the product has to fulfil are certain attributes in the domain of security, maintenance, ergonomics, monitoring, or handling. (Pahl et al., 2007, p. 56, 58)

Standardisation of mechanical, electric, or software interfaces is necessary to eliminate problems when combining different subsystems. Products should be designed in a way that allow future alterations or functional enhancements if the market requires so. (Pahl et al., 2007, p. 101)

Analysis and rating

The checklist for embodiment design contains multiple elements that describe the idea behind robust design very well. (Pahl et al., 2007, p. 313)

According to Pahl et al. (2007, p. 101) standardisation plays an important role. While SBCE attempts to encourage engineers to use standardisation rigorously for both process and technical aspects, their model highlights the importance of standardised interfaces of all kind.

Rating: ++++

6.2.3 Establish feasibility before commitment

The technical feasibility of products has to be checked. Moreover it is important that there also exists a market and an according marketing strategy for selling the product. All theoretical combinations have to be analysed and narrowed down to a realistic field of solutions. Before the engineers commit to one idea, they are assessed based on technical and economic factors. (Pahl et al., 2007, p. 119-120, 160, 232, Figure 6.1)

6.2.3.1 Narrow sets gradually while increasing detail

Concepts of this SBCE principle within Systematic Development

Evidence of the principle of narrowing down the set of possibilities to one choice can be found in the description of both production planning and evaluation methods as well as in the "concept" phase.

Functional connections should at first only be categorised into very broad functional areas, and then gradually broken down into more complex partial functions. Chosen working structures get described in more detail. This allows an effective grading of the working structures in a quantifiable way. All assessments are done against the initial requirements list. (Pahl et al., 2007, p. 253, 263, 266, 268, 273)

Initially, the focus should only be on the most promising solutions. A typical step is to narrow down the typically big number of developed solutions, starting with the very promising on the one on the hand and very unlikely ideas on the other hand. Pahl et al. (2007) suggest the following criteria for selection in this order: compatibility, meeting requirements, feasibility, further effort, security and ergonomics, existing and required knowledge. (Pahl et al., 2007, p. 162, 164, 172)

Working interrelationships are the base for decisions that ultimately lead to detailed planning. All decisions regarding the further refusal of ideas have to be made in accordance with design and manufacturing teams. Once possible solutions have been identified and get more concrete and detailed, it is necessary to involve sales, marketing and manufacturing into the development process. (Pahl et al., 2007, p. 56, 117, 119)

Abstraction is the creation of working structures. At first, concepts are described on a very abstract level. As possible solutions get more defined and concrete, it becomes easier to obtain quantifiable data from them. There are different types of analysis methods, depending on the level of abstraction or detail an element has. (Pahl et al., 2007, p. 93, 166, 261)

Analysis and rating

As the development process continues, the remaining ideas are analysed and assessed in more detail with the newly obtained information and a method matching of the current level of abstraction takes place. This process is repeated as the product evolves over the different phases. This represents very much the idea of SBCE, where the sets are narrowed down in stages. In opposition to SBCE, the elimination of alternatives is not done by all different teams in parallel. (Pahl et al., 2007, p. 93)

There is no reference to expand this principle to suppliers.

Rating: +++

6.2.3.2 Stay within sets once committed

Concepts of this SBCE principle within Systematic Development

Ideas of this principle are found in the "conceptualise" and "finalise" phases. Additionally there are references in the proposed methods.

After teams have defined a concept that has evolved from multiple ideas and alternatives, they commit to and pursue one concept. When working on a concept, many working steps include changing or correcting certain aspect. A need for changes is possible, as the knowledge about the problem causing component is not deep enough. (Pahl et al., 2007, p. 274-275, 306, 310-311)

Pahl et al. (2007, p. 150, 153) suggest the use of catalogues containing proven solutions for specific problems. These solutions vary in terms of concretion range and application area.

Pahl et al. (2007, p. 663) do not recommend using a modular approach for newly developed products. They rather recommend to use it when there is a demand for a broad range of functionality from one product. Only in this case a modular product is economically feasible.

Analysis and rating

Once a concept has proven itself in the early stages, engineers do not change it. Nevertheless there are expected to be changes to the concept as the remaining details are not worked out yet. This is a direct contradiction to the front-loading process of SBCE. There all concepts are analysed in full detail in early stages to ensure with the help of constantly updated engineering checklists that concepts, the team committed to, do not need to be altered, but only fully developed. To deal with this the development teams need to redo previous activities and resolve the problem. (Pahl et al., 2007, p. 274-275, 310-311)

Modularised elements should only be introduced after a product has proven itself on the market, and there are other applications for it, which can be achieved via a modularised approach (Pahl et al., 2007, p. 663). This step alone results in additional rework. SBCE suggests the use of modules from the very beginning, as this also enhances the compatibility and independence of components.

Rating: +

6.2.3.3 Control by managing uncertainty at process gates

Concepts of this SBCE principle within Systematic Development

Pahl et al. (2007) mention the management of uncertainty in the "concept" phase and suggest a specific method to deal with it.

When assessing ideas that are still in the concept stage, the underlying uncertainty has to be accounted for. In early stages the knowledge of new technologies is very limited. To address the resulting uncertainty, Pahl et al. (2007) suggests a systematic approach and names the growth-share matrix as an example. Furthermore, they recommend the use of Fuzzy Logic to cope with the uncertainty of realising ideas, as well as the formulation of requirements and targets. (Pahl et al., 2007, p. 112, 180, 274)

Analysis and rating

The production planning stage as well as the subsequent four main phases "plan and clarify the assignment", "conceptualise", "design" and "finalise" have very specific demands towards the level of detail of the product at their respective end. While these are not technically process gates, they do serve as certain milestone events the development teams work towards.

Pahl et al. (2007, p. 80, 112) recommend to use methods such as growth-share matrix or fuzzy logic to deal with uncertainty in the early phases of product development.

Rating: ++

6.2.4 Other observations

Engineers need to know the overall company strategy and its targets as well as their relationships and importance (Pahl et al., 2007, p. 102). Khan et al. (2011a, p. 4) also mention this as an important first step in their proposed SBCE process.

Pahl et al. (2007, p. 103) recommend interdisciplinary teams only if the size of the company allows it.

Pahl et al. (2007, p. 229) describe the requirements lists are the foundation for knowledge management systems, which contain the experience and knowledge gained from past projects. Khan et al. (2011a, p. 5-6) list a knowledge-based environment as one of the key enablers of LeanPPD and a supporter of SBCE.

There is a differentiation between different grades of innovation, ranging from developing an overall new product to re-engineering an existing one (Pahl et al., 2007, p. 94). Khan et al. (2011a, p. 4) define the classification of projects in a project portfolio as one of their SBCE principles.

6.3 Summarised results of Systematic Development

Most principles are very poorly presented within the model of Pahl et al. (2007). Especially "stay within sets once committed" shows strong contradictions to the core idea of

SBCE as changes to somewhat developed concepts are expected. Contrary to this, the idea of "conceptual robustness" is very well established. Table 6.1 shows the results for this model.

No.	Principle	Rating
Map the design space		
1	Define feasible regions	++
2	Explore trade-offs by designing multiple alternatives	++
3	Communicate sets of possibilities	++
Integrate by intersection		
4	Look for intersection of feasible sets	+++
5	Impose minimum constraint	++
6	Seek conceptual robustness	++++
Establish feasibility before commitment		
7	Narrow sets gradually while increasing detail	+++
8	Stay within sets once committed	+
9	Control by managing uncertainty at process gates	++

Table 6.1: Overall results of the comparison between Systematic Development and SBCE's principles

7 Methodical development of technical products

Lindemann (2009) proposes the Munich Proceedings Model, or MVM (*Münchener Vorgehensmodell*), as an product development model to assist companies with the development of technical products. The approach is very flexible as all seven elements of the model can be used independently, as well as co-dependently in form of a multiple-step process model. The MVM itself is situated in the Munich Product Concretion Model, or MKM (*Münchener Produktkonkretisierungsmodell*) which serves as a framework and reference for the proceedings model.

7.1 Characteristics of methodical development of technical products

This section describes the MKM framework as well as the seven elements of the MVM. Furthermore, Lindemann (2009, p. 55-57) suggests several principles of action which need to be taken into consideration throughout the entire development of a product.

7.1.1 Munich Product Concretion Model MKM

The Munich Product Concretion Model (*Münchener Produktkonkretisierungsmodell*) (MKM) shown in Figure 7.1 serves as a navigation and guidance model for the development process. A very important dimension for this model is the currently considered level of detail for the developed product. In parallel to the increase of detail, requirements get updated and more tangible, creating the "Requirements Scope" (*Anforderungsraum*). The four levels that represent this degree of concretion are (Ponn & Lindemann, 2008 in Lindemann, 2009, p. 44-45):

- **Requirements model** (*Anforderungsmodell*)**:** Targets product features and specifications, evolves and gets more detailed in steps as the product development process continues.

- **Functional model** (*Funktionsmodell*)**:** Description of functions on an abstract level, as well as their connections and interdependencies.
- **Effect model** (*Wirkmodell*)**:** Presentation of the actual solution for a technical problem, master plan is formed on this level.
- **Construction model** (*Baumodell*)**:** Describes parts and modules as well as their connections in the structure of the overall product.

