NTNU
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Set-based Concurrent Engineering in Norway

Investigating promoting and constraining factors for SBCE, with regards to implementation in Norwegian product manufacturing industry.

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Thank you Torgeir Welo, for granting me the opportunity to carry out the project, and thank you for your supervision.

Thank you to all the participants and companies who have been so welcoming.

Thank you Sif, for going outside your interests and field to support and assist me. Thank you Nikolai, for taking the time to help, I really owe you. Thanks to the both of you for your very valuable feedback.

Thank you NTNU and Trondheim, for these beautiful years.

Summary

English

The objective of the research was as follows:

To investigate prevalence of promoting and constraining factors for set-based concurrent engineering, with regards to implementation in Norwegian product manufacturing industry.

In order to complete the research objective, *set-based concurrent engineering* (SBCE) as a product development methodology was studied through literature. Effects from use and implementation efforts were also studied. Core elements of the methodology were identified based on the literature study, and were identified as *customer value focus, knowledge-based environment, set-based design, concurrency, decision delay, frontloaded resource distribution, supplier involvement,* and *manufacturing involvement.*

To examine the prevalence of these elements in Norwegian product manufacturing industry, a qualitative research approach was decided upon. A sample of companies with a wide variety in parameters like size, location, and type of industry were interviewed. This broad approach was to enable better grounds for the research objective. Respondents from the companies were interviewed on a semi-structured form, following an interview guide that was designed to identify degree of use of the SBCE elements identified in the literature study. The interview data was analyzed, and the companies were ranked in alignment with each of the SBCE elements, providing a score table that were used when looking for patterns between the companies. Using pattern matching, promoting and constraining factors for SBCE practice were identified. The promoting factors were identified as *exposure, growth, levelled organization, market tempo, in-house production,* and *modern tools.* Constraining factors were identified as *instability, internal discord, developer isolation, limitations of current product development model, strong project-mindset, resistance to change* and *product type*.

The factors were discussed in relation to implementation efforts in Norwegian industry, considering the degree of alignment with SBCE elements across the sample in general. Developed elements in Norwegian industry were found to be *knowledge-based environment, concurrency* and *manufacturing involvement*, which were linked to internal relations and practices. Mid-level developed elements were found to be *customer value focus* and *supplier involvement*, which are connected to external relations. Low-scoring elements were found to be *degree of set-based design, resource distribution*, and *decision delay*, which are related to knowledge about benefits of SBCE. The promoting and constraining factors had interplay with these elements in several ways.

Norwegian

Målet med forskningen var som følger:

Å undersøke fremmende og begrensende faktorer for "set-based concurrent engineering", med hensyn til implementering i norsk produktindustri.

For å fullføre forskningsmålet ble "set-based concurrent engineering" (SBCE) som en produktutviklingsmetode studert gjennom litteratur. Effekter fra bruk og imlementering ble også studert. Kjerneelementer i metodikken ble identifisert basert på litteraturstudien, og ble identifisert som *kundeverdi-fokus, kunnskapsbasert miljø, sett-basert design, samtidsutvikling, utsettelser av avgjørelser, tidlig tung ressursfordeling, involvering av leverandører,* og *involvering av produksjon.*

For å undersøke forekomsten av disse elementene i norsk produktindustri ble det valgt en kvalitativ undersøkelsesmetode. Et utvalg bedrifter med et bredt spekter av parametere som størrelse, beliggenhet og type industri ble intervjuet. Dette brede omfanget skulle gi bedre grunnlag for å nå forskningsmålet. Respondenter fra selskapene ble intervjuet i halvstrukturert form, etter en intervju-guide som ble utformet med det hensyn å måle i hvor stor grad praksis var i tråd SBCE-elementene som ble identifisert i litteraturstudiet. Intervjudataene ble analysert, og selskapene ble rangert i samsvar med hver av SBCE-elementene. Dette ga en tabell som ble brukt som indikator for å lete etter mønstre mellom selskapene. Ved hjelp av mønstermatching ble det identifisert fremmende og begrensende faktorer for SBCE-praksis. De fremmende faktorene ble identifisert som *eksponering, vekst, flat struktur, markedstempo, produksjon på lokasjon,* og *moderne verktøy.* Begrensende faktorer ble identifisert som *ustabilitet, intern dissonans, utviklerisolasjon, begrensninger av dagens produktutviklings-modell, sterk prosjekt-orientering, motstand mot endring* og *produkttype*.

Faktorene ble diskutert med hensyn til implementering i norsk industri, med utgangspunkt i graden av praksis i tråd med SBCE på tvers av utvalget. Utviklede elementer i norsk industri ble funnet å være *kunnskapsbasert miljø, samtidsutvikling* og *involvering av produksjon*, som var knyttet til interne relasjoner og praksis. Mellom-utviklede elementer var *kundeverdi-fokus* og *involvering av leverandør*, som er knyttet til eksterne relasjoner. Lite utviklede områder var *grad av sett-basert design, tidlig tung ressursfordeling* og *utsettelse av avgjøreser*, som alle er relatert til kunnskap om fordelene med SBCE. Fremmende og begrensende faktorer hadde samspill med disse elementene på flere måter.

Preface

This thesis has been submitted to the Norwegian University of Science and Technology (NTNU) for the degree of Master of Science (M.Sc.). The work has been carried out at the Department of Mechanical and Industrial Engineering (MTP) under the supervision of Torgeir Welo. The work was conducted in the period of January-June 2018. The work counted for 30 ECTS.

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Abbreviations

CAD	=	Computer Aided Design
CE	=	Concurrent Engineering
DoE	=	Design of Experiments
FEA	=	Finite Element Analysis
LM	=	Lean Manufacturing
LPD	=	Lean Product Development
NDA	=	Non-Disclosure Agreement
NSD	=	Norsk Senter for Forskningsdata (English: Norwegian Center for Research Data)
PBD	=	Point-based Design
PD	=	Product Development
RCA	=	Root-Cause Analysis
R&D	=	Research and Development
SBCE	=	Set-based Concurrent Engineering
SBD	=	Set-based Design

Chapter 1

Introduction

1.1 Objective

In an ever-increasingly globalized society, competition across industries is increasing (Overvik Olsen & Welo, 2011). In efforts to increase profitability, more efficient management of new-product development (NPD) are sought after. The goal is to maximize value in products, relative to cost. A proposed approach is the *Lean product development* (LPD) management framework. One of the main enablers within this framework is *set-based concurrent engineering* (SBCE) (Al-Ashaab et al., 2013; Hille, 2015). SBCE is a methodology for the actual product development (PD) process, the ”practical” part of LPD. Literature show promising effects from use. The formulation of the objective was done in collaboration with the project supervisor, and is as follows;

To investigate promoting and constraining factors for SBCE, with regards to implementation in Norwegian product manufacturing industry.

Based on this, following tasks were identified:

1. Identify core elements of SBCE from literature
2. Examine how these elements are prevalent in Norwegian product manufacturing industry
3. Identify promoting and constraining factors for SBCE practice
4. Discuss how these factors affect potential implementation efforts

The objective calls for questions in the tasks that are typical that of case studies. Case studies are appropriate for ”how/why”-type research questions to contemporary phenomena that the researcher has little or no influence of (Yin, 2014). Therefore, the foundations of field the research was based on the works of Yin (2014).

1.2 Scope

The companies need to have the relation to suppliers and customers displayed in figure 1.1, having original equipment manufacturing-suppliers (OEM) upstream (OEM meaning suppliers of manufactured products). The companies considered develop physical non-commodity units for manufacturing (i.e. not services, or continuous processes like fluids), reliant on more than one functional department (industrialization, design, electronics, or product-specific subsystems). The companies were required to have launched new products developed in their in-house PD department within the last 5 years, and have current efforts in place for new launches in the future.

The companies included are older than 5 years. The companies have international competition, as this is relevant for how Norwegian companies differentiate themselves in a global context.

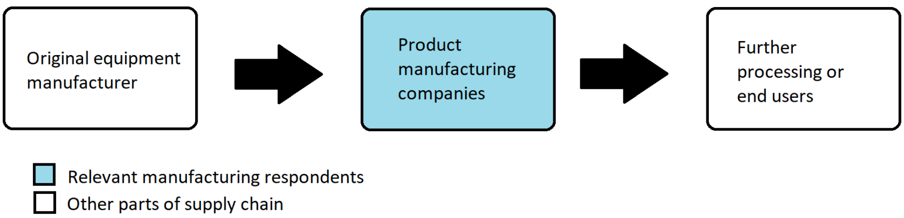

Figure 1.1: Companies of interest

Apart from this, the study includes companies of a variety of industries, number of employees, location, production size, manufacturing in/out of company (and so on) to see the bigger picture. This was chosen to allow a wide search for answers to complete the research objective. The study aim to include between 20-30 companies for a good foundation for conclusions.

The types of companies presented here are what is referred to when "Norwegian industry" is used as term in this thesis.

1.3 Significance

The PD process is often fuzzy and expensive, and much of the cost is related to the demand for rework due to premature design decisions (B. M. Kennedy, Sobek, & Kennedy, 2014). Rework is common in traditional methodologies, and many developers are under the impression that rework is a natural part of the process (Fricke, Gebhard, Negele, & Igenbergs, 2000). Research shows that SBCE is efficient at reducing rework (B. M. Kennedy et al., 2014), and is thus a way of making the PD process faster and cheaper, all the while promoting innovation (K. M. E. Kennedy Michael; Harmon, 2008).

Prevalence of SBCE in Norway is a relevant research topic because it can give an indication of how Norwegian PD evolves to increase competitiveness. Many Norwegian companies report their selling points to be quality and innovation, and suffer more risk in global contention if lower-cost countries ”catch up” in these areas. Prevalence of SBCE elements in Norway has not been addressed before.

1.4 History and context

Japanese industry suffered a dip in productivity following WWII due to a weakened economy, but in the 1980’s, it became clear that they were overtaking western competitors (Welo, 2011). Research started to better understand where the competitive advantage came from. The idea of *Lean* thinking was identified after a 5 year study conducted by Massachussets Institute of Technology and Womack et al. (1990) in the book ”The machine that changed the world”. The book tells the story about how Toyota considered the whole production system rather than the individual pieces of it (machines, storage, workstations) through their ”philosophy” of Lean thinking. In short, this method of thinking that Toyota employed focused on customer value, continuous product flow, ”pull” rather than ”push” production, reducing waste, and continuous improvement.

Lean thinking in Toyota was primarily linked to their manufacturing department. However, the principles of Lean thinking can also be applied to the PD processes (A. Ward, Liker, Cristiano, & Sobek, 1995). Welo (2011) highlights the difference between PD and manufacturing; unlike in manufacturing, the PD process is not repeating, as the objective is to create something new with each process. The materials one works with are abstract ideas, rather than concrete products. Also, an engineer is not a machine; shortening the time spent by the engineer can easily harm more than help. The focus should be on increasing value perceived by the customer through knowledge-based decisions, rather than reducing resources allocated to the PD process, to increase profitability. This is the idea behind *Lean product development* (LPD), a PD management framework that promotes value-maximizing PD. *Set-based concurrent engineering* (SBCE) is a subset of the LPD. SBCE is a PD methodology for the actual development of a product.