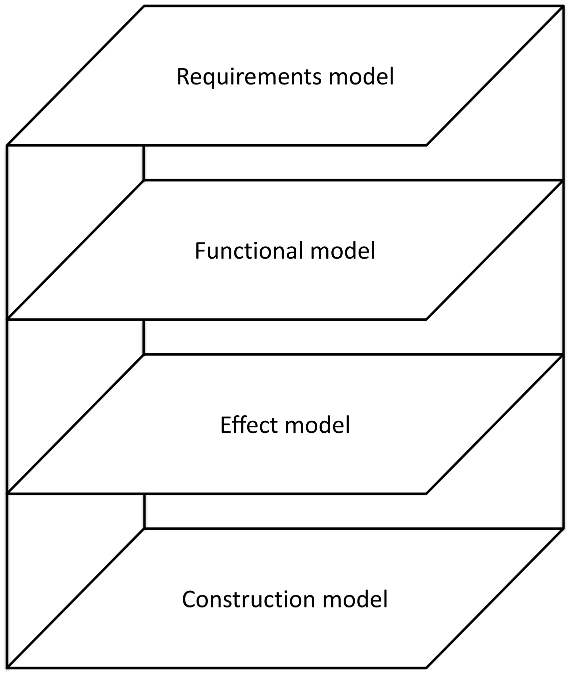

Figure 7.1: The Munich Product Concretion Model MKM, according to (Ponn & Lindemann, 2008 in Lindemann, 2009, p. 45)

The levels themselves are not rigid, as the product development process faces multiple iterations and there are constant changes and alterations to the product design. One solution is often not enough. As a result, the initial loose concept is refined as the product evolves. (Lindemann, 2009, p. 46)

7.1.2 Munich Proceedings Model MVM

The *Münchener Vorgehensmodell* (MVM), translating to Munich Proceedings Model, was developed to combine the best of existing models and is applied as a helpful tool when planning a development process, a problem solving approach, or as an analysis method of proceedings. It consists of three main steps that ideally lead to the solution of the regarded problem (Lindemann, 2009, p. 46):

1. Clarify on target or problem.
2. Generate possible solutions.
3. Make a reasoned decision.

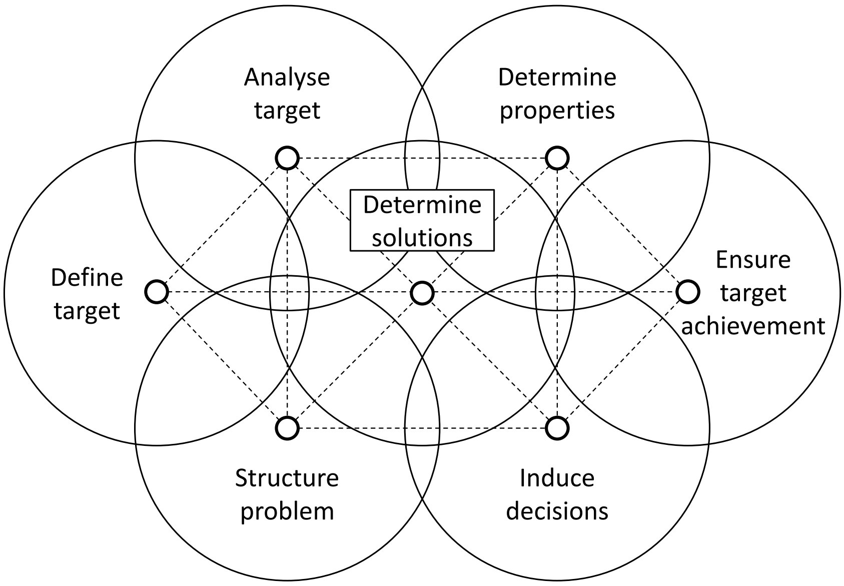

Figure 7.2: The Munich Proceedings Model MVM, according to (Lindemann, 2009, p. 47)

Literature and industrial studies showed that, both the preventive actions taken as well as the development of a thorough understanding of a problem, are important steps to find a successful solution (Lindemann, 2009, p. 46). The MVM model is shown in Figure 7.2 and proposes the following seven elements (Lindemann, 2009, p. 47-50):

- **Define target (*Ziel planen*):** The aim of this element is the analysis of the current situation and the creation of concrete measures and future steps. Furthermore, teams decide on important factors which help in the target analysis and outline them. There are several external influences on the product development which are considered in this stage. Examples for this are market, customer, competition, or political influences. On an operative level, the target can also be a successful meeting. A situation analysis estimates the overall situation, while considering possible future issues.

- **Analyse target (*Ziel analysieren*):** To enable this element, design teams need very detailed requirements from the beginning. All connections between these different requirements need to be documented in a meaningful way. Once this has been completed, the design teams develop multiple design concepts which are ultimately assessed by a committee. These activities are often done on an operative level.

- **Structure problem (*Problem strukturieren*):** The purpose of this stage is to decide on the focus areas for future problem solving. To avoid a confusing representation of early concepts, ideas are presented on an abstract model and divided into subsystems. This results in the definition of a design space. The underlying problem can then be either structured into subsystems, viewed as a part of the overall system, or as a single desired technical function that the product has to fulfil.

- **Determine solutions (*Lösungsideen ermitteln*):** The objective is to generate a number of different solutions, presented in a clear and structured way. Engineers need to consider and create alternatives as the first found solution does not necessarily lead to the optimal design. Therefore, they need to combine different options and subsystems to achieve the best possible overall solution. In early phases alternatives are developed following the working principles and aesthetic design choices are not made until later stages.

- **Determine properties (*Eigenschaften ermitteln*):** This element describes the analysis of properties and features of created and chosen solutions along with their alternatives. Furthermore, engineers compare the system to the initial target. As a product gets more detailed and concrete, there are more possibilities and methods available to determine properties and features. In early stages teams determine the general feasibility of ideas, while in later stages they focus on specific properties such as cost, weight, noise, or performance, relevant to the final product.

- **Induce decisions (*Entscheidungen herbeiführen*):** This element represents the assessment and evaluation of generated solutions, the determination of possible alternatives and choosing a concept. The selected concept needs to fit the initial requirements. Throughout the development process many small decisions will be made. They need to be treated with the same affection to detail as the seemingly more important ones. This is because even small decisions can have unpredictable effects on the final product.

- **Ensure target achievement(*Zielerreichung absichern*):** The final element covers risk management. The minimisation of risk and taking precautions to guarantee the delivery of the final product (as it was agreed upon in the target definition) are crucial. A first step towards this is to uncover potential risks, evaluate them and, if necessary, initialise actions to minimise them.

The application of these elements in the real world is the following: Depending on the situation, the team decides which elements can help them with their issue, combine them and implement them into their development process. There is, however, a recommended standard procedure that would suit most situations (Lindemann, 2009, p. 50):

1. Define target
2. Analyse target
3. Structure problem
4. Determine solutions
5. Determine properties
6. Induce decisions
7. Ensure target achievement

The MVM allows for a very flexible adoption of a product development process, meaning the process does not need to be started with the first element "define target". This flexibility is especially useful, as the final product is not yet known at the beginning of process planning. It is recommended to reflect on completed elements to verify if the current approach supports the progress and, if required, perform the relevant changes. (Lindemann, 2009, p. 52, 54)

Individual elements can be re-visited if necessary, or even replaced by another iteration of the MVM model, resulting in a recursive approach to solve difficult partial problems. Ideally, certain elements can be processed in parallel to speed up the development process. One example for this is to "determine solutions" and to "determine properties". In this case a structured and very well coordinated communication between the involved parties is necessary to enable a successful exchange of information that is beneficial to both sides. (Lindemann, 2009, p. 53)

7.1.3 Principles of action

In addition to the above explained model, an orientation towards certain principles increases the chances of successfully completing a product development project. These principles represent favourable behaviour and can guide activities. (Daenzer & Büchel, 2002 in Lindemann, 2009, p. 55, Pahl et al., 2005 in Lindemann, 2009, p. 55)

Lindemann (2009, p. 55-57) collected the following principles from multiple sources:

- **Create systems thinking:** To comprehend and understand complex systems, teams need to view them on a model based holistic level. This reduces the risk of a narrow perspective on problems. Furthermore, it allows them to go beyond the usual boundaries. Altogether it simplifies handling complex systems. (Daenzer & Büchel, 2002 in Lindemann, 2009, p. 55)

- **Divide problems:** Complex issues and problems appear quite often during the product development process. In order to solve problems successfully, it is often necessary to divide them into smaller partial problems which are more easy to handle. Thereby, each solving of a partial problem is a crucial step towards the overall solution. An example for this are sub-processes as part of the whole product development process. (Dörner, 2003 in Lindemann, 2009, p. 55)

- **Top down approach:** The area of attention should be wider and more generic at the beginning and gets more focused step by step. An example application of this can be the structuring of a problem or the generation of solutions. Sometimes the reversed approach, bottom up, can be useful as well. (Daenzer & Büchel, 2002 in Lindemann, 2009, p. 55)

- **Move from abstract to concrete:** Engineering teams are encouraged to use levels of abstraction. When the abstraction decreases ideas get more concrete. Nevertheless it is possible that concrete ideas can get more abstract again, if this is required. Ultimately, concrete ideas describe parts of the product. (Pahl et al., 2005 in Lindemann, 2009, p. 56)

- **Controllable proceedings:** Each proceeding should have a dedicated target. This target should ideally be measurable in some meaningful way and, if needed, should present the base for the next target. This method can be supported by following relevant questions such as: "What exactly is the problem?" or "What is the next target?". (Wulf, 2002 in Lindemann, 2009, p. 56)

- **Reflect on the essential:** When working under pressure it is important to keep focusing on the target. Both, accomplished and failed targets, need to be reflected in a critical way. The thereby gained knowledge and experiences need to be analysed as they pose the base for an improvement for future iterations. (Badke-Schaub & Frankenberge, 2004 in Lindemann, 2009, p. 56, Dörner, 2003 in Lindemann, 2009, p. 56)

- **Thinking in alternatives:** Design teams are encouraged to generate multiple alternatives to the first found solution. However, it is intended to focus on a decent number of realistic and feasible solutions that meet the requirements, rather than producing a great amount of not well thought out alternatives. This increases the chance of an innovative solution to a specific problem. Thinking in alternatives is not restricted to product design, but can also extend to the guiding process models. (Daenzer & Büchel, 2002 in Lindemann, 2009, p. 56-57)

- **Modality change:** When there is no progress while working on a solution for a problem, it can often be helpful to change the perspective or the considered item/part/component to create new results. This change can be in or between certain categories (e.g. abstract and concrete, system level or detailed, bottom up and top down). (Lindemann, 1999 in Lindemann, 2009, p. 57)

7.2 Comparison of the MVM to the principles of SBCE

This section discusses the presence of elements of SBCE within the MVM and compares them directly to the concepts of all of the principles of SBCE.

7.2.1 Map the design space

The description of the target product is done at an operative level, while attempting to classify the product along the way. A clear and structured presentation of ideas play an important role in early phases. Overall, the MVM is more focused on the requirements beforehand, rather than developing the solutions. (Lindemann, 2009, p. 48-49)

7.2.1.1 Define feasible regions

Concepts of this SBCE principle within the MVM

The definition of feasible regions is not done in a dedicated phase of the development process. The elements "analyse target" and "structure problem" however suggest some concepts that have the same purpose.

Before looking for solutions the requirements are considered and collected in form of a requirements list. This list has to be complete and serves as a base for finding solutions. Implicit requirements can be retrieved via questioning, while explicit knowledge can be gathered with the help of text analysis. Popular requirements are categorised and collected in lists to be able to access them in future projects. These collections are referred to as checklists which have to be updated continuously. (Lindemann, 2009, p. 96, 98)

The MVM produces feasible ideas with the help of variance analysis. The purpose of this analysis is to avoid committing to a technically superior solution, which turns out to either not meet the requirements or be too risky. This process starts on system level and continues down to the individual elements. The output is the definition of fixed and modifiable elements or subsystems. By defining these boundaries the development teams now have a design space within the feasible regions defined by the requirements and targeted risk level. Within this space the engineers can begin working on solutions. (Lindemann, 2009, p. 127-128)

Analysis and rating

Lindemann (2009, p. 127) suggests the use of variance analysis to produce feasible ideas which represent the essence of this first sub principle. Nevertheless, there is no mentioning of input from past experiences or expertise other than the design teams.

The idea of representing requirements on lists is similar to the engineering checklists used in SBCE. However, in SBCE the engineering checklists contain different information such as design standards or manufacturability. Engineering checklists are only an assisting tool to achieve the target of this first sub-principle, although it is used throughout the entire development process.

The early definitions from each functional group or team are missing.

Rating: ++

7.2.1.2 Explore trade-offs by designing multiple alternatives

Concepts of this SBCE principle within the MVM

Evidence of the idea of developing multiple concepts can be found in the element "determine solutions", while the idea of exploring trade-offs based on quantifiable data is discussed in "analyse targets" and partially in "induce decisions".

Targets are investigated in terms of inconsistency and redundancy. Furthermore, there will always be conflicts with requirements, and certain trade-offs will need to be made. This issue gets more important the more complex the product is, as the interdependencies of their subsystems increase. This reciprocity can be weighed with the help of a consistency matrix. The MVM suggests this weighing based on Kano models, therefore in dependence of the customer's priorities. (Lindemann, 2009, p. 102-103, 106-107)

In order to maximise the overall system score it is important to be willing to comprise on partial solutions. This is especially relevant when solutions are graded based on for example their compliance to the initial requirements list. (Lindemann, 2009, p. 189)

Developing multiple solutions allow for fast corrections. Conflicts can be resolved by compromises between two targets or a change of concept. (Lindemann, 2009, p. 139, 148)

Analysis and rating

Lindemann (2009, p. 104) mentions that these comparisons of trade-offs can be a starting point for very innovative products. In SBCE, when looking at the principle framework from Sobek et al. (1999), this is in fact one of the early steps. These compromises are made based on grading solutions according to their compliance with the initial requirements.

Detailed analyses are not made until late stages (Lindemann, 2009, p. 162), while SBCE suggest detailed studying of ideas in early project stages. This also means decision making based on quantifiable data is difficult in early stages.

For both, the MVM and SBCE, the purpose of these trade-offs is to find the overall best system combination of modules. Nevertheless, suppliers get strict requirements and are not encouraged to develop multiple alternatives. The extension of these principles to suppliers is very important, as their supplied parts are equally important for the overall system as the developed parts.

Rating: ++

7.2.1.3 Communicate sets of possibilities

Concepts of this SBCE principle within the MVM

There are only minor references to the concept of communicating sets of ideas, rather than individual ideas. The element "structure problem" covers some of these sub-principles essences.

Subsystems are organised according to their attributes and associated with their respective solutions. Recommended representation forms are boards or a computer assisted display. (Lindemann, 2009, p. 150-151)

Analysis and rating

Lindemann (2009, p. 48, 150-151) mentions the consideration of subsystems and interfaces and proposes a clear representation of the solutions, similar to what SBCE suggests.

Different functional teams are not directly encouraged to exchange their capabilities within the previously defined design space. The way how ideas or possible solutions are communicated is not discussed in detail. However, as the development process continues, the target is to find a solution and then communicate this one idea. In SBCE on the other hand, sets of ideas are communicated until very late stages.

Rating: ++

7.2.2 Integrate by intersection

Assessment and grading of solution is done by all involved teams. In order to keep discussion objective, multidisciplinary team meetings help keep decisions objective. (Lindemann, 2009, p. 182)

7.2.2.1 Look for intersections of feasible sets

Concepts of this SBCE principle within the MVM

The MVM's element "determine solutions" covers the intersection of feasible sets very good. Additionally, "analyse target" provides supporting details for this task.

Because of the complexity of most technical products, each partial problem gets multiple solution ideas, developed by corresponding specialists in the field. These ideas need to be organised and combined into a consistent overall solution. The overall concepts are graded by teams. Assessment and selection of the possible solutions can be supported by the requirements list. (Lindemann, 2009, p. 108, 138-139, 151)

The process of finding feasible combinations is supported by the application of morphological analysis. This helps to visualise realistic combinations and separate them from infeasible ones. (Lindemann, 2009, p. 152)

Engineering teams need to be willing to compromise in order to optimise the overall system. (Lindemann, 2009, p. 189)

Analysis and rating

All solutions are discussed by all affected teams collectively. This guarantees the feasibility for all involved functional teams. The SBCE process suggests the same. Furthermore, partial solutions are organised and combined, aiming for an overall ideal system. (Lindemann, 2009, p. 138-139, 151, 189)

The assessment and selection is supported by the requirements list from the early project stages (Lindemann, 2009, p. 108). In SBCE, the engineering checklists are used throughout the process and also have an important role within this sub-principle. They state certain properties that engineering and design teams use to combine developed alternatives. Lindemann (2009, 152) suggests the use of morphological analysis to assist in this matter.

Rating: ++++

7.2.2.2 Impose minimum constraint

Concepts of this SBCE principle within the MVM

The MVM mentions some concepts found in the elements "structure problem" and "analyse target" that translate roughly to the idea of imposing minimum constraint.

In the early project phase, when the problems are being structured, ideas are presented on an abstract level. One of the options to do this is to model systems as a black box, only considering in- and output. This can help to understand the core functionality of individual items. (Lindemann, 2009, p. 118)

There are often multiple boundaries like requirements or pre-defined interfaces that are fixed. Attributes or features that are not fixed often pose a risk if changed. Consequently, the solution space for these features gets certain boundaries. (Lindemann, 2009, p. 127)

Suppliers receive very detailed requirements that describe his expected deliveries and services. These requirements need to be treated as unchangeable. (Lindemann, 2009, p. 109)

Analysis and rating

In early project stages ideas are presented on an abstract level, as this helps to create an isolated view of each component (Lindemann, 2009, p. 118). Further, Lindemann (2009, p. 127) states that certain requirements should be classified as fixed as changing requirements are a possible risk factor. When compared to SBCE, these views leave the option of delaying some decisions. However, it is unclear to which kind of decisions this applies.

SBCE emphasises on the importance of extending this principle to the supplier. Lindemann (2009, p. 109) however insists that these requirements remain unchanged. Manufacturing involvement is not discussed explicitly.

Rating: ++

7.2.2.3 Seek conceptual robustness

Concepts of this SBCE principle within the MVM

Lindemann (2009) does not describe any manufacturing related methods. Therefore the idea of robust design, as described by Taguchi (1988), is not discussed.

However, development teams consider market and customer target definitions and their influence on the development and production process. (Lindemann, 2009, p. 83, 87, 92)

A standardisation of specific process stages is mentioned implicitly by the fact that all the elements of the MVM can be used in any order. (Lindemann, 2009, p. 50, 53-54)

Analysis and rating

The MVM does not necessarily aim at short development cycles achieved through a standardisation of processes or other parts of the development cycle. Nonetheless, the different elements of the model were designed to be repeatable and interchangeable. (Lindemann, 2009, p. 53-54)

Modularity of components or market robust design as described by Taguchi (1988) are not mentioned.