A case study by A. Ward et al. (1995) started by investigating how the Japanese automotive manufacturers were getting ahead in the global market. It became clear that Japanese and U.S. automakers had many similarities in how concurrent their and their supplier’s engineering work was. However, Toyota stood out as something curiously different. Toyota was at that point consistently increasing market shares, releasing high-quality products rapidly to market, despite postponing decisions in development. Deeper investigation of the Toyota practices led to what is referred to as the SBCE principles, described by Sobek, Ward and Liker in their paper ”Toyota’s Principles of Set-Based Concurrent Engineering” (1999).

SBCE is a composite of two ideas; *Set-based design* (SBD) and *concurrent engineering* (CE). SBD was first introduced by name by A. C. Ward (1989) in his PhD thesis: ”A Theory of Quantitative Inference Applied to a Mechanical Design Compiler”. There are two main aims of SBD: Increasing flexibility, and reducing rework. The ”set-based” computer program provided all possibilities of standard components from a catalog based on input requirements, enabling a range of mechanical designs. The more detail in specifications, the fewer components available. The core idea was to keep all possible design variations open as long as possible in the design process, only eliminating infeasible options. Carrying sets of solutions opposed the idea of *Point-Based Design* (PBD), where options are generated and one is chosen for further development of the design (Singer, 2009). PBD is often seen as the ”traditional” approach to a PD process (Sobek II, 1996). An illustration of the difference between the two can be seen in figure 1.2. The final adjustments in the point-based approach can be too extensive, making changes impossible. This can lead to a sub-optimal design.

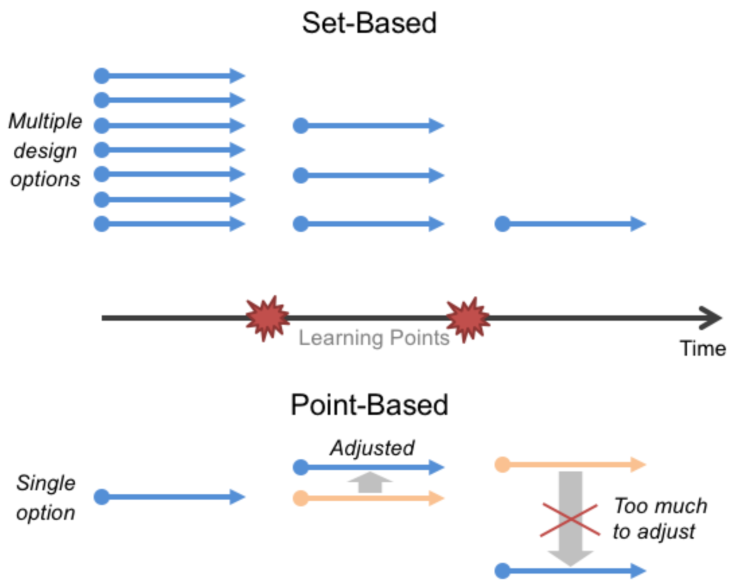

Figure 1.2: SBD vs PBD. Collected from LeanKit (2018).

Concurrent engineering (CE), or *simultaneous engineering*, is a term that also emerged in 1989. It is based on the idea of having subsystems in a product developed in parallel, rather than the traditional approach of developing in sequence. CE is illustrated in relation to sequential (”over-the-wall”) engineering in figure 1.3. For a car manufacturer like Toyota, this means engineers behind design, materials, electronics and engine all occasionally work in interdisciplinary teams to better integrate the different elements into a final design (Sohlenius, 1992). Toyota is seen as one of the originators of CE A. Ward et al. (1995).

1.5 Structure

The project in itself was structured in 6 phases:

1. Formulation of objective
2. Literature review
3. Field work research design

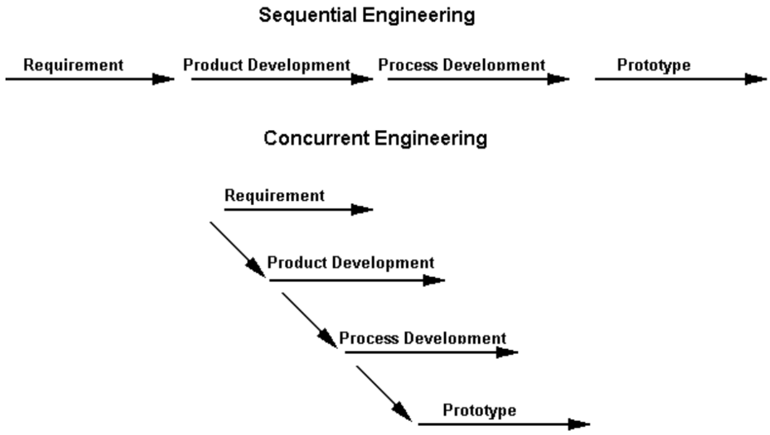

Figure 1.3: Difference between sequential and concurrent engineering, from Winner et al. (1988).

4. In-field data collection
5. Analysis
6. Discussion and conclusion based on analysis

The structure is inspired by the works of Yin (2014) on case study design. The formulation of the research objective has already been addressed earlier in this chapter.

The literature review will describe conventional models and limitations of these in short, before moving on to describe LPD. This is to understand the contrast between old and new practices. SBCE will be described at-length to identify core elements. Effects from use reported in academia will be presented, to better understand benefits. The prevalence and growth of LPD and SBCE will be addressed, and topics around implementation will be discussed.

The field work research design will then be discussed, including reflections on reliability and validity. Following is an analysis based on the data collected, where all the companies are evaluated for alignment with each SBCE element. That analysis will be the basis for pattern matching, whereby the promoting and constraining factors will be identified and presented. The overall performance of the sample in each element is also analyzed, and linked to the factors identified.

A discussion on how these factors affect implementation efforts follow. The potential for SBCE in Norwegian PD based on the findings is discussed, before the thesis finishes up with reflections and implications of the study.

Chapter 2

Literature study

2.1 Study strategy

In order to complete the objective, a descriptive approach to literature study is needed to deduce defining elements of SBCE, in accordance with Yin (2014).

The literature study started with the most cited works that returned on search word combinations like *"set-based concurrent engineering"* or *"Lean product development"* on Oria (NTNU's own literature search engine) and Google Scholar. Keywords such as *rework*, *effect*, and *implementation* was later added. By now it was clear which authors who were more productive in the field. By looking at their more recent articles and their citations, a big selection of relevant articles was obtained. Many articles on conventional models referred to in the literature on SBCE were read for better understanding.

Several books on the LPD subject exist, examples being *The Lean Machine: How Harley-Davidson Drove Top-Line Growth and Profitability with Revolutionary Lean Product Development* (Oosterwal, 2010) and *Ready, Set, Dominate: Implement Toyota's Set-Based Learning for Developing Products and Nobody Can Catch You* (M. Kennedy, 2008). Extracts available online were read through.

The purpose of the review is to contextualize SBCE in relation to conventional models. This is to better understand the shortcomings of traditional practices, better understand how SBCE is different, and understand the benefits it proposes. It was also necessary to understand LPD as a framework for which SBCE can operate, and so this is also studied.

2.2 Conventional PD models and their limitations

2.2.1 Point-based design

Liker, Sobek, Ward, and Cristiano (1996) describes the "typical" approach to PD processes. The process begins with a problem definition, and idea generation for a solution. An analysis is made, and the engineers choose the most promising concept. This concept is modified, analyzed and evaluated until a satisfactory solution to the problem definition is met. If a solution is not met, the process starts over, often by redefining the problem. The key here is that only *one* solution is worked on at any one time, despite a rich idea generation in preliminary phases. This is called *point-based design* (PBD). PBD is analogous to climbing a hill, as the engineers are continually changing the design to reach a level of a satisfactory solution to the problem definition. However, the engineers run the risk of reaching only a local optima (a sub-optimal solution), not a global optima (the best solution available). That is, if they reach a satisfactory solution at all.

A product needs to cross several different functional groups in the PD process (e.g. specification, design, mechanical engineering, electrical engineering, manufacturing, etc.). A particularly wasteful process within PBD is the ”over-the-wall” engineering, where the process has a distinct downstream motion, working through these different functional groups. Over-the-wall means that the engineers related to different departments finish their job before the project moves on to the next department (the project gets ”thrown over the wall”), often with little communication. This causes knowledge gaps. Problems might arise downstream, and work must be redone. The further the product comes downstream before changes are made, the more expensive they become, as more details must be redone (B. M. Kennedy et al., 2014).

An effort to repair this is to have the functional groups develop simultaneously. In other words, employ concurrent engineering (CE), opposed to sequential engineering. Establishing cross-functional teams focusing on sub-systems can help with circumventing downstream troubles. Alas, other issues arise. As Bernstein (1998) points out, CE encounters the chicken-and-egg problem: group A might need information from group B before doing their tasks, and vice versa. In order to help against this problem of design order, much effort is put into task sequencing and design partition. Other problems then arise, like sub-optimal task sequencing, wasteful meeting activity, one-issue focus, or concealment of known problems (Ford & Sterman, 2003).

2.2.2 Stage-gate

Cooper (2008) reports that around 70% of American companies are using a gated process model PD process, and the number is likely similar in Norway (through shared western culture). Gated processes (*stage-gate* or *phase-gate*) are often used as control tools for identifying defective solutions. The purpose of the gates is to make sure the project complies to pre-defined criteria, map future progress, and kill any process that risk not returning profit. Although the very early phases can have several concepts considered, the model uses PBD, in that generally only one concept is iterated upon to keep costs down. The model often requires much documentation (often to make sure everyone approves design to mitigate risks) and is often criticized for being too much of a business-oriented governance model, not incorporating the flexibility that a PD project needs (Ringen & Welo, 2013). A generic stage-gate process is illustrated in figure 2.1.

2.2.3 Resource drains in inefficient PD

Rework

B. M. Kennedy et al. (2014) defines rework by any work that must be done that invalidates

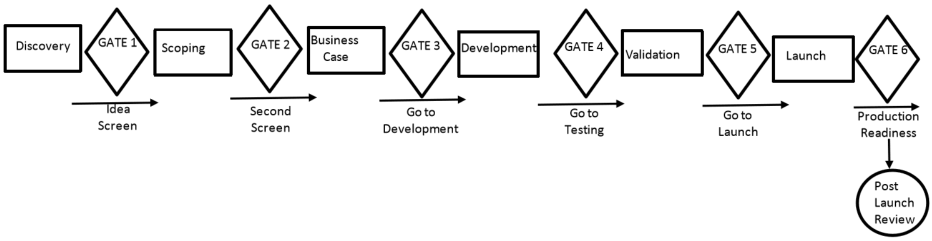

Figure 2.1: Generic stage-gate model. Illustration from Ringen and Welo (2013).

previous decisions in the development process. Occasionally, development teams must change design decisions that were assumed to be final due to flawed judgment earlier. By *final*, it is meant that the team expects the decision to be valid for the remainder of the project (i.e. there is no reason to believe it needs to change). Rework is not to be confused with design decisions made for rapid learning, where experimental approaches are used to get customer feedback or testing for data on performance. Rework is one of the biggest drain in time and resources in PD projects, using as much as 50% of engineering capacity (Terwiesch, Loch, & Meyer, 2002). B. M. Kennedy et al. mentions the following examples for when rework occurs, with suggested solutions:

- Two or more incompatible designs
  - At least one group must redesign to be compatible with the rest
- Customers not liking trade-offs made in design
  - Key features must be changed or lower sales must be accepted
- Manufacturing team not capable of producing important feature decided upon further up the development stream
  - Redesign and delaying product delivery or invest beyond what was budgeted

As we can imagine, the solutions can be costly. The first and last point are examples of rework across cross-functional groups, resulting from inaccuracies communicated laterally or downstream. A typical scenario is that unstable, high-precision information of most-likely result is communicated, leading to rework when it changes (Terwiesch et al., 2002).