Rating: ++

7.2.3 Establish feasibility before commitment

Along with the pre-selection, the feasibility of the developed solutions is assessed. Feasibility is measured by general criteria such as compliance to the initial requirements or the tolerance towards connected subsystems. Moreover, before design teams choose one solution or perform a more detailed planning of a single solution, the expected outcome is compared to the primary targets. (Lindemann, 2009, p. 180, 195)

7.2.3.1 Narrow sets gradually while increasing detail

Concepts of this SBCE principle within the MVM

The reduction of remaining alternatives is discussed mostly within the elements "determine solutions" and "determine attributes". Ideas from "analyse target" and "induce decisions" support the process of eliminating ideas. An example for this is the requirements list which can be used to make an initial screening of alternatives.

The large number of concepts need to be trimmed down to a more manageable amount of meaningful combinations. It is reasonable to do this gradually, starting with the most promising idea and combination of subsystem solutions. (Lindemann, 2009, p. 139)

The previously performed morphological analysis yielded results which can now be used to make decisions when choosing concepts. In addition, the final selection of solutions can be supported further by referring to the initial requirements list. (Lindemann, 2009, p. 108, 152)

Detailed analysis of product attributes increases their and the system's understanding. In general, these analyses should be made at early stages to avoid costly rework later on in the development process. The explorations get more detailed as the development progresses, since concepts are still very abstract at early stages. On the other hand, when facing immediate important decisions, it is necessary to study certain attributes/concepts/data in more detail. (Lindemann, 2009, p. 158, 162, 183)

There is a pre-selection of alternatives based on the requirements list. This is to reduce the number of alternatives that need to be studied on detail. (Lindemann, 2009, p. 180)

Analysis and rating

Lindemann (2009) focuses on grading alternatives when it comes to narrowing them down. The MVM does not encourage the different design and engineering teams to work together in this process.

Analyses do get more detailed as the design of the product evolves from abstract to more concrete ideas. This is similar to the concepts of SBCE as there is an increased need of detailed understanding for each idea, as well as a need to be able to face immediate decisions with new information. (Lindemann, 2009, p. 162)

Rating: ++++

7.2.3.2 Stay within sets once committed

Concepts of this SBCE principle within the MVM

The idea of modularising products is mentioned implicitly throughout all the elements of the MVM.

Analysis and rating

Lindemann (2009) mentions a modular approach in form of developing subsystems or partial solutions and combining them into one overall system multiple times in the MVM. As the aim of the MVM is to find one single design, the author makes the assumption that teams commit to it once they decided on a suitable solution. SBCE aims to find multiple feasible designs and make the final decision very late in the development process.

The MVM suggests a recursive usage of specific elements if there is need for it (Lindemann, 2009, p. 53-54). This can be viewed as rework for all participating teams, although it is intentional and within the target time frame. SBCE wants to eliminate rework by staying within the previously defined sets.

Rating: ++

7.2.3.3 Control by managing uncertainty at process gates

Concepts of this SBCE principle within the MVM

The element "induce decisions" explains that uncertainty is managed to a certain degree by verifying feasibility in early stages by analysing all developed alternatives. (Lindemann, 2009, p. 180, 195)

Analysis and rating

There are no scheduled gates presented in the model that try to control the state of the product development process.

Rating: +

7.2.4 Other observations

If a problem occurs during the development process, it is imperative that the incident is documented. This will enable a continuous improvement of the guiding process. (Lindemann, 2009, p. 223)

A parallel approach of handling multiple different elements at the same time is possible and encouraged (Lindemann, 2009, p. 53). However, this does not necessarily mean that different teams perform tasks within one element in parallel.

7.3 Summarised results of the MVM

The MVM of Lindemann (2009) showed both very high and very low representation of SBCE principles. While the principle "control by managing uncertainty at process gates" only received the minimum rating, the principles "look for intersection of feasible sets" and "narrow sets gradually while increasing detail" scored the best possible rating. The whole assessment is summarised in Table 7.1.

No.	**Principle**	**Rating**
Map the design space		
1	Define feasible regions	++
2	Explore trade-offs by designing multiple alternatives	++
3	Communicate sets of possibilities	++
Integrate by intersection		
4	Look for intersection of feasible sets	++++
5	Impose minimum constraint	++
6	Seek conceptual robustness	++
Establish feasibility before commitment		
7	Narrow sets gradually while increasing detail	++++
8	Stay within sets once committed	++
9	Control by managing uncertainty at process gates	+

Table 7.1: Overall results of the comparison between the MVM and SBCE's principles

8 Success strategies for idea-to-launch innovation processes

Cooper (2010) introduced the Stage-Gate process as a very marketing accentuated product development proces. His approach is more at a strategic and managerial level in comparison to for example the models of Pahl et al. (2007) or Lindemann (2009). This chapter describes the Stage-Gate process and its supporting elements and compares them to the principles of SBCE.

8.1 Characteristics of the idea-to-launch innovation process

The Idea-to-Launch Innovation Process is characterised by a number of key activities (described in section 8.1.1) and the critical success factors of a successful product development project (explained in section 8.1.2). Together these two supporting elements create the framework for the Stage-Gate process shown in section 8.1.3.

8.1.1 Key activities in product development

Time to market is very important. Nevertheless, the overall quality and attention to details must not be cut short. Activities that were rushed through often need to be completed at a later stage, which results an increased time and resource effort. It is worthless to bring a product faster to the market than the competitor if it does not meet the expectations of the target crowd. As a direct consequence, the product needs to be aimed and tailored to the customer. The own product always has to provide a certain value to the customer that other products do not. All this can only be achieved if development teams focus on one or a few projects, rather than risking resources with a multitude of product development projects. (Cooper, 2010, p. 41)

Cooper (2010, p. 31-37) lists 13 key activities which must be completed during the development of new products. By following these, companies reduce the risk of failure:

1. Initial screening
2. Preliminary market assessment
3. Assessment of technological implementation feasibility
4. Detailed market analysis
5. Financial analysis
6. Product development
7. Internal testing
8. Testing by selected customers
9. Market tests
10. Pilot production
11. Sales analysis before commencing sales
12. Beginning of production phase
13. Roll-out

8.1.2 Critical success factors

To have an effective product innovation it is necessary to do the right projects, the right way. There are a number of success factors which are common across successful products. The combination of technical capabilities, market orientation, and customer focus are key components for the success of a product. (Cooper, 2010, p. 43-45)

A formal process guiding all activities and tasks over the course of product innovation and development must be in place to enable a working interaction of personnel and multi disciplinary teams. The process must be actively administrated by top management and incorporated into the company culture. All steps within the process must be completed with the same high level of quality, which again encourages a formal process model. (Cooper, 2010, p. 45-46, 52, 63)

Cooper (2010, p. 85-124) collected 15 critical success factors over the years from industrial studies and analysing multiple companies. Each of them provides an advantage to the company if implemented correctly across the whole company, down to the operational level.

1. Success factor number one is a unique, superior and sophisticated product which brings the customer unique advantages and superior value.
2. Distinct market orientation is essential for success: an innovation process which is dictated by the market and aimed at the customer.
3. Aim for a product for the whole world: international alignment of product design, development and target marketing secures decisive advantages during innovation.
4. The actual product development cannot start until all tasks of preliminary design

have been completed.

5. Clear and early definitions of product and project are one of the key differences between winners and losers of newly developed products.
6. A well planned and executed market entry has a central meaning for the success of an innovation. The core of this is a solid marketing plan.
7. Structure, design and climate of the organisation are key factors for success.
8. Support of top management does not guarantee success, but it can help. Nevertheless, too many cooks spoil the broth.
9. The interplay of all core competences are crucial for the success, since developing in unexplored waters sometimes inevitably leads to failures.
10. Products with attractive target markets perform better: the attractiveness of the market is a key criteria for the selection of projects.
11. Successful corporations include relentless control mechanisms into their innovation process which actually do cancel projects. This results in a better concentration on the promising ones.
12. The success of innovations can be measured: integrity, relation and execution quality of core activities are aspects which need to be emphasised from the beginning to the end.
13. Available have to flow towards the right places - there are no handouts while innovating products.
14. Speed is everything - as long as it does not affect the execution quality.
15. Companies which follow a disciplined process divided into multiple phases - a Stage-Gate process - perform significantly better.

8.1.3 Stage-Gate process

A successful and effective product development process helps to manage the new products and speed up the overall process in a structured way. Furthermore it is important to consider the critical success factors and proven methods. The guiding product development process has to ensure a high level of quality. Moreover the process needs to contain activities and criteria that separate the final product from others. (Cooper, 2010, p. 125, 137-138)

Cooper (2010, p. 128-137) lists seven targets that a process has to aim for:

1. Quality of execution
2. Stricter focus, better prioritisation
3. Parallel process handing with a fast pace
4. A truly inter-divisional team
5. Distinct market orientation and integration of customer assessment

6. Well established preliminary design
7. Products with a competitive advantage

These seven targets, the critical success factors from section 8.1.2, as well as the key activities during product development presented in section 8.1.1 create the baseline for the Stage-Gate process. The Stage-Gate process shown in Figure 8.1 is a conceptual and operational model to bring an idea effectively and efficiently to the market. It is divided into multiple sections, separated by specific gates. These gates function as checkpoints and decide whether to continue or stop the project. All available information is then used to decide if the project should be continued, and if so, it is given a priority grade. (Cooper, 2010, p. 145, 147-148)

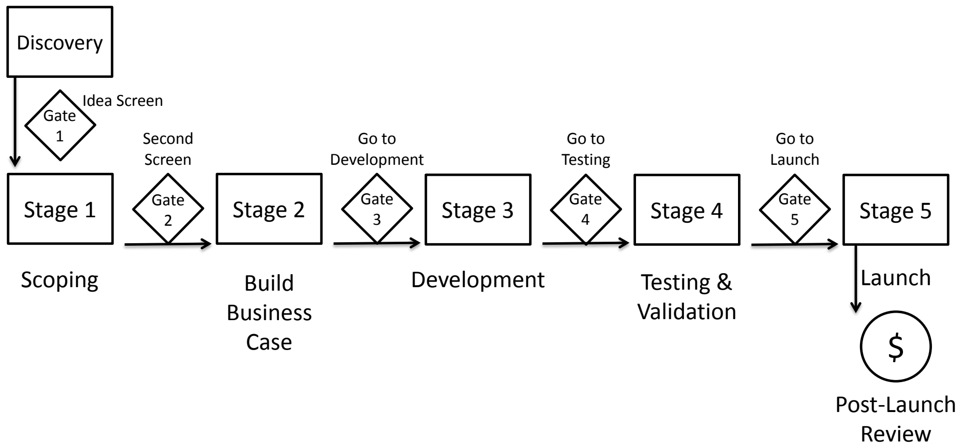

Figure 8.1: The Stage-Gate process model (Cooper, 2009, p. 2)

All stages are meant to complete the tasks and activities required to pass the upcoming gate. Each stage includes activities that are completed from all functions, meaning there are no stages focusing on one particular department. Strategic planning takes place across all stages. (Cooper, 2010, p. 146-147)

In front of every stage there is a gate. All gates expect specific results defined at the end of the previous gate. Additionally each gate has certain criteria which allow the assessment of involved teams. This includes a checklist listing all requirements to identify failing projects. Gates have a pre-defined output. It include the made decision (continue, abort, wait, redo), an approved plan of action or the next stage, and the list of expected results for the next gate. (Cooper, 2010, p. 148-149)

The recommended stages and gates are the following (Cooper, 2010, p. 149-161):

- **Discovery:** New ideas are always the trigger for the development process. Companies often dedicate an own phase or stage to the generation of ideas. This can include technical basic research, cooperation with leading customers to determine unmet needs, or strategic planning to detect gaps within a market.

- **Gate 1 - Idea screen:** The first gate is an initial narrowing of new ideas. They are assessed and limited resources are appointed to continue working on them. The gate only prescribes basic criteria such as strategic alignment, feasibility, market readiness, or advantages for the product, but not financial criteria. Teams often use checklists to assess the ideas on the defined criteria and order them based on the first screening.

- **Stage 1 - Scoping:** The purpose of the first stage is to determine and elaborate the technical and market related advantages of the product. This research is mostly desk based and consists of activities such as an internet and library search, or a quick test of a very basic concept with a selected customer. It can be handled within a small team and does not include deep technical research.
  The target is to determine the supposed market acceptance and give the concept a first shape. Another aspect in this stage is to estimate costs or juridical restrictions. All this information are collected to enable a second assessment at the upcoming gate.

- **Gate 2 - Second screen:** After "scoping", the idea passes through a second gate. It is essentially a repetition of the first gate, although the level of detail is much higher. The criteria also stay the same and additional ones can be added if they were assessed during stage one. Examples for new additions are distribution possibilities, customer reactions, critical juridical, technical, or regulatory variables.

- **Stage 2 - Build business case:** The second phase is critical to the success of the product and involves cross-functional teams from all departments. It is the preparation for the actual product development. Detailed analyses help define the product and asses the attractiveness of the product before too many resources were committed.
  Teams work mostly on the definition of the target market, the presentation of the product concept, and the advantages of the product and the value proposition. The product receives the required and requested product attributes, properties, requirements and specifications. A more detailed market and competitor analysis to understand the customers better is suggested as well. Further financial analysis uncover possible risks.
  Output of this stage is a business case for the project including a project plan and a justification.

- **Gate 3 - Go to development:** This gate is the last point where the project can be aborted before massive costs amass. All activities from stage two are assessed and their quality is reviewed. This is followed by the checking of the previously defined criteria for this gate. The financial analysis is a central element of the screening since a large investment has to be approved.
  In case of a positive feedback, development, execution and marketing plans need to be developed. Lastly, the complete project team gets appointed.

- **Stage 3 - Development:** In the third stage the development and execution plans are put into practice. Simulations and alpha tests confirm that the product meets the requirements. The development can be controlled by multiple milestones. Difficulties can arise in the technical field as management works in parallel together with the technical development. Ongoing market analysis and feedback from customers need to be included.
  Teams create production plans and further detail the financial analysis. The expected result from this stage is a tested and functional prototype.

- **Gate 4 - Go to testing:** The fourth gate controls the quality of the activities from stage three. It validates that all necessary criteria are fulfilled. The financial analysis gets updated with the newly gained information, while the marketing and production plans get elaborated in preparation for the following tasks.

- **Stage 4 - Testing & validation:** This stage is all about testing and validating all parts of the project. This includes the product, production process, customer acceptance and the financial aspect. Important activities within this stage include a thorough testing of the product within the company, user and field tests to test the product in realistic conditions and study how customers react to it.
  A limited production helps identify difficulties and determine product costs and capacity more precisely. These production samples can then be used on a sample target market to gain more customer inside on a broader basis. Finally, the business case and financial analysis get updated and are used to determine the likeliness of success.
  It is possible that the results from testing are not satisfactory. If this is the case, stage three needs to be repeated either partially or completely.

- **Gate 5 - Go to launch:** The final gate opens the door to marketing, marketing entry, and full scale production. This is the last possibility to abort a project. Again, the gate verifies the quality of the test and validation tasks from the previous stage four. The most important criteria that the project has to pass are based on the financial analysis and acceptability of marketing and production plans.

- **Stage 5 - Launch:** In the last stage the production and marketing plans are executed. If they are well thought out and enough resources back them up, there are no expected difficulties.

- **Post-launch review:** After the product has been on the market for some time (6-19 months), it is a good point to draw a conclusion of the success of the product. Income, costs, expenses, earnings and timings can be compared to the initial expectations to assess the overall performance of the innovation project. Participating teams also receive a feedback and possible improvements are discussed.

Cooper (2010, p. 166-167) describes his process as flexible, meaning stages and/or gates can be either left out or even combined. It is part of risk management to decide which steps can be left out or less emphasised. These gates can have more than the two obvious go or no-go outcomes. The decision is made without relevant information and the continuation of the project depends on the positive outcome of a certain event in the future.

All stages overlap in some way. This means certain activities are started before the gate of the previous stage gets passed. Nevertheless, this does not mitigate the importance of these gates, as they still need to clear the funds for the most time and resources consuming tasks of the following stage. (Cooper, 2010, p. 168-169)

The Stage-Gate process can be altered to be more focused on technology development or science projects, rather than pure product development. In such a case the alignment is more towards strategic interest of the company, rather than financial interest. (Cooper, 2010, p. 193)

8.2 Concepts of SBCE principles within the Stage-Gate process

Despite the many marketing and financial focused task within the Stage-Gate process, various concepts of the principles of SBCE can be found. This section presents the findings for each of the principles in the Stage-Gate process model and analyses them directly against the core elements of these principles.

8.2.1 Map the design space

Activities and tasks within the process can be handled in parallel. This creates an function-overlapping environment where multidisciplinary teams, such as marketing and engineering, work together. (Cooper, 2010, p. 132, 146, 298)

8.2.1.1 Define feasible regions

Concepts of this SBCE principle within the Stage-Gate process

Most of the outline and definition of the product is covered in stage two "build business case" with additional pointers in the critical success factors and general considerations. Furthermore, the capture of objective information is mostly done in stage four "testing & validation".

Cooper (2010, p. 177-206) discusses the discovery pre-stage in great detail. In this stage the focus is on idea discovery. Ideas can often evolve from certain scenarios developed with the help of customer focus and interaction.

The initial customer expectations are best collected with the help of questionnaires. Interviewees need to be representative for the customer interests. Adding own technicians to the interviews in addition to marketing personnel can help identify additional wanted product attributes. Translating the customer expectations into an actual product concept needs to involve activities such as creative problem solving, technique like QFD, deep literature and patent research, consulting expert knowledge, and the actual physical and technical work. (Cooper, 2010, p. 223-224, 229)

Customer requirements are categorised into three levels of detail, namely strategic, tactical and detailed. These customer requirements are then converted into technical specifications which lead to a technically feasible product concept. The definition and consent on specifications and product attributes has to be done in agreement with all involved functional departments. (Cooper, 2010, p. 97-98, 231, 233)

Product concepts should be presented and described in a way the customer understands. This creates the opportunity for improvement and a more customer-tailored product. Additionally, this enables teams to point out the advantages for the customer. (Cooper, 2010, p. 97)

Engineers need to consider and plan for the time and resources it takes to construct a functional prototype or set up a simulation. (Cooper, 2010, p. 229-230)

There should be multiple test phases over the course of development. This includes an internal test phase, followed by tests performed from selected customers and finally testing inside a specific market. Testing the product concept in a reasonable way allows the customer to gain final feedback, confirm that the product features meet the expectations, to examine market acceptance and make alterations before the product development stage. (Cooper, 2010, p. 34-35, 234-235, 307-316)

Analysis and rating

All tasks that are capable of it should be performed in parallel and all teams are multi-disciplinary (Cooper, 2010, p. 132-133, 146, 164). Therefore it can be assumed that the definition of feasible regions is not done independently by all different functional teams, but in collaboration with other functional teams. Ultimately this means the teams do not define multiple feasible regions, one for each function, but one overall feasible region. A disadvantage of this can be that the optimal intersection of all possible feasible regions is not found and/or used.