In the Systems Engineering Handbook from Haskins, Forsberg, Krueger, Walden, and Hamelin (2006), the Defence Acquisition University made a figure based on statistical analysis on projects in the US Department of Defence (1993), which can be seen in figure 2.2. Here, the bars represent the actual life cycle cost, or devoted resources, accumulated up to that point (e.g. 15% after the Design phase). The curve for "Commited Costs" represent how much of the life cycle cost is committed by the decision taken this far (e.g. 70% of the cost is determined by the decisions made in the Concept stage). The cost of extracting defects from development at a late stage can exceed by as much as 1000 times the original cost (Haskins et al., 2006).

The defects can also hurt the company or product in the market and possibly damage growth potential. Internal organizational environment can also be affected. Other studies confirm that 60-75% of life cycle costs are decided in the concept/architecture phase (Anderson, 2004; Hari, Shoval, Kasser, et al., 2008). The PD phase is the biggest contributor to profitability (Duverlie & Castelain, 1999).

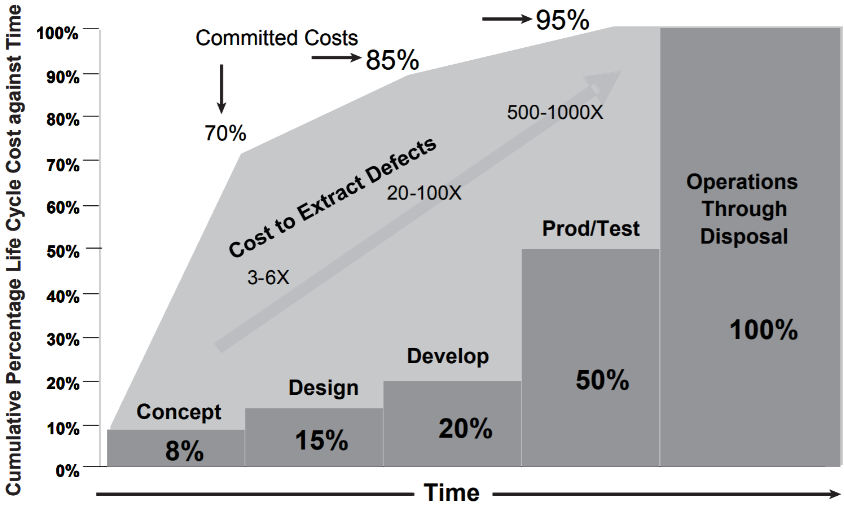

Figure 2.2: Cost distribution in PD, illustrated by Haskins et al. (2006).

There are many reports on how much of development efforts are dedicated to rework, but ”typical” values range from 30-70% (Osborne, 1993; Reichelt & Lyneis, 1999). Other studies report that development engineers view rework as simply inevitable (Fricke et al., 2000).

Starvation

Starvation happens when downstream processes are unable due to waiting for more information from upstream processes. Waiting can be costly for two reasons; the direct man-hours spent waiting (if they have no other projects running), and the time that passes, lengthening lead time (Terwiesch et al., 2002). Concurrency is a common way of addressing the issue, but again the precision of information matters. Starvation typically occurs where low precision (but stable) information is communicated. The low precision information can make downstream processes do low-precision work, but they have to wait for more information in order to continue.

Discontinuation

Stage-gate is not engineering guidance; it is closer to a governance tool with roots from finance and investment thinking (Ringen & Welo, 2013). The gates evaluate future potential based on current possibilities. The purpose of the early-stage gates is to eliminate projects without promising potential, without committing too much cost. A typical resource distribution is to increase spending as the project matures, because then the potential is promised by passed gates. Spending less early means less learning early. Less learning early means higher risk of learning something at a more expensive stage.

Point-based approaches govern iteration and rework. The risk of point-based stage-gate is that the cost of rework exceeds the profitability of the project. The company developing can encounter a dilemma: spend even more to at least have a return, or drop everything and gain nothing. The higher the sunk costs, the worse the nightmare. If the possibilities are limited (i.e. only one point in the design space), the risk of discontinuation increases. Cooper (2008) reports that the stage-gate innovation failure rates are anywhere between 70-98%. This is mostly discontinuation in earlier gates, but the waste is still immense.

2.2.4 Reasons for wastes

Mascitelli (2007) states that value can be *”any activity or task is value-added if it transforms a new product design (or the essential deliverables needed to produce it) in such a way that the customer is both aware of it and willing to pay for it”*. Any activity that does not conform to this is considered ”waste” (Mascitelli, 2007). The resource drains just introduced are among the bigger types of wastes. By the works of Mascitelli (2007), Oppenheim (2004), and B. M. Kennedy et al. (2014), the following points are listed as reasons for why waste occurs:

- Chaotic work environment
- Lack of available resources
- Poor communication across functional barriers
- Poorly defined product requirements
- Disruptive changes to product requirements
- Over-designing
- Too many meetings
- Delays/waiting
- Extra processes and relearning
- Partially done work
- Task switching
- Defects
- Unused employee creativity
- Late learning

- Making critical decisions too early
- Uninformed decisions

Some of these have already been discussed and are related to rework and starvation, and can lead to low-quality development resulting in discontinuation. Many of the points are related to each other. The list is not limited to these points, but it provides a picture in which many companies find familiarity. A proposed framework for working against these wastes is LPD. An enabler for LPD is SBCE (Al-Ashaab et al., 2013; Hille, 2015). For example, SBCE promotes early learning, which battles problems related to late learning and too early or uninformed decisions, leading to rework (B. M. Kennedy et al., 2014). Early learning means lower chances of discontinuation at expensive stages as well. However, SBCE does not suggest e.g. meeting policy specifically, but suggests a work process that might reduce the need for correspondence on adjustments, which meetings often are used for. Before addressing SBCE, it is useful to look at the surrounding framework, which is LPD.

2.3 Lean Product Development

Womack and Jones 1997 define Lean thinking in 5 points:

1. Specifying value from the customers' perspectives
2. Identifying the value stream
3. Making the value-creating activities flow
4. Let customer ”pull” value
5. Pursuit for perfection

Lean has been a hot topic in manufacturing since its infancy. LPD serves as an extension of Lean thinking applied in new-product development (NPD). By NPD, it is meant *”the collective activities or systems, that a company uses to convert its technology and ideas into a stream of products that meet the needs of customers and the strategic goals of the company”* (Welo, 2011).

Welo highlights the focus on value and value stream mapping. By the definition of Browning (2003), LPD is *”a company-wide product development system aimed at maximizing customer or user value, within the constraints of value of other stakeholders.”* LPD is not to be mistaken with Lean manufacturing (LM), described by Womack et al. (1990), which is a common association to the word Lean. LM is about smoothing operations in production systems; minimizing time spent at each station, reducing excess material, reducing inventory, etc. These are tangible, repeatable, measurable inputs and outputs. Product development processes are intangible, invisible, and no two processes are identical; not even in content or timeframe (Welo, 2011). This makes the matter more complex.

There are different interpretations of Lean in PD. For example, Liker and Morgan (2006) describes 13 principles based on a sociotechnical system consisting of three primary interrelated and interdependent sub-systems: *process, people* and *tools and technology*. Inspired by this and other interpretations of the Toyota PD system, Welo (2011) introduced a model containing 6 core components. This serves as a model for lean practices in PD for companies with strategic focus on high-value-added products. The characteristics are to some extent adapted to the specific culture, climate, organization, and management style of Norwegian manufacturing (and similar western) companies (Welo, 2011). An illustration of the model is shown in figure 2.3.

Figure 2.3: Components of a Lean product development system. From Welo et al. (2013)

As displayed, the areas of interest is *customer value, continuous improvement, culture, knowledge, stabilization* and *standardization*. These are related to the management level of an organization and serve as a framework for high value-generating PD processes. A brief explanation of the points follow, based on the works of Welo et al. (2013):

Customer Value. Value is the cornerstone of Lean thinking, as the word ”lean” hints at cutting excess mass in a system (Womack et al., 1990). Waste has already been discussed, but there are different types of waste. Type 1 waste (necessary waste) enables value generating activities (e.g. administration, validation, documentation). Type 2 waste (e.g. waiting, communication failures, defective products, too much detail) does not generate any value (Walton, 1999). By the nature of the definition, some type 1 waste is necessary, but type 2 should be eliminated completely, to make room for more value generation.

Related to this, customer value can be defined on a fundamental level by a simplified mathematical expression. According to Browning (2003), customer value is equal to the perceived benefits divided by the price, i.e.:

$$Customer\ Value = \frac{Benefits}{Price}$$

Where the price is comprised of the cost and margin. If cost is reduced (through elimination of type 2 waste), margin can be increased while customer value is kept constant. Benefits must be explicitly or implicitly acknowledged by the customer, and tools exist for identifying these benefits. Customers needs should be understood through e.g. interviews, focus groups, surveys, observation, market research, or workshops (Welo, Olsen, & Gudem, 2012). The product value attributes should be categorized, mapped for interdependencies, and system targets should be discussed based on this. Diagrams, charts, spread-sheets and matrices are tools for clear, visual communication (Welo et al., 2012).

Culture. According to Welo (2011), the culture in a lean environment should be based on trust, respect and responsibility. Opinions should be respected and considered, responsibility is delegated to the one closest to the problem, and decisions should be fact-based. Further, problems should be solved at root cause, and the environment should accommodate learning and out-of-the-box thinking, and visual communication should be used (Welo, 2011).

Stabilization. The management should plan for predictable conditions regarding resource and workload planning (Welo, 2011). Task switching is considered wasteful. A clear technology and product strategy is essential, especially when knowledge generation and design reuse is used as a tool for continuous improvement (Welo, 2011). Establishing long-term relationship with faithful suppliers also help in having stable conditions, and involving them early in the design process helps avoid late changes to products and the costs associated (Liker et al., 1996).

Standardization. Welo (2011) states that standardization can be applied to process, technology, products, etc. Making things standardized frees up time for innovation and experimentation, but also helps reduce risk, waste and development time . Although standardization can sound like something that can affect creativity in a negative way, having a better overview over past solutions (not having to redo them every time) makes more room for improvement (Welo, 2011). Product architecture and modular systems are particularly effective tools in this regard, but also standardization of processes is important, like employing LAMDA (Look-Ask-Model-Discuss-Act) as a problem solving approach (A. C. Ward & Sobek, 2007).

An analogy for standardization is the English alphabet; it has 26 letters as a standard, but outputs several tens of thousands of words.

Knowledge. Effective capturing of knowledge is vital for an organization who wants to accommodate continuous improvement (Welo, 2011). This goes for the standardization as well. This is particularly important when new people are employed, so they better can adapt to working environments and contribute past what is already learned, but also in downsizing; the knowledge might simply disappear with the people.

The key is to have a culture and system for keeping the knowledge, so no two mistakes are the same. Finding the core of the problem is important in order to abstract it to knowledge that is applicable to future projects as well. An approach to achieve this abstraction is root-cause analysis (RCA). One very simple tool for RCA is the ”5 why’s”: One asks ”why did it go wrong?”, and as an answer follows, one again asks ”why did that happen?”, and keep asking why until the root of the problem is found.

Generating knowledge as the project runs is also important to make knowledge-based decisions. Gut-feel or ”best guess” is often what dictates choice of concept in traditional approaches (B. M. Kennedy et al., 2014). Early testing in cheap phases should be the basis for knowledgeable decisions, opposed to best guess (Welo, 2011).

Continuous improvement. Lean is not a state, but a direction (Karlsson & Åhlström, 1996). Nothing is ever perfect, and processes can always be improved upon. Being on the look-out for parameters that can indicate improvement in PD processes is important for measuring the improvement over time; PD lead-time, product cost, customer perception, number of new products, etc (Welo, 2011). These performance indicators can reveal if the company is on the right track.

2.4 Set-based Concurrent Engineering

2.4.1 SBCE in short

SBCE is counted as one of the main enablers for LPD (Al-Ashaab et al., 2013; Hille, 2015). It involves the ”practical” part of the PD process, i.e. the making of a product. SBCE resonates well with the framework presented by Welo et al. (2013). SBCE does not function well without the stability, knowledge retention, standardization, etc. that LPD provides, as it can simply just cost more resources without adding more value if not executed correctly.

SBCE was first introduced as a concept some time after being observed at Toyota by Ward et al. In 1995, the paper ”The Second Toyota Paradox: How Delaying Decisions Can Make Better Cars Faster” was published. The process observed was summed up in 5 points:

1. The team defines a set of solutions at the system level, rather than one single solution.
2. The team defines sets of possible solutions for various subsystems
3. The team explores these possible subsystems in parallel, using analysis, design rules, and experiments to characterize a set of possible solutions.
4. The team uses the analysis to gradually narrow the sets of solutions, converging slowly toward a single solution. In particular, the team uses analysis of the set of possibilities for subsystems to determine the appropriate specifications to impose on those subsystems
5. Once the team narrows the set for any part of the design, it does not change that decision unless absolutely necessary.

By a set, it is meant more than only one proposed design/solution. It can be ranges, or discreet alternatives. It might be helpful to look at a every-day example from A. Ward et al. (1995) on why working in sets might be better than working in points. Imagine organizing a meeting with e.g. five people; the person organizing the meeting will likely set a time that is convenient for himself. As invitations are sent out, one attendee replies that she is not able to attend. The organizer and this first respondent then agree on a different time and send out invitations once again. A third person responds that this new time does not fit his schedule, and so it goes. The more people and the more busy they are, the lengthier process of finding a suitable time for everyone.

There are some common approaches to this problem. One is having a short meeting on deciding a common meeting time. This speeds up the communication process, but at the expense of time. Another approach is to have an organizer force a time for the others, often at regular intervals, but this can also be a sub-optimal solution if other activities should be prioritized by some members.

The set-based approach to this problem would be to have everyone submit all slots they are available. A good solution can be found at all intersections. This is analogous to engineering processes: SBCE is about exploring solutions within the realm of what is possible for each subsystem, finding a well-functioning combination between functional departments. An illustration of this can be found in figure 2.4.

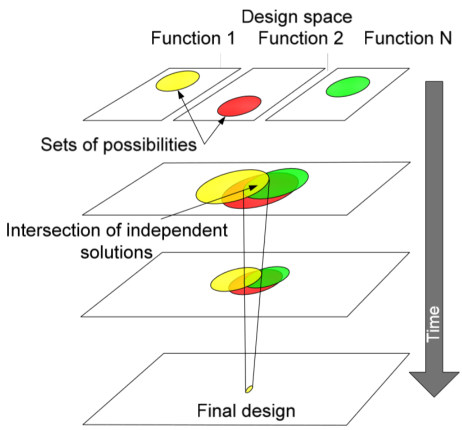

Figure 2.4: Illustration of an SBCE process. From D. Raudberget (2010).

While aspects of the methodology had been around for several decades, it was the works of Ward et al. that defined it as a system when they investigated the Toyota PD system.

2.4.2 SBCE principles

Overview

As mentioned, the SBCE ideas were first publicly introduced in the Sloan Management Review in 1995 A. Ward et al. (1995). D. Sobek, one part of the research team, later defined the principles for what constitutes SBCE in 1999. The SBCE process principles, which is the basis for this research project's identification of core elements, were defined accordingly:

1. Map the design space
    - Define feasible regions.
    - Explore trade-offs by designing multiple alternatives.
    - Communicate sets of possibilities.
2. Integrate by intersection
    - Look for intersections of feasible sets
    - Impose minimum constraint
    - Seek conceptual robustness
3. Establish feasibility before commitment
    - Narrow sets gradually when increasing detail
    - Stay within sets once committed
    - Control by managing uncertainty at process gates

Following will be an explanation of the principles introduced by Sobek et al. in their studies of Toyota. All statements will be taken from the works of them, unless otherwise stated. The purpose is to understand how this system works, so that this can be translated into core elements that can be used in-field to complete the objective of this study.

Principle 1 - Map the design space

Define feasible regions. A project starts with an exploration phase. It should come from a clear understanding of what is wanted to be achieved (based on e.g. value analysis), and where the critical knowledge gaps are. The purpose is to define the opportunities and limits of a room, to ensure broad ideation. By the "design space", it is meant all possible design possibilities. Building on what was explained in section 2.2.3 on rework, the early phases are naturally the most critical for resource allocation. The most crucial decisions should be based on knowledge for proper judgment. SBCE promotes spending more time and resources on this phase compared to traditional processes, to make subsequent phases cheaper and faster.

Each functional department maps constraints related to the project, saying what should or should not be done. This information can come from past experience, analysis, experimentation, testing or through researching the development environment. The latter can mean to investigate the possibilities of production from potential suppliers. Doing this early, asking questions like "what can you do for me?" rather than "can you do this?" is important in order to communicate in "sets". This keeps the design space open.

Organizing knowledge is important. PD projects create learning that is useful in the future. This is commonly kept in mind and perhaps discussed in a "lessons learned"-session, building personal experience, but SBCE puts emphasis on documenting it and making that information available. This is called *engineering checklists*, and include information on functionality, manufacturability, government regulations, reliability, etc. It can be strict points for compliance or guidelines that improve quality or reduce cost.

Recording high-value information is key: Short, concise and accurate. It should not be too constraining, and there should not be too much noise (many entries). The project manager should confront this document and extract relevant points at the start of the project, and have the engineers read through, accept and update it in case of new technology. This is also used in design reviews.

The document can include ranges of flange angles that produce a good component, delivery times on products, geometries and sizes possible in production, etc. Companies without design standards such as these rely on good communication across all parties and mental maps of design space acquired through experience. EC's make tacit knowledge explicit.

Any product has a set of requirements, which can be seen as an input. Mapping out how these requirements interact with each other is a way of defining feasible regions and mapping trade-offs. An example of how defining feasible regions can be seen in figure 2.5, based off works by Araci, Al-Ashaab, and Maksimovic (2016). Designing a car seat, the feasible regions were defined as:

- Max tensile strength between 350 and 550 $\frac{N}{mm^2}$
- Density should be less than 7 $\frac{kg}{m^3}$
- Material cost should not exceed £1,000 per tonne

Based on these inputs, the feasible regions and performance were plotted, and material 3 and 4 were subject for further analysis, as they both are within (or close) to the pre-defined feasible area.

Explore trade-offs by designing multiple alternatives. During ideation, several solutions to a problem are identified. Traditional companies then select the most promising concept, but this approach may be very limiting if the decision is not knowledge-based (B. M. Kennedy et al., 2014). Exploring options of subsystems by testing them in different variations and combinations makes for more knowledge and better decisions.

Combining different variations of subsystems enables trade-off data. These are mathematical relationships, abstracted and interpolated from prototype data or analyses. This investment in research on quantifiable data give better grounds for decision making. These set-based prototypes or test-rigs from which the data is gathered can be modular, adjustable and/or function specific, for more effective use of resources.

B. M. Kennedy et al. (2014) provides an example of this test-rig approach using the Wright-brothers, who were particularly effective in this regard when they designed the first aircraft ever. By identifying their knowledge gap of, among others, "the generation and application of the power required to drive the machine through the air", they realized they needed a different approach than their predecessors who spent much time and resources building a system, but only a few seconds testing the system (before they crashed). The

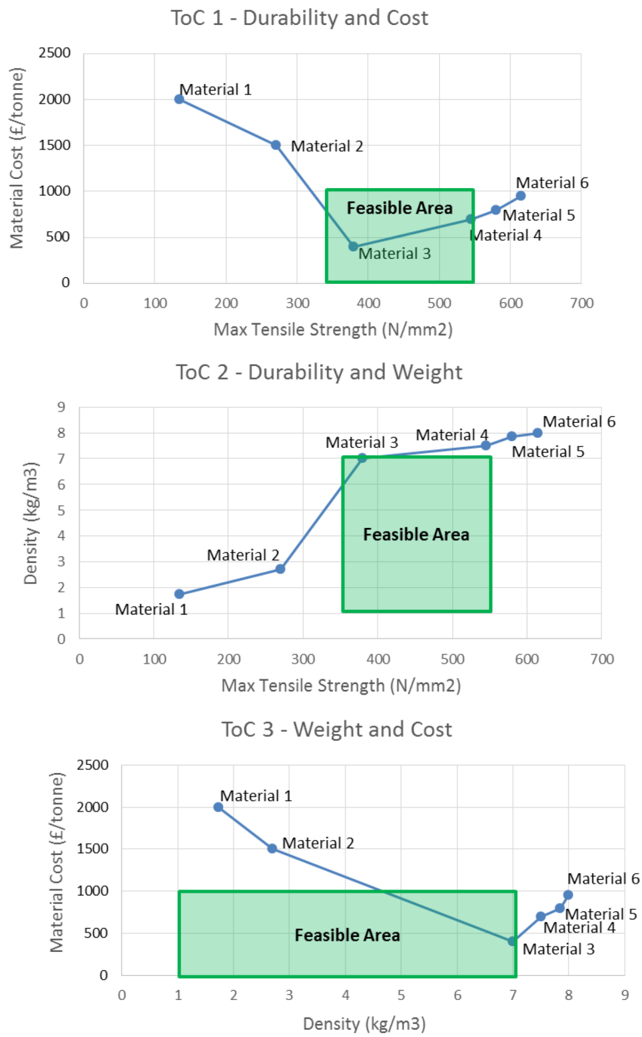

Figure 2.5: Illustration of trade-off-curves and feasible regions. From Araci et al. (2016).

Wright-brothers designed the first wind tunnel ever, which gave them the opportunity of safely testing out many different wing profiles for longer time spans, giving clear indications on lift and drag performance for the different alternatives. This approach is often referred to as test-before-design, as opposed to the traditional design-then-test approach, where a best-guess design is built and tested to see if it satisfies requirements (which gives a binary result of yes/no). Test-before-design is an excellent way of accelerating learning in early phases, as it better maps performance relative to design inputs. Design-then-test does not reveal potential noise factors or generate any kind of reusable knowledge Oosterwal (2010).

Consider figure 2.6. The materials that were evaluated in figure 2.5 have now been subject to further analysis, giving a clearer indication of performance across variables.