Testing plays a big role in the Stage-Gate process. Most of the tests focus on the market acceptance and financial aspects of producing and selling the final product. A functional prototype is an important step and the main goal of the "development" stage (Cooper, 2010, p. 291). There are no further technical details on the different test phases, but their importance is implicit.

Cooper (2010, p. 223-224, 229, 231, 234-235, 307-316) involves the customer heavily into the definition of requirements, attributes, and product features, as well as in testing. Nevertheless, the final definition of the specifications need a consensus of all involved teams (Cooper, 2010, p. 97-98).

There are, however no clear references to how the new technical information is communicated within a multi-disciplinary team or amongst different teams. In SBCE, engineering checklists are used as a form of communicating and updating each other on the latest developments, as well as to ensure the work stays within the feasible regions of all teams.

Rating: +++

8.2.1.2 Explore trade-offs by designing multiple alternatives

Concepts of this SBCE principle within the Stage-Gate process

Evidence of this principle are found mostly in the project and product selection recommendations. Moreover stage one "scoping" and three "development" feature additional parts.

Teams need to define clear and measurable criteria to make best use of the gates. The development and selection of alternatives is discussed mostly on a project level. A meaningful selection of projects with high chances of success can be achieved with one of the following three ways: value-benefit analysis and techniques, economic models, and portfolio compositions and management methods. The recommended selection technique is the value-benefit analysis as it is easy to work with, provides a strategically oriented product portfolio, represents priorities of the company and leads to effective and efficient decisions. (Cooper, 2010, p. 248-250, 255-256)

Value-benefit analysis are generic decision methods and can also be used within the product development to select between alternative solutions. The teams use customised criteria to make selections and compare a multitude of options. Results are presented to the whole team on a flip-chart, followed by discussion and a second round of individual assessment until a consensus has been found. Another method is the selection based on a scored assessment. Teams assign certain criteria and weights to specific attributes or features and create a very objective result. This allows an easy ranking or prioritising. (Cooper, 2010, p. 256-257, 259-260)

A partnership with suppliers can complement the technical capabilities and means of a project. Nevertheless, this bears some risks, as it is not guaranteed that this increases the performance of the product. (Campbell & Cooper, 1999 in Cooper, 2010, p. 213)

Target of the third stage "development" is the production of a prototype or design that meets all customer needs. A continued involvement of the customer into the development process helps to keep the product on track and can speed up the process. It is even recommended to incorporate customer representatives into meetings, discussions, and early in-house testing. (Cooper, 2010, p. 292-293, 295-296)

Analysis and rating

The development of multiple solutions for each product and its subsystems is mentioned implicitly but not elaborated in more detail. (Cooper, 2010, p. 256)

Most decision techniques are related to project selection and not selection between different parts or alternate solutions for the actual product. For project selection, the criteria are very often financial and often supported with economic and/or financial models. (Cooper, 2010, p. 250, 260-263)

Value-benefit analysis is used to perform trade-off comparisons with customised and tailored criteria. This allows teams to compare a number of alternatives and make a decision based on quantifiable and objective data. Results and findings of the exploration of all options are presented to the entire team and discussed as a whole. (Cooper, 2010, p. 256-257) These steps follow the principles of SBCE very closely.

Cooper (2010) talks about supplier involvement, but not to the degree of extending this SBCE principle to them. The focus is more on selection based on technical capabilities for the current project. (Campbell & Cooper, 1999 in Cooper, 2010, p. 213)

The overall target of developing an optimum system is not highlighted, as Cooper lays the focus on maximising the profit of the company by focusing and choosing promising projects. (Cooper, 2010, p. XV, 3, 95, 263)

Rating: +++

8.2.1.3 Communicate sets of possibilities

Concepts of this SBCE principle within the Stage-Gate process

Elements of this principle are found in the critical success factors as well as in the second and third phase ("build business case" and "development").

The technological cooperation is relevant to product innovation. A project must be able to make use of all the available engineering, development and manufacturing capabilities. During meetings, engineers represent the interests, problems, and comments of their department. (Cooper, 2010, p. 108, 132)

The core members of each multi-disciplinary team need to stay the same throughout the entire product development. (Cooper, 2010, p. 133)

Customers receive a presentation of the product concept in a reasonable way. This can be for example a model, a collection of detailed drawings, listings of technical data, a dummy product, or a virtual prototype. (Cooper, 2010, p. 235-236)

Products as well as projects should be split up into independent parts wherever possible.

This reduces their complexity and ultimately reduces the time requirements. (Cooper, 2010, p. 299)

Analysis and rating

Meetings often focus on an effective cooperation of all available capabilities of participating teams. This is achieved by having a representative of each department within each team, who represents their interests, concerns, capabilities, and feedback for inter-functional collaboration. (Cooper, 2010, p. 108, 132-133, 164)

During conferences with customers, teams present concepts in a clear form and way to help them understand the resulting product. Examples for this are models, listings of technical data, or a prototype. (Cooper, 2010, p. 235-236) There are no recommendations for the presentation and communication of technical alternatives.

Since Cooper (2010) focuses heavily on the marking aspect of a product development project, he does not cover the topics of considering subsystems and their interfaces in great detail. He does, however, suggest to split up projects and products whenever possible to decrease the complexity, which implies the idea of subsystems at least to a certain degree. (Cooper, 2010, p. 299)

Rating: +++

8.2.2 Integrate by intersection

Cooper (2010) does not elaborate the identification of acceptable alternatives which are feasible for all functional departments. Rather he discusses the importance of market analysis, customer integration and focus on extensive planning.

8.2.2.1 Look for intersections of feasible sets

Concepts of this SBCE principle within the Stage-Gate process

Minor aspects of combining feasible solutions with each other to create an optimal system can be found within the stage "development" and the critical success factors.

The chosen solutions and their specifications and functional descriptions have to satisfy the needs and concerns of all different participating functional teams. (Cooper, 2010, p. 97-98)

Meetings during the development stage should involve representatives of the customer. They have a different view on the product evolution than the participating engineers. This enables them to uncover problems and possible details which are of importance to the customer. Their feedback is then used to alter the parts of the product or system. (Cooper, 2010, p. 296)

Analysis and rating

The chosen solution must satisfy all participating teams (Cooper, 2010, p. 97-98). However, this does not necessarily mean each team makes full use of their capabilities within their specific feasible regions.

Cooper (2010, p. 256-257, 296) even recommends to include the customer in meetings during the "development" stage and incorporate their feedback, along with the new information from all teams, into updating the product. This is also to safeguard the compliance to the customers initial requirements for the product. In SBCE the engineering checklists serve as a guarantee that the chosen solution meets the given requirements and given range of specifications.

Rating: +++

8.2.2.2 Impose minimum constraint

Concepts of this SBCE principle within the Stage-Gate process

Features of this principle are described partially in stages one, two, and three. Further references can be found in the critical success factors and process targets.

All specifications and attributes of both the product and the process have to be finalised early on, prior to the beginning of the actual product development. This needs to include which parts or components are defined as unchangeable and which ones are viewed as variable. (Cooper, 2010, p. 97, 99, 135, 217)

Incorrect product definitions are one of the two major problems in the "development" stage, the other one exhibits unexpected change. This is mostly caused by misunderstood, not captured, or ignored customer expectations. (Cooper, 2010, p. 291-292)

Cooper (2010, p. 132) suggests a truly inter-divisional team. Therefore, team members do not have specific time slots dedicated to cooperate with other functional groups, but are a full time member of an inter-disciplinary team. Manufacturing and/or production are/is already involved as early as in stage one to determine the manufacturability of the potential product. (Cooper, 2010, p. 212)

The project plan needs to examine the available production facilities, machinery and personnel, as well as their additional costs. It might require the outsourcing of the production to a partner company. (Cooper, 2010, p. 230)

Analysis and rating

All product specifications and attributes need to be finalised before the "development" stage. Some parts are classified as variable, meaning their specifications are possible and allowed to change. (Cooper, 2010, p. 97, 99, 135, 217) Nevertheless, there are no further explanation on the range of possible adjustments or the intentions behind this. These are direct contradictions to this principle. SBCE intentionally reduces limitations and delays decisions to create flexibility and allow an exploration of all alternatives.

Manufacturing engineers get included from the first stage to input on, and determine the manufacturability of the potential product (Cooper, 2010, p. 212). This ensures that the concept of the product can in fact be manufactured and subsequently sold to the intended target market.

Other than the possibility of outsourcing the production to a partner company due to a lack of manufacturing capabilities, Cooper (2010) does not discuss the involvement of suppliers in the context of this principle.

Rating: +

8.2.2.3 Seek conceptual robustness

Concepts of this SBCE principle within the Stage-Gate process

In the Stage-Gate process there are multiple relations to this principle's aim of keeping the development cycles short. They are covered in the third stage "development", the critical success factors, as well as in form of general advice.

The speed or time requirements of developing a product and bringing it to the market is a critical success factor. Aiming at short development cycles create a competitive advantage, higher profits and reduces risk of undesired events. Nevertheless, speed should not outweigh diligence and accuracy to customer demands and requirements.

Ideally the development process should be a parallel process, handled with a fast pace. (Cooper, 2010, p. 3-4, 41, 131)

The actual development of the product has to be completed as soon as possible. This leads to minimising the possible external influences, as well as realding to an advantage over the competition with an early market entry. (Cooper, 2010, p. 293)

Another important activity while developing a new product is a "detailed market analysis". Additionally, as one of the critical success factors state a distinct market orientation is essential for success. This highlights the emphasis of Cooper (2010) on the importance of marketing considerations in addition to the usual consideration of technical aspects during product development. (Cooper, 2010, p. 33-34, 90)

Analysis and rating

Cooper (2010) mentions the importance of a short development stage multiple times. This gives the product a high robustness against market changes. (Cooper, 2010, p. 3-4, 41, 131, 293)

On the other hand, robust design as characterised by Taguchi (1988) is not discussed. Neither is the idea of standardising processes and product modules across multiple projects, and therefore across different products. However, one might argue that the Stage-Gate process itself with its pre-defined gate objectives can be regarded as the overlying standardised process.