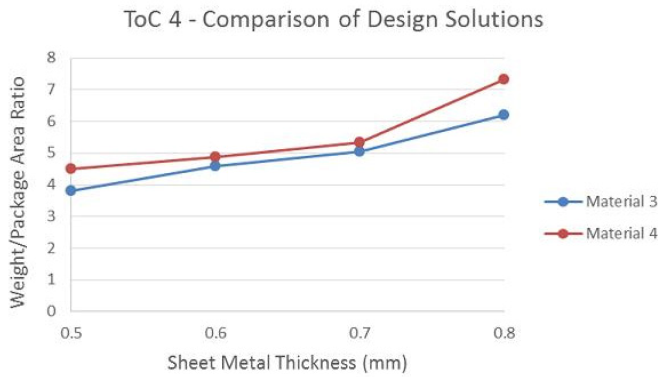

Figure 2.6: Illustration of trade-off-curves between alternative materials. From Araci et al. (2016).

This notion of designing multiple alternatives is not limited to in-house production. Toyota has shown examples of ordering 10 to 20 (in an extreme case, up to 50) different exhaust systems from suppliers to better learn effects on the system as a whole. This might be the point that is the most counter-intuitive from a traditional perspective. From a management point of view, it sounds incredibly wasteful to spend time and resources on more than one concept when only one is needed. However, the point of working in sets is to learn skills and knowledge that will be helpful in future projects either directly (actual application of concept) or indirectly (through improved learning).

Communicate sets of possibilities. Traditionally, it is normal to communicate one idea as a solution to a problem. This often leads to responses including corrections needed to accommodate needs of other departments. Iterations follow, which can lead to waste, and it leaves out other opportunities for optimization. By communicating about the ideas as sets, the engineers can carry all the alternatives through the process. This uses more of the design space. Communication is not limited to the physical design of a product, but can include trade-off curves, performance charts, etc. An example of this kind of communication can be the performance chart displayed in table 2.1. The table shows that one solution might be excellent from one perspective, but unsatisfactory from another. Examples of performance measures can be manufacturing time, weight, strength, customer value perception score, number of suppliers for sub-components, etc.

Table 2.1: This is an example matrix for communicating alternatives. Shows score in accordance to requirements. ⋆ = Excellent, • = Good, ○ = Acceptable, × = Unsatisfactory

Concepts\Functions	Cost	Size	Performance 1	Performance 2	Etc.
A	⋆	○	○	•	
B	○	•	○	⋆	
C	○	×	•	⋆	

When one functional department is communicating to another, it is important to keep the communication clear and understandable. Often simple, visual tools help in this regard. A popular tool within Lean is to formulate current status, problems, targets etc. using only an A3 paper to condense information (D. Raudberget & Bjursell, 2014). Communication should focus on transferring key issues and aim to minimize constraints.

Principle 2 - Integrate by intersection

Look for intersections of feasible sets. Similar to the meeting-time example presented earlier, a best match between the components of the system should be identified. Traditional approaches normally try to fuse individually optimized components, while SBCE strive to optimize system performance as a whole. This might that mean some subsystems are performing at a lower level than optimal, but the overall system should be more important.

Impose minimum constraint. In traditional PD, key decisions about dimensions are made early to have everyone ”on board” on what the design is. This is to avoid confusion across departments. The problem is that the freezing of these hard points eventually cause a problem because it might be constraining down the line, causing rework or sub-optimal performances.

In SBCE, decisions are delayed as long as possible. In order to enable a larger design space and increased flexibility. If a change in requirements arise from e.g. market, last minute adjustments are still possible within the set at lower costs compared to PBD.

The engineers at Toyota argue that the look of a car is more important to customers than the fact that it is 4400 mm long. They therefore retain a flexibility of up to a centimetre in vehicle hard points. Body engineers send drawings to manufacturing, with only nominal dimensions, with the request of making the parts as close to the drawings as possible. The manufacturing department makes dies, stamps out parts, assemble them and look for imperfections. The dies are adjusted, prioritizing the cheapest fixes, and the final parts are considered the ”master” parts, and the original drawings are updated to match the physical parts. The final length of the car might be 4410 mm, but this is unimportant as long as the perceived customer value is kept.

Seek conceptual robustness. Conceptual robustness means that the individual subsystems should be unaffected by changes in one another. This means that the interfaces between them are well defined and constant, but change or eliminations within each set only matters to that subsystem. This removes the need for lengthy meetings and updates on changes that the other functional departments must accommodate.

Robustness can also be achieved on component level, through robust design. This in short means designing for minimizing the unpredictable effects of wear and manufacturing variations. According to Taguchi, Chowdhury, Wu, et al. (2005), any part that is produced will have an associated variance with regards to tolerances, based on statistics and Gaussian distributions. This can lead to scrapped parts, which is costly.

Consider part A in figure 2.7. This part can be an example of a fastening interface with two holes for bolts, locking the part up in X and Y transverse direction and rotation around Z. It is important that the distance between the holes are close to nominal dimension, as an offset in e.g. the x-direction will affect the way it lines up with the holes of the matching component. If the offset is too great, the part must be scrapped. Part B in figure 2.7 is more forgiving; a variation in the matching part is accommodated while the part is still constrained in X and Y direction (by the left hole) and rotation around Z (by the right hole).

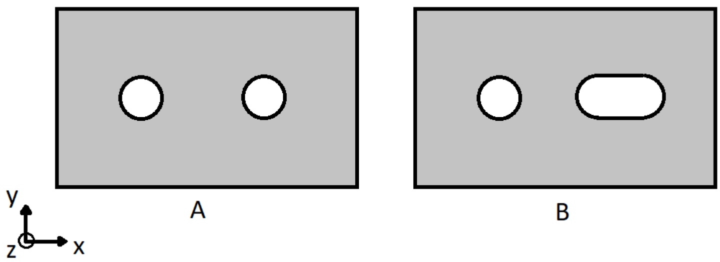

Figure 2.7: Example of constraint minimization (Taguchi et al., 2005). Part B is less sensitive to variation in production, while doing the same job as part A.

”Robust design”, ”robust engineering”, ”design for Six Sigma”, ”design for manufacturing” (etc.) are related terms and cover techniques like tolerance analysis for minimization of errors in production.

Principle 3: Establish feasibility before commitment

Narrow sets gradually when increasing detail. According to Sobek et al. (1999), the SBCE process can be viewed as a funnel, which is illustrated in 2.8. The figure shows an example of communication between design and manufacturing. Starting in the wide end of the funnel with many rough designs, the engineers aim to eliminate contenders. Large sets are difficult to manage and more designs mean more time and resources in further development. However, nothing should be eliminated before logically required to do so. This means the engineers should find logical arguments for why a design will not work. As the sets are narrowing in, the level of detail is increasing.

Stay within sets once committed. The engineers should not deviate from the set to a design outside the funnel. This may cause confusion and rework. If a new design arises,

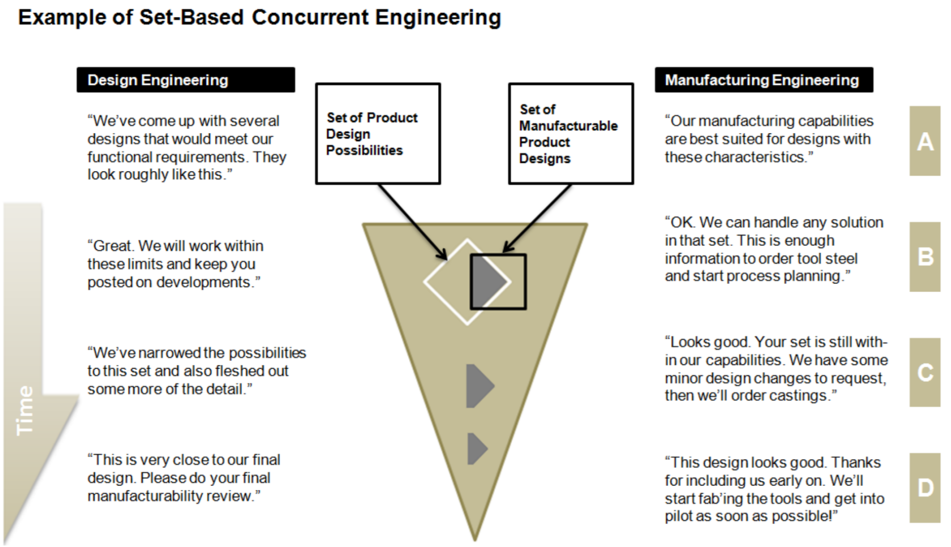

Figure 2.8: SBCE in practice. Adopted from Sobek et al. (1999).

it is evidence that the previous groundwork was not performed thoroughly, as anything outside the design space should have been proven not to work. To better make sure the sets converge to a working solution, the team can carry a conservative design. This is called a *fall-back*-design. This will by any means work, but typically does not have a very innovative side to it.

Fall-back designs are helpful for being more radical in company innovation. As set-based approaches require many ideas, naturally more radical solutions will emerge as the engineers do not stop simply when a satisfactory solution is found. Keeping a fall-back design in the set can make the engineers more comfortable in project success and more playful in their other designs. The fall-back design should be very well understood, as this is what will be chosen if the others do not make it (due to price of production, performance, likely market response, etc.).

The set-based approach enables the team to map specific areas for innovation. Particular subsystems can be focused on for improvements, while keeping the other subsystems stable or conservative. This can be communicated in the fashion displayed in figure 2.9.

Control by managing uncertainty at process gates. To ensure forward momentum, a set time is defined for when it should be finished. A typical process gate can be gates where sub-components are integrated into the system. The risk of the project should be eliminated at these gates. In automotive industry, a transmission system is among the most complex and expensive subsystems. Naturally, this is a problem that should be dealt with very early in the development process, years before launch, removing the risk of the subsystem failing. Exhaust systems, which are much simpler, can be managed at a much later stage.

If the radical designs are not thoroughly tested and understood before the relevant

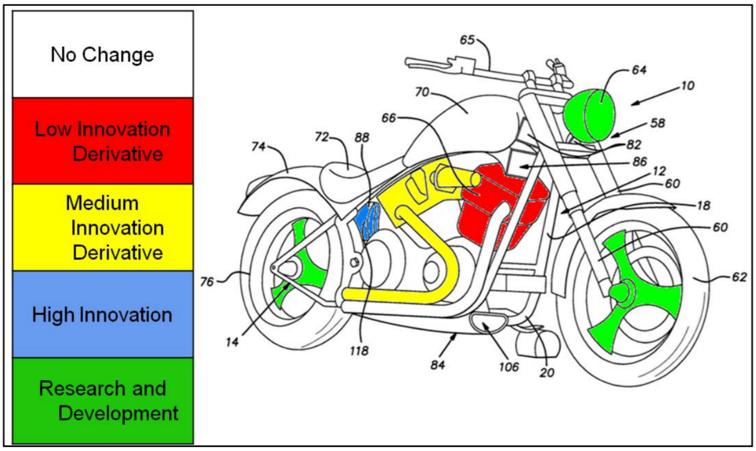

Figure 2.9: Targeting areas for improvement and innovation. Illustration from Khan (2012).

gate, the fall-back design is chosen. If, however, the engineers communicate that they know that a good solution lies within the design space, the managers should trust this and allow further development of the ideas. Knowing when to make a decision is a key skill of the project manager (or ”chief engineer”, as Toyota calls them).

Benefits over conventional models

Al-Ashaab et al. (2013) sums up the benefits of employing set-based design over traditional PBD in the following 6 points, based on the works of M. Kennedy (2008); Khan (2012); D. Raudberget (2010); Sobek et al. (1999); A. Ward et al. (1995):

- Avoidance of costly reworks in later design stages.
- Reaching optimum solutions by ensuring that all functions are involved in the design process simultaneously, and all the alternative solutions fall within the intersection of these functions.
- Efficient communication where the whole set of possible solutions is described, and where earlier communications are still valid but gradually become more detailed and precise.
- Innovation and creativity are enabled by set-based solutions, flexible designs, delayed decisions and gradual convergence.
- Organizational knowledge and learning is promoted by capturing, sharing and implementing the knowledge procued throughout the entire PD process.
- Risk of failure is reduced because of the considerable number of generated solutions.

SBD and PBD approaches are illustrated in figure 2.10. This is an analogy where the design space is illustrated by an x-y-scale coordinate system. Here it is illustrated that

SBD covers more of the design space, and is more likely to uncover all possible solutions (valid solutions being points on the x-y-scale analogy). This way, SBD can better arrive at a global optima. The PBD approach must "climb" its way to the solutions, risking stopping at only a satisfactory solution (local optima).

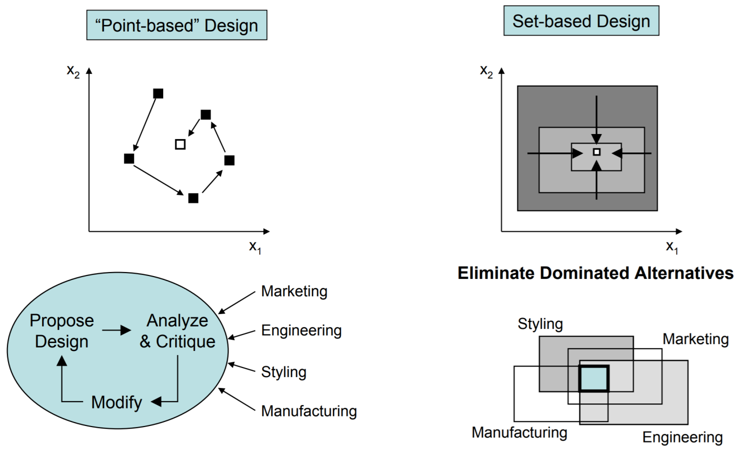

Figure 2.10: Comparing point-based design to set-based Design (Paredis et al., 2006).

2.4.3 Case studies

Evaluating the effectiveness of SBCE, we can start by looking at Toyota. Their success is evident in their world leading production numbers (OICA, 2017). Their use of SBCE is likely only a small fraction of the reasons for their immense success. However, SBCE can have helped Toyota reach their market share, as the PD process is the most influential contributor to profitability (Duverlie & Castelain, 1999). And interestingly, A. Ward et al. (1995) notes that Toyota seemed to be using around 50% fewer person-years than the much comparable Chrysler corporation in an automotive development project.

Gray, Rigterink, and McCauley (2017) presented a case study comparing two design teams designing a ship and being served changes in requirement. One team applied SBD, the other PBD. The findings display clear differences in results between the two approaches, which are presented in the following lists:

Point-based Design team

1. Design decisions largely driven by the designer's preferences.
2. Design decisions that were made early were largely set throughout the process (ship sizing and system architectures).
3. Design progressed rapidly, with iterations on detailed analysis happening early.
4. Requirements changes caused significant rework.
5. As cost requirement decreased during the experiment there was not much flexibility to adapt. Without exploration of the design space, the PBD team had to guess how to achieve cost reductions.
6. Final design was high performance but complex with high risk and lower reliability.

Set-based Design team

1. Design decisions were driven by design/analysis data, with each design decision formally documented.
2. Decision space was open until the end of the design process. Subsystem design was done before the ship was sized, leaving ship sizing as one of the last steps.
3. Design progressed slowly at first, with significantly more work done up front with lower fidelity tools to reduce the design space to a point where more detailed analysis could be performed in an economical manner.
4. Requirements changes caused no rework, and actually facilitated the set reduction process.
5. Set-based process provided the team with robust information to do measure of effectiveness versus cost goal tradeoffs.
6. Final design had high performance with lower risk and high reliability.

Maulana et al. (2017) presents a case study of application of SBCE on the development of a surface jet pump for reviving production of oil/gas in dead wells. After employing SBCE, the team had three final possible solutions. Through probability tests in the study, success rate of projects increased to 96%, compared to 33% success rate for traditional point-based approaches. Interestingly, the study also reported that the risk of having a failed design was reduced from 20% to 0.8 %.

D. Raudberget (2010) reports of the experiences of a test of SBCE in four companies, where the companies reported improvement across product cost, product performance, robustness to change, level of innovation, project risk, warranty costs and number of engineering changes. Worth noting was particularly higher scores for level of innovation and product performance. There were below average scores in lead time and development costs, but it was commented by the engineers that this was an unfamiliar way of working, which might affect result. Although the development cost were higher, one manager expressed surprise over amount of knowledge gained compared to budget increase. Finally, when companies were asked of future expectations when using SBCE, the average score was significantly higher for all categories: lead time, development costs, competitiveness and competence.

Overall, the literature shows very promising effects of SBCE use across a variety of products, both through reports from case study participants, and through more tangible performance indicators. For further reading, consider Al-Ashaab et al. (2013); Al-Ashaab, Howell, Usowicz, Hernando Anta, and Gorka (2009); Kerga, Rossi, Taisch, and Terzi (2014); Liker et al. (1996).

2.5 Identifying core SBCE elements

The purpose of the literature study was to understand what SBCE truly is, and deduce how practices that are well aligned with the methodology looks. This is important in order to know what to look for when examining companies. Based on the literature study, 8 core elements were extracted, which will be used for evaluations of performance. The elements are described in accordance with SBCE literature. The list is as follows:

- **Customer value focus.** SBCE emphasizes customer value, and it should be thoroughly understood through more customer interaction or thorough value analyses. When challenges appear in development and compromises must be done, the choices should be based on what adds value to the customer.

- **Knowledge-based environment.** SBCE promotes value-adding (i.e. knowledge generating) activities. Good knowledge management means researching parameters to find trade-off curves, knowledge retention using checklists. Decisions should be based on knowledge and not hunch. A knowledge-based approach maps the design space systematically, and knowledge capturing helps re-use.

- **Set-based design.** SBCE promotes the use of SBD and using the design space in full. At any level, a developer is set-based in that several concepts or components are considered. However, few traditional practices do not carry these alternatives longer than just the ideation phase.

- **Concurrency.** SBCE promotes parallel collaboration between functional departments. Sequential engineering is considered the opposite. The purpose is to avoid knowledge gaps and obtain optimal systems from a holistic perspective, and reduce time spent in development by doing activities in parallel. Concurrency in this regard focuses on collaboration between functional departments of development (e.g. electronics and mechanics).

- **Decision delay.** SBCE promotes delaying decisions to ”as late as possible” to keep design space open. Decisions are made on the premise eliminating alternatives based on knowledge.

- **Frontloaded resource distribution.** SBCE requires a higher expenditure of resources in order to ”fail early to succeed sooner”. A broad start is expensive, but helps in cheap learning. SBCE promotes intentionally using more resources early for this exact purpose, avoiding the expensive rework efforts.

- **Supplier involvement.** SBCE promotes supplier involvement. Including suppliers in the development project early potentially help reduce cost, as they know better what they are able to do and can shape their delivery in accordance with what the ordering company as a customer desires. This typically means collaboration and adjusting design specifically for optimal supplier compliance. This opposes traditional supplier relationships of just ordering a part based on technical drawings or one specification.

- **Manufacturing involvement.** Much related to the same aspects as the ”suppliers”-element, SBCE promotes early involvement of manufacturing to help reduce cost and lead-time. Robust engineering or design for manufacturing is also in line with SBCE.

These categories were chosen as the most indicative activities of a well-functioning SBCE system. Many of these are entangled at some level if executed correctly. For example, the more set-based the approach, the more knowledge-based the approach, as alternatives in set are likely to be eliminated on the basis of knowledge generated.

When evaluating the level of SBCE practice in Norwegian industry, the companies will be investigated for their performance in each element.

2.6 Theory on implementation

2.6.1 Propriety

Type of product

The specific product types are not extensively listed, but studies report positive effects with using it in helicopter engines, surface jet pumps, ship design, and car seats, to mention a few (Al-Ashaab et al., 2013; Araci et al., 2016; Gray et al., 2017; Maulana et al., 2017). In general, according to Bernstein (1998), set-based techniques are appropriate when a project is characterized by:

- A large number of design variables
- Tight coupling between variables
- Conflicting requirements
- Flexibility in requirements to allow trades
- Technologies or design problems that are not well understood and require rapid learning

On the other hand, point-based techniques apply to characteristics like:

- Requirements for specific technologies
- Requirements to optimize the design along only one or two parameters

- Well-understood technologies or design problems

Well aligned with these points, Raudberget reported feedback from a case study where four companies tried set-based techniques (with effects discussed in section 2.4.3). The engineers from the study said SBCE should be used "always", except in very tight schedules and where the solution is obvious 2010.

Cost evaluation

Downstream concurrency (initiating e.g. manufacturing preparations for industrialization) must be coordination in a way that eliminates waste. The troubles of rework and starvation was discussed in chapter 2, and were identified as wastes related to PD information exchange downstream. Another situation that can occur with set-based practices is duplication, which means another solution is developed. Recall the situations:

- **Rework** - Upstream gives high-precision information based on likelihood, but the final design release is likely to change, and downstream must adapt to this instability.
- **Starvation** - Upstream processes releases only certain information with (likely) low precision. Downstream process risk being idle before final design is released, because they have too little information to proceed.
- **Duplication** - Downstream pursues all scenarios communicated by upstream. Stable information.

These situations are illustrated in figure 2.11. The left a typical example of an iterative approach, whilst the right can be the result of a set-based approach. The middle one is possible in both approaches depending on the precision of the information, but is primarily related to a set-based situation in Terwiesch et al. (2002).

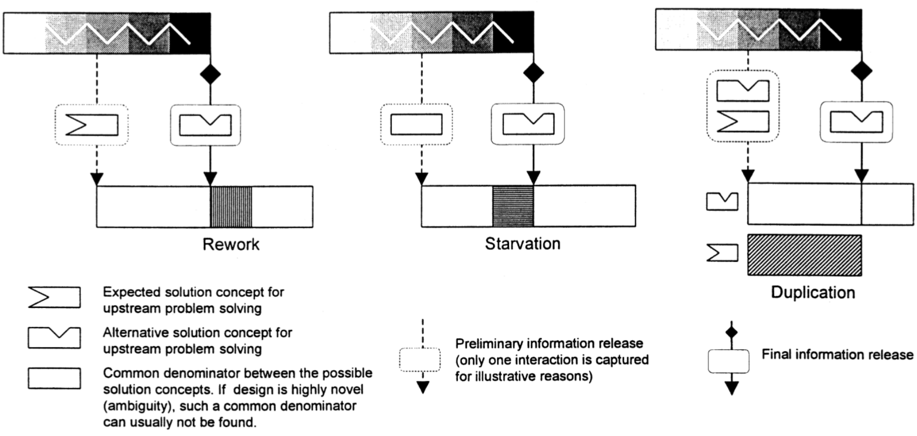

Figure 2.11: Downstream concurrency options, illustrated by Terwiesch et al. (2002).

Each of these have a cost associated to them, and whether or not an iterative strategy (risking rework) is chosen, or starvation or duplication are considered better options. Rework was discussed at length earlier, and starvation depends on workload (more things to do means less risk of starvation). Duplication means knowledge gained, but can be expensive if knowledge retention ability is low. These are the factors that come in play when choosing approach, and evaluations should be made at the start of every project, based on type of product, uncertainty, time restrictions, knowledge gap, learning potential, etc.