Rating: ++

8.2.3 Establish feasibility before commitment

The basic feasibility of an idea such as chances on the market, or compliance with core competences, is often already tackled within creative meetings during idea generation. (Cooper, 2010, p. 195)

Cooper (2010, p. 33) states that one of the key activities in product development is the "assessment of technological implementation feasibility". This includes a technical analysis to uncover technical risks and problems. The overall decision whether a project is continued past the first preliminary design phase is based on an assessment of the project. (Cooper, 2010, p. 136)

Many tasks in the first two stages try to assess the feasibility of an idea. This includes market, technical, financial, economical and production related factors. (Cooper, 2010, p. 208, Figure 7.1)

8.2.3.1 Narrow sets gradually while increasing detail

Concepts of this SBCE principle within the Stage-Gate process

Very little information about the gradual elimination and detail increase of alternatives could be found in the second stage, "build business case", as well as the first gate.

A first screening and selection of ideas is done in the first gate. In the foregoing stage product definitions are still very vague. (Cooper, 2010, p. 207-208, 212)

At the end of stage two, "build business case", the seemingly most promising solutions and the along going product should already be somewhat clear for the engineers. (Cooper, 2010, p. 230)

Analysis and rating

While the SBCE process focuses on the narrowing of interesting solutions, Cooper (2010) focuses on the narrowing of product projects based on marketing related analysis. His narrowing funnel is therefore on a higher level. He does, however, state that a first screening of ideas is done within the first gate, where product definitions are still very unclear. At the end of the stage two ("build business case"), engineers need to have a clear picture of the product concept and specifications before passing the second gate and proceeding to the "development" stage. (Cooper, 2010, p. 157, 207-208, 212, 230)

Cooper (2010) implicitly mentions the elimination of ideas at the first two stages and gates. Even though all activities are done by all teams in parallel whenever possible (Cooper, 2010, p. 146, 164), this does not necessarily mean that the actual elimination of solutions is done independently by all functional departments, as it is recommended in SBCE.

The Stage-Gate process does not discuss the idea of extending this principle to a company's supplier.

Rating: ++

8.2.3.2 Stay within sets once committed

Concepts of this SBCE principle within the Stage-Gate process

Minor elements of this principle are covered in stage four "go to testing".

One way of testing the market acceptance of the product is showing a prototype to the customer. This also creates the possibility of feedback in form of wanted improvements or changes to the current design. Should these be severe, the product design may need to be restarted from the concept stage. (Cooper, 2010, p. 307)

Analysis and rating

Cooper (2010, p. 307) aims to reduce the number of rework by including the customer into product design. Engineers present a prototype to the customer and thereby gain feedback to minimise the risk of later changes to the product. In general, there are multiple references to the importance of the customer involvement in the entire development project (Cooper, 2010, p. 223-234, 229, 231, 233-235, 307-316).

The Stage-Gate process does not directly suggest the use of a modular system and there are no references to keep a safe solution as a backup.

Rating: +

8.2.3.3 Control by managing uncertainty at process gates

Concepts of this SBCE principle within the Stage-Gate process

Cooper (2010) presents gates as control mechanisms within the Stage-Gate process. Further pointers are listed in the "development" stage.

The purpose of the gates after every process step are to check the quality of execution, the continued outlook for an economical and financial success of the product/project, and the plan of action. Project assessments at these gates are very uncertain in terms of the reliability of financial information (Cooper, 1983 in Cooper, 2010, p. 267). Most data like production costs or expected returns are only available after the development stage and test. (Cooper, 2010, p. 265-267)

Deadlines have to be treated very seriously. Delays are unacceptable and must be met with an increase in effort and resource commitment. (Cooper, 2010, p. 299)

Cooper (2010, p. 300) suggest measurable and defined milestones within the third stage. These milestones allow to control the project and to determine if it is still on track and within budget.

Analysis and rating

The main gates within the Stage-Gate process at the end of each stage can not be compared to the process gates as they were described by Sobek et al. (1999). This is because the suggested process gates are within the actual development. Cooper (2010, p. 300), however, does recommend milestones, which are essentially process gates, to control the project and check if it is still within the intended time schedule. In SBCE, the purpose of the process gates is to control the remaining number of sets and their level of exploration.

Similar to SBCE, the Stage-Gate process considers delays or problems that cause delays as unacceptable and meets these issues with an increase of effort and resources. (Cooper, 2010, p. 299)

Rating: +++

8.2.4 Other observations

Cooper (2010, p. 13) explains that the categorisation of products in relation to their novelty is based on six criteria: new product lines, improvements of existing products, changes to achieve cost reduction, additions to existing products, change of the market position of a product, and completely new products.

There are different grades of innovation; namely high, moderate, and low level of innovation. (Cooper, 2010, p. 16)

Product features and attributes need to be of value for the customer. It is necessary to analyse what is of value to the customer and what he is willing to pay for. Therefore there is an interplay between these product features and the customer's perception. (Cooper, 2010, p. 218-219)

A specific role is often assigned to take on the role of a referee who keeps track of all teams acting and supporting their communication (Cooper, 2010, p. 170). This is somewhat similar to the chief engineer position.

Cooper (2010, p. 170-171) recommends a regular update and review of the innovation process but does not specify this in more detail. Rather it depends on the company and its adaptation of the Stage-Gate process. Khan et al. (2011b, p. 6) listed this as one of the main enablers of lean product development besides SBCE.

8.3 Summarised results of the Stage-Gate process

The Stage-Gate process model of Cooper (2010) features many elements of SBCE. Most of them are within the first category of principles, "map the design space". On the other hand, two principles are not represented very well. "Stay within sets once committed" and "impose minimum constraint", where the latter even contradicts with the Stage-Gate process. The findings are summarised in Table 8.1.

No.	Principle	Rating
Map the design space		
1	Define feasible regions	+++
2	Explore trade-offs by designing multiple alternatives	+++
3	Communicate sets of possibilities	+++
Integrate by intersection		
4	Look for intersection of feasible sets	+++
5	Impose minimum constraint	+
6	Seek conceptual robustness	++
Establish feasibility before commitment		
7	Narrow sets gradually while increasing detail	++
8	Stay within sets once committed	+
9	Control by managing uncertainty at process gates	+++

Table 8.1: Overall results of the comparison between the Stage-Gate process and SBCE's principles

9 Evaluation and results

The last capter prior to concluding this thesis evaluates the results from Chapters 4 to 8. First, a quick review summarises each of the five models and points out interesting observations. Thereafter the findings of all models are compared to each other and the SBCE principles are discussed across all models.

9.1 Review of discussed models

The W-Model

Eversheim (2003) presents a well rounded W-Model in terms of the presence of SBCE's principles. Some of the better represented principles are for example "communicate sets of possibilities", as the proposed introduction of an information model aims to achieve and help with many of this principle's elements. This also adds value to the process while "looking for intersections of feasible sets", as the information model can be used to access newly gained information, while still considering initial target definitions. The information model is therefore an instrumental part of the overlying "integrate by intersection" principle. The idea funnel enables an effective "narrowing of sets gradually while increasing detail", and pre-defined targets for each of the phases serve as a control mechanism.

Networked Product Development

Even though Gausemeier et al. (2006) put a strong emphasis on integrating suppliers into the product development process, only one of the three SBCE principles mentioning the involvement of suppliers is highly represented within networked product development. This principle is described as "explore trade-offs by designing multiple alternatives". Both remaining principles from "mapping the design space" contain multiple references to the ideas of SBCE without contradictions. This is in opposition to "integrate by intersection" and "establish feasibility before commitment". All their underlying principles showed very little evidence of SBCE concepts.

Systematic Development

Pahl et al. (2007)'s methodical product development shows evidence that the overlying principle of "integration by intersection" strongly resembles many of SBCE's features. However, the emphasis on an early definition of all specifications and requirements negates most of the thereby gained advantages. Teams do not discard a concept if it causes problems at later stages. This results in additional rework, which is a lot of effort, since modularity is only introduced for proven products. All this is reflected in the poor result of the "stay within sets once committed" principle.

The Munich Proceedings Model MVM

For the MVM of Lindemann (2009), two SBCE principles stand out, because they are very well represented. "Looking for intersection of feasible sets" involves everyone into the decision process, highlights requirements lists and aims to maximise the overall system. The "narrowing of sets while increasing detail" is done individually by design and engineering teams and evolves from an abstract to a more concrete level of detail. Ultimately, because of the possible recursive use of individual elements of the model, all activities within a project can be met with the required level of detail. This means resources can be invested where they are needed the most. One weak point was the absence of scheduled control mechanisms within the product development process.

The Stage-Gate process model

Even though Cooper (2010) focuses heavily on marketing, the core idea of several SBCE principles are present within the stage-gate process. The "definition of feasible regions" in the Stage-Gate process leads to only one region collectively worked out by all affected teams. Nevertheless, a strong emphasis on testing, using specific methods to explore trade-offs with objective data, heavy customer integration and effective project meetings show several connections to SBCE. The necessity of finalising specifications and attributes before the actual product development begins contradicts the essence of the important SBCE principle "impose minimum constraint".