2.6.2 Executing the change

Adopting model

According to Karlsson and Åhlström (1996), Lean should not be viewed as a state, but as a direction. Management naturally plays a crucial role in that journey, and should focus on particularly two aspects in changing customs; establishing an awareness of the concept as a whole (and the awareness of need for a change), and the concurrency of the changing process (meaning everyone throughout the organization should be involved). Furthermore, consistency in ways of working, and sufficient time allocation for maturation is also highlighted as driving factors for success. The use of systematic breakdown of objectives and continuous materializing of functions and processes help the organization grasp it. Introducing everything at once likely leads to failure (Karlsson & Åhlström, 1996).

The PD model to be introduced should have some similarities to existing models in place, for an easier adoption. In the case study of Al-Ashaab et al. (2013) for example, the Rolls Royce team built in the SBCE principles into their already existing System Design & Integration model, which made the transition easier.

Another noteworthy systems engineering model is the V-model (seen in figure 2.12). Advanced systems need careful dissection, and the purpose of the V-model is to break down the problem into smaller pieces, finding solutions to subsystems, and then integrating these pieces in a systematic manner, verifying functionality as the system is built (Forsberg & Mooz, 1991). This is point-based by default, but is also compliant with a set-based mindset. B. M. Kennedy et al. (2014) discusses the alteration of the V-model to include a more set-based mindset on the left side of the V, horizontally aligning off-core activities to include considerations of downstream plans. This is to keep the set open and avoid the point-based and iterative nature that the V-model suggests. This keep things more open, and downstream changes does not cause rework, but rather reduces the set, all the while a familiar work environment is kept. The augmented front end of the V-model can be viewed in figure 2.13

There have been attempts at ”set-basing” the stage-gate process, which is a very common PD model, as discussed. de Souza and Borsato (2016) suggest the same approach as a standard stage-gate model, and suggests simply increasing the number of concepts to start with, and carrying more than one through the other gates. The main focus of the article in question was sustainable development rather than the mix of the two models, and subsequently the mix was not thoroughly described. The research presented positive results, but further research is advised before implementing without more regard. After all, stage-gate and SBCE are generally very different approaches (e.g. resource distribution-wise), and

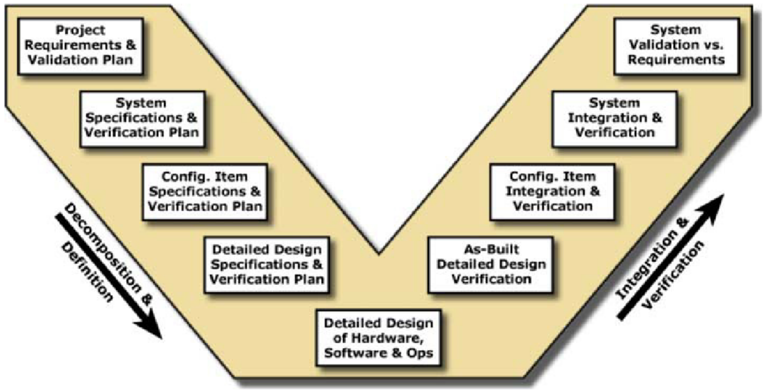

Figure 2.12: V-model. Based on Forsberg and Mooz (1991), figure illustrated by B. M. Kennedy et al. (2014).

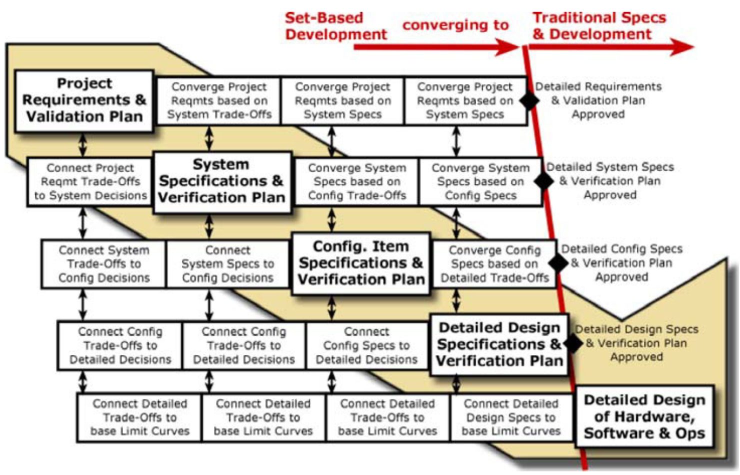

Figure 2.13: Set-based approach on front end of V-model. Illustration collected from B. M. Kennedy et al. (2014).

the transition seem trivialized in the article. In any case, the stage-gate process should be more event-driven (meaning actions result from input, rather than a standard process) for a more knowledge gap-closing focus, rather than a process-progress focus Ringen and Welo (2013). This is to enhance the flexibility required in a PD process, as no two processes are the same.

There have been efforts in creating a phase-based model governing SBCE. Khan et al. (2013) proposed a model for governing the SBCE process. A 5 step model with underlying activities was made, as can be seen in 2.14

1. Define Value	2. Map Design Space	3. Develop Concept Set	4. Converge on System	5. Detailed Design
1.1 Classify projects	2.1 Identify sub-system targets	3.1 Extract (pull) design concepts	4.1 Determine intersections of sets	5.1 Release final specification
1.2 Explore customer value	2.2 Decide on level of innovation to sub-systems	3.2 Create sets for sub-systems	4.2 Explore possible product system designs	5.2 Manufacturing provides tolerances
1.3 Align project with company strategy	2.3 Define feasible regions of design space	3.3 Explore sub-system sets: simulate, prototype & test	4.3 Seek conceptual robustness	5.3 Full system definition
1.4 Translate value to designers (via product definition)		3.4 Capture knowledge and evaluate	4.4 Evaluate possible systems for lean production	
		3.5 Communicate sets to others	4.5 Begin process planning for manufacturing	
			4.6 Converge on final system	

Figure 2.14: SBCE process model. From Khan (2012)

The model describes the phases for how a PD process in an LPD environment looks. The underlying activities have been described or touched upon to a sufficient level for this model to be understood on a superficial level without further in-depth explanation. The process is illustrated figuratively in figure 2.15.

The model is detailed in its process and systematically broken down to specific actions. It is general enough to be applied to a range of products, serving as a baseline. It was attempted in a case study where the purpose was to design a surface jet pump, and the results were positive, as mentioned earlier (Maulana et al., 2017). The case study is fairly recent, and the business implications of it remains unclear. This is implied to be the future work focus of the research team behind the study, elevating the level of business orientation of SBCE, as it currently is mostly focused on development performance.

Starting small

In accordance with the saying *"it's easier to act your way into a new way of thinking, than thinking your way into a new way of acting"*, a practical approach should be chosen. Most

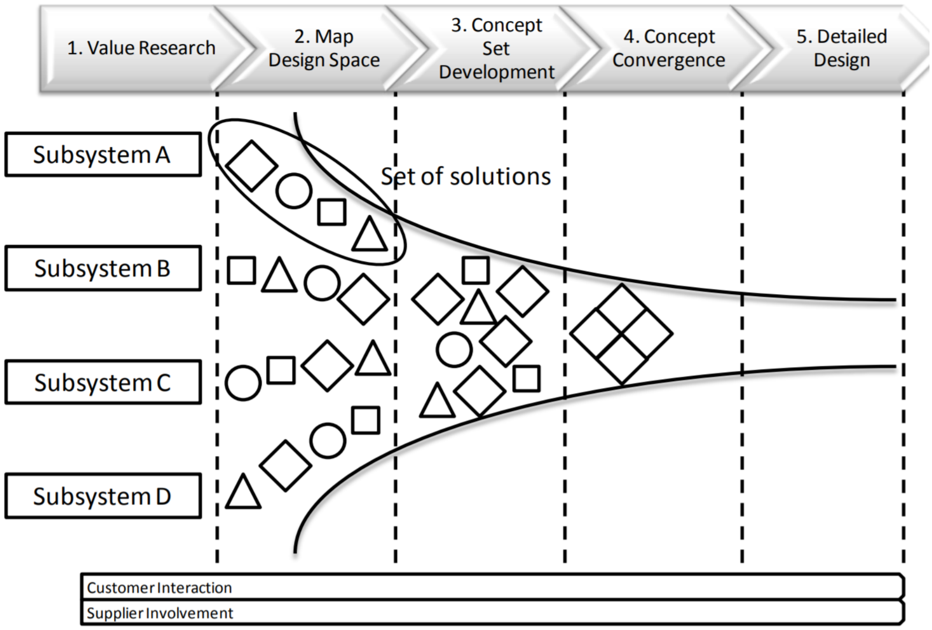

Figure 2.15: SBCE process model illustration. From Khan et al. (2013).

academic publications on the matter focus on the SBD of the SBCE, as this is what seem the most counter-intuitive from traditional practices.

Among the more leisurely approaches for introducing set-based design, we find e.g. Ström, Raudberget, and Gustafsson (2016) and Kerga et al. (2014). The former suggests an approach for ”instant set-based design” and basically uses simple methods for idea generation, evaluation of solutions, and design morphology mapping. The workshop suggests using the 6-3-5 method for idea generation (6 participants come up with 3 concepts each, and these concepts are passed to the neighbor for further development on each concept for a total of 5 times), post suggestions on wall and eliminate the ones with many weaknesses. The team comes up with new solutions based on what is on the wall, and the solutions are mapped in a morphological chart to show which solutions work together. Using evaluation matrices, the least promising solutions are eliminated again. The project concludes with identifying knowledge gaps, which form the basis for further work, should it have been a real project.

The latter (from Kerga et al.) is actually a case study comparing PBD and SBD using Lego, but serves as a light-hearted way of understanding the mindset. Four engineers in a team is responsible for a subsystem of a plane design, and by mapping out alternatives for length and width of body and cockpit (i.e. width and length of the Lego bricks), and by using customer requirement ranges, the team is able to map possible combinations and eliminate infeasible designs without consulting testing department or part-delivery (which give penalties in the game). For an illustration, the team is supposed to come up with a plane design that has room for between 92 and 109 passengers. Each point on a Lego brick can carry 3 passengers, meaning a brick with width 2 and length 6 can carry 36 passengers. The teams can choose from bricks of width 2, 3 and 4, which makes for the trade-off curve seen in figure 2.16. This immediately eliminates many options. This way of analytically sketching up the dependency of size of the plane with available materials makes for a clear understanding of what works and what does not. This is an example of the test-build-design using trade-off curves, contrary to the much more common design-build-test.