9.2 Discussion

After analysing each of the five models individually, they were assessed collectively. Table 9.1 summarises the collected results of all models presented in the Tables 4.1, 5.1, 6.1, 7.1, and 8.1. The following list recaps the nine reference principles as elaborated in section 3.4 (Sobek et al., 1999, p. 73-81):

Map the design space

1. **Define feasible regions:** Independent and parallel by all teams; input from simulations, tests and past experiences; usage of engineering checklists.
2. **Explore trade-offs by designing multiple alternatives:** Analyse relation between parameter and effect; target an optimum system; make all decisions based on quantifiable data; share findings amongst all teams; supplier involvement.
3. **Communicate sets of possibilities:** Comprehend capabilities of participating teams; consider subsystems and interfaces; clear presentation of sets.

Integrate by intersection

4. **Look for intersections of feasible sets:** Find solutions suitable for everyone within the defined design space; incorporate new information from meetings into each team's set of ideas; chosen solution must conform with engineering checklists; maximise system performance.
5. **Impose minimum constraint:** Reduce limitations to create flexibility; delay decisions to allow thorough exploration of all sets; manufacturing involvement from the beginning; extend principle to suppliers.
6. **Seek conceptual robustness:** Robust design; short development cycles; standardisation and modularity.

Establish feasibility before commitment

7. **Narrow sets gradually while increasing detail:** Leaves more time to study remaining sets; performed in stages by all functions in parallel; applies to suppliers.
8. **Stay within sets once committed:** Staying inside sets guarantees compatibility to eliminate rework; have safe solution available as a backup; modularised elements.
9. **Control by managing uncertainty at process gates:** Uncertainty is defined as the number of remaining alternatives and their understanding of it; sets have wanted uncertainty level at each gate; conflicts are met with additional resources.

Both Pahl et al. (2007) and Lindemann (2009) show very little representation of SBCE's ideas for "mapping the design space". Their strong areas on the other hand are the "integration by intersection", as well as the principle "narrow sets gradually while increasing detail". This reflects the nature of their models as they focus on problem solving approaches and methods, especially Lindemann (2009).

No.	Eversheim	Gausemeier et al.	Pahl et al.	Lindemann	Cooper
Map the design space					
1	+++	+++	++	++	+++
2	++	++++	++	++	+++
3	+++	++++	++	++	+++
Integrate by intersection					
4	+++	++	+++	++++	+++
5	++	+	++	++	+
6	++	++	++++	++	++
Establish feasibility before commitment					
7	+++	++	+++	++++	++
8	++	++	+	++	+
9	+++	+	++	+	+++
*Total/*36+	23+	21+	21+	21+	21+

Table 9.1: Overview of the results of all discussed models

Nevertheless, the concepts of "mapping the design space" are generally not exclusive to SBCE. Many features can be found in the models of Eversheim (2003), Gausemeier et al. (2006) and Cooper (2010). In comparison, they are somewhat more high level than Pahl et al. (2007) and Lindemann (2009), who aim more at an operational application of their models. This is also reflected by the fact that the two latter discuss the importance of keeping changing requirements list updated more often than the other three.

The actual "definition of the feasible regions" for each individual function, team, or responsible person does not seem to be done by other models. Eversheim (2003), Pahl et al. (2007), Cooper (2010) and especially Lindemann (2009) intend to make full use of each teams capability, but because of the lack of individually defined feasible regions to be intersected, some potential might be left out. This means that "the intersection of feasible sets" is more or less only happening on a component level for most other models, not within the feasible regions of each functional area. This reflects the claim of SBCE to create the truly optimal system by making full use of the capability of all teams by intersecting all feasible regions.

All models suggest or imply the idea of conceptualising multiple alternatives, at least in the early stages of product development. However, Gausemeier et al. (2006) is the only one of the covered models who emphasises on the exploration or detailed analysis of each possible alternative and using trade-offs to decide between all the available solutions with the help of the GEN.

There is very little evidence of the principle to "impose minimum constraint" in all models. It is a very essential SBCE principle as it enables most of the other principles and allows them to be used advantageously. With restrictions to specifications and product attributes the early exploration of trade-offs would make little sense. This is because it confines teams to a certain design space, which might not make full use of their potential feasible regions, leading to a system which potentially could have performed better. Moreover, the narrowing of sets would become pointless as there would be no more evolution, only composition and elaboration of very specific details.

Pahl et al. (2007) and their Systematic Development were the only ones who truly "aimed for conceptual robustness". The importance of standardisation of processes, skills and interfaces is complemented by checklists that focus on the concept of robust design. The other four models do promote standardised processes, tasks, or stages, but the target of achieving robust design as described by Taguchi (1988) is not covered to the same extend as in the Systematic Development model.

The concept of reducing the remaining number of ideas or possible solutions gradually, while increasing the detail of their analysis and design work, seems to be widely used amongst most models. The exception to this are the model of Gausemeier et al. (2006) using the GEN and the Stage-Gate process of Cooper (2010). However, both of them do not aim to provide guidelines on how to eliminate and select between remaining alternatives.

The second principle which turned out to be under-represented in all models is to "stay within sets once committed". The obvious reason for this is that they do not work with sets of ideas, but focus on one concept design once it has been selected. Pahl et al. (2007) even expects changes to appear and modularity is only introduced after the product has been finished and proven itself. Cooper (2010) is not concerned or does not cover the issue of rework other than by involving the customer heavily into the concept stages. While this is good, no technical or manufacturing related problems are considered as they usually appear later in the development process, specifically with the point-based approach of the Stage-Gate model.

While the technical, or in the case of Cooper (2010), marketing related feasibility is often verified before committing to one concept or project, there is a general trend to quickly converge towards one solution. The reason behind this are concerns of increased costs and project delays. Nevertheless, the SBCE process claims to lead to a reduction of costs as rework is reduced significantly (Ward et al., 1995, p. 43).

In relation to this are the proposed process gates of the principle "control by managing uncertainty at process gates". While all five models have some form of control mechanism or quality check, they are described as regular process gates or milestone events only by Cooper (2010) as milestones within the development stage and by Eversheim (2003) in form of detailed targets for each phase.

The extension of the principles "explore trade-offs by designing multiple alternatives", "impose minimum constraint" and "narrow sets gradually while increasing detail" to suppliers is rarely mentioned and never in great depths. It often depends on the kind of supplier as their development approach needs to be compatible to the one from their customer. Gausemeier et al. (2006) tried to attend to exactly this matter with the use of the GEN.

10 Conclusion

The aim of this thesis was to compare modern product development models of recent years to the principles of Set-Based Concurrent Engineering (SBCE). This was achieved by analysing five models in detail, looking for evidence of features or elements of SBCE's principles. The analysis was enabled by an extensive literature review which established the necessary background knowledge of SBCE and each of its nine principles as described by Sobek et al. (1999). The five models discussed were the W-Model as described by Eversheim (2003), Networked Product Development proposed by Gausemeier et al. (2006), Systematic Development introduced by Pahl et al. (2007), the Much Proceedings Model MVM of Lindemann (2009), and lastly the Stage-Gate process model of Cooper (2010).

The assessment (see Table 9.1) showed that even though the overall level of representation of SBCE's principles was nearly identical for all models, the individual principles partially yielded very different results for the individual models. The principles that separate SBCE most from the here discussed models are to "impose minimum constraint", "stay within sets once committed" and "control by managing uncertainty at process gates". Additionally, the independent "definition of feasible regions" for every functional department seems to remain exclusive to SBCE. Ultimately, these four principles are indeed how SBCE is defined:

- By "defining the feasible regions" independently and in parallel, SBCE enables the full use of all engineering capabilities which in the end lead to the optimal solution.

- The willing delay of important decisions is the most important aspect of the principle "impose minimum constraint".

- Communicating, and therefore using sets of ideas instead of one solution is what separates SBCE from traditional point-based engineering. Committing to a set in later development stages is therefore not possible for a non set-based approach.

- Lastly, the emphasis on "control by managing uncertainty at process gates" evolves around the idea of defining and controlling the level of evolution for each set at certain points throughout the development process.

The core essence of the principles to "look for intersections", or "narrow sets gradually while increasing detail" was almost always present in the five assessed models. Also the concept of "[. . .] designing multiple alternatives" was mentioned in all of them.

- Combining the expertise of different teams is always a part of product development. The level of detail or similarity to the SBCE equivalent of "looking for intersections of feasible sets" varied from model to model, but it was always a part of them.

- Similar the selection and concretion of product concepts. Products typically start as abstract concepts or even ideas and evolve through information and data gained through research, testing, external input, or mistakes resulting in rework.

- All models recommend or imply the design of multiple alternatives, rather than conceptualising and developing only one idea.

Results for the remaining two principles "communicate sets of possibilities" and "seek conceptual robustness" varied from model to model. While none of the discussed models use sets of possibilities as the way of communicating, subsystems are usually considered and used. The targeted robustness of a concept or product depends on the focus area of each model's author

A possible extension of this thesis could be the attempt to assess the overall presence of SBCE in the here discussed, or other, product development models. To achieve meaningful and applicable results this would require further in-depth studying of SBCE, especially in the field of applications in industry. Of course this would also require to look at other definitions and descriptions of SBCE than the principles of Sobek et al. (1999) which served as a baseline for this thesis. This could be further enhanced by analysing additional product development models, especially from the Anglo-American region, to gain a better understanding of the differences between SBCE and traditional point-based product development approaches.

Another option can be to compare product development models which claim to be Lean Product Development (LeanPD) models to the original Toyota Product Development System. This could highlight both differences and similarities on the interpretations of LeanPD models.

Concluding, it can be said that SBCE partially distinguishes itself significantly from the models assessed in this thesis, while also featuring ideas and principles common amongst other industrial product development models.

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