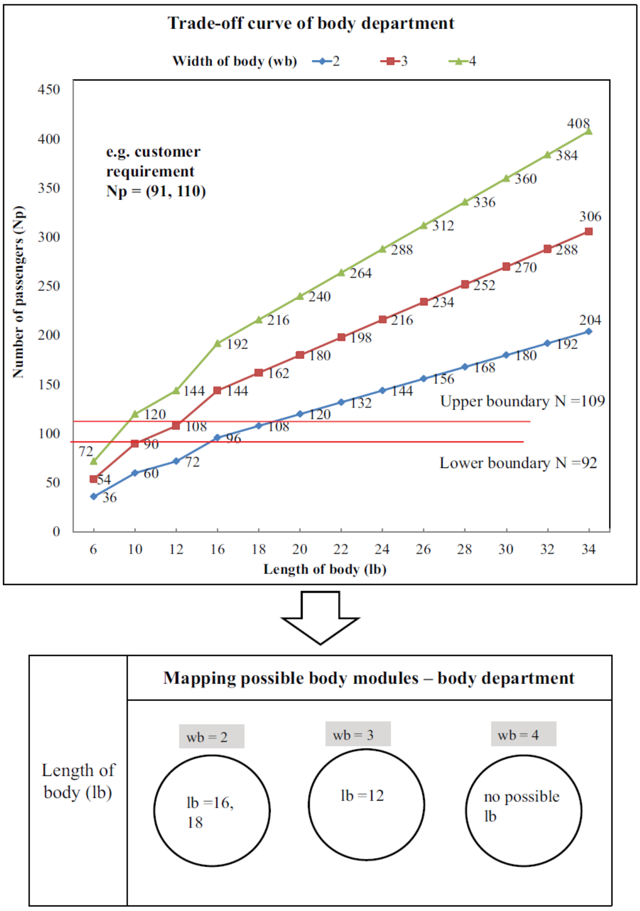

Figure 2.16: Trade-off curves in Lego plane design. Collected from Kerga et al. (2014).

These two are simple examples of how one can familiarize staff with the mindset of set-based thinking. Furthermore, changing culture of a project organization is not easy, and efforts should be focused primarily on pilot projects first to find out what works for the company Ringen and Welo (2013).

2.6.3 Barriers for implementation

At the time of writing, there exist few commercially available computer tools that directly facilitate the management of SBD approaches directly (at least that an internet search can easily show for). There are some tools that facilitate SBD, like the one used in Gray et al. (2017), where design space for ship can be explored using Rapid Ship Design Environment, a computer tool using Design of Experiments (DoE). DoE is a strategy of systematically varying variables across a collection of experiments (Telford, 2007). Work on both morphological charts and links between CAD-models and functions have been conducted (D. S. Raudberget, 2011; D. S. Raudberget, Landahl, Levandowski, & Müller, 2016). However, this seem to still be on research-stage, and not commercialized. Development of special CAD software for SBD has also been attempted, but still remain a work in progress (Inoue, Nahm, Okawa, and Ishikawa (2010); Nahm and Ishikawa (2006)). However, version control on contemporary CAD software enables for many variants within the same file hierarchy, so this problem can be dealt with using common tools.

On the more managerial side, Al-Ashaab et al. (2013) stresses the need for a common terminology across the business units. This is to ensure the right soil for a knowledge-based environment where knowledge can easily be captured, represented, and reused. Supply-chain collaboration has also been identified, which is also supported by our data.

Priority from management must be in order before new methods are adopted, according to D. Raudberget (2010). The case study in question highlights the need for stability and time. Maturation is also stressed by Ringen, Aschehoug, Holtskog, and Ingvaldsen (2014).

Another thing that can appear is the focus on the waste in designing parallel alternatives, as the developers feel it is redundant when they already have one concept (D. Raudberget, 2010). It fights their perception of how development truly *is* (i.e. a process of trying and failing).

2.7 LPD popularity

2.7.1 LPD in Norway

The closest study to prevalence of SBCE elements is that of Welo et al. (2013), which is an assessment of the relationship between LPD practices and NPD performance. The study is survey-based research. The sample of the study were companies with ”minimum 50 employees in company, having in-house product development department, manufacturing of physical non-commodity products (i.e. not services), at least 30% value added in manufacturing process, and customer specific or engineered products” (Welo et al., 2013). 258 respondents from 35 companies participated on the survey. The survey used 24 questions to assess the performance on the 6 LPD principles of Welo (2011). A Likert-scale of 1-5 was used, where 1 was ”strongly disagree”, 3 was ”neutral” and 5 was ”strongly agree”. The results can be viewed in appendix C. While the study in itself did not focus on the exact same characteristics as this thesis, some of the similar topics have been touched upon. In figure 2.17, the average score of each LPD category is shown.

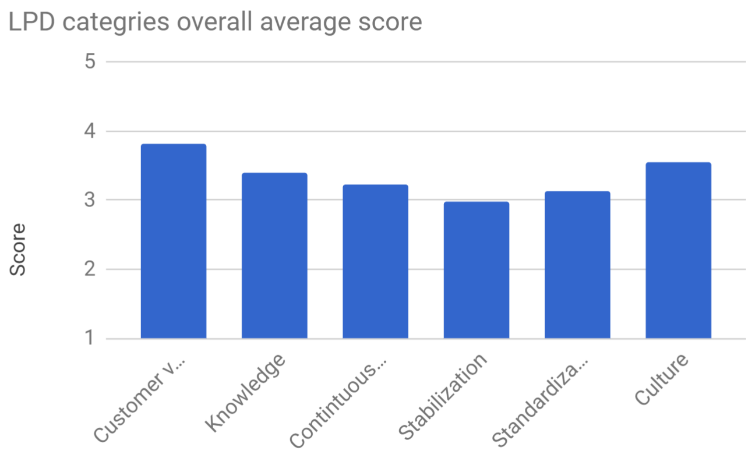

Figure 2.17: Average scores across LPD categories, from Welo et al. (2013) survey. See appendix C for full scores.

2.7.2 Growth of LPD/SBCE

Regarding the advancement of the SBCE-idea, a measure is the return on the search term in literature by each year. Figure 2.18 shows the development year by year since 1995 (when ”The Second Paradox” was published). 117 results are returned for ”Set-based Concurrent Engineering” in 2017. The graphs indicate that the number of publications each year will keep going up. The search term ”Lean manufacturing”, arguably a more well-known and established area of Lean thinking, returns 6090 results in 2017 for comparison (versus 224 in 1995).

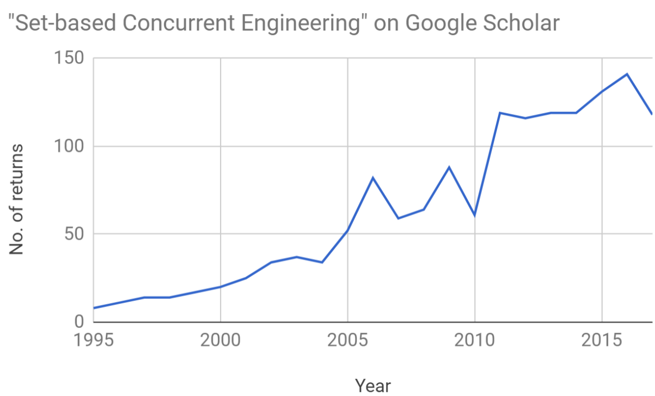

Figure 2.18: Returns for ”Set-based Concurrent Engineering” in Google Scholar, by year.

Looking at figure 2.18, we can see that SBCE plateaus somewhat, which might be explained by interchangable terms which might communicate elements of the same idea in a similar fashion for LPD environments. For comparisons with LM and LPD, The search term [”Set-based concurrent engineering” OR ”set-based engineering” OR ”set-based design”] was used, which returns 244 results in 2017. It is to be expected that it returns fewer results than ”Lean product development”, as it is a subset of the latter. LPD had 10 search results in 1995 versus 469 in 2017, and will likely be an increasingly important research subject the coming years, and subsequently the SBCE concept will become increasingly more common practice, similar to Lean Manufacturing. As can be seen in figure 2.19, LM is around ten-fold more common research area comparing to LPD. All of the graphs all have similar growth when logged, and LPD is currently at the level that LM was in 1998/99 - so approximately 20-25 years behind in commonality by visual inspection. From the same graph, it seems that the fastest-growing years have passed, but it is too early to tell.

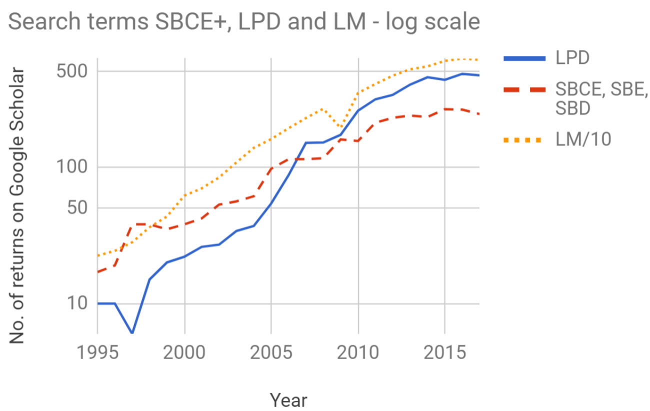

Figure 2.19: Returns for ”Set-based Concurrent Engineering” OR ”Set-based Design” OR ”Set-based Engineering” (SBCE, SBD, SBE), ”Lean Product Development” (LPD) and ”Lean Manufacturing” (LM) in Google Scholar, by year. The results are logged (base 10) and LM is divided by 10 to better highlight the connected growth.

2.8 Discussion

LPD and SBCE is still research material. The implications it has on business performance overall is still not fully understood, and experiences with implementation and use still needs more research. The potential negative sides of applying it has not really been discussed, and not failed attempts on implementation (e.g. product type incompatibility) either. The prevalence of SBCE and how it spreads is not understood either, but this study might shed some light on that in particular. There is also little on the use of computer tools for organizing an effective SBCE process, but this type of detail discussion will likely follow with the maturation of the subject. The literature is also limited on the subject of SBCE with use in e.g. electronics and software (the only considered study was that of Al-Ashaab et al. which only reports positive attitudes and impressions rather than concrete numbers).

No case studies were found that focused on measuring improvements in development lead-time related to SBCE specifically (Liker and Morgan did comment on reduced lead-time in a holistic LPD setting), despite that A. Ward et al. (1995) explain that Toyota developed products faster. Reducing time-to-market can give more profit through added time in market. On a fundamental level, PD lead time can be reduced by doing activities faster, reducing the amount of activities, or doing activities in parallel. SBCE promotes reducing time spent on non-value-adding activities and using CE (i.e. tasks in parallel). This is why SBCE possibly reduces time-to-market, but this should be investigated further.

There have been reports of slow starts using SBCE. B. M. Kennedy et al. (2014) reports of a unpublished presentation from 2007 by D. Hein, a vice president at Nexen (a Canadian company in the petroleum sector) where the VP talked warmly about a program called 4-2-1. He required four solid models, reducing to two prototype alternatives, before selecting one final design in each new PD program. Hein reported of a dip in productivity the first 18 months when getting used to the system, but a 50% increase in productivity over a 2-year period followed. Models not used were useful for future products, the engineers were more innovative and rework decreased.

The original article from Sobek et al. (1999) defining the three principles that formed the basis of what SBCE *is* emphasizes the use of a chief engineer, or strong project manager. This was purposefully left out as a criteria because it was not aligned with the Norwegian adjustment to LPD that Welo (2011) presents (who made alterations to Morgan and Liker (2006) which also included a Chief Engineer). Al-Ashaab et al. (2013) lists Chief Engineer as a main enabler of SBCE. These perspectives hint at a dissonance between SBCE (in its originality) and Norwegian organizations.

Chapter 3

Field work

3.1 Methodological choices

3.1.1 Qualitative approach

An inductive approach was chosen for the field research, meaning that theory is generated through data (Yin, 2014). The purpose was to use the field data to find arguments for why certain companies might be more aligned with SBCE than others. It was decided to structure the field research as a multiple case study, because it was desired to analyze several companies individually to predict similar results or contrasting results for anticipatable reasons Yin (2014). This was reasoned to give the best ability to complete the research objective.

On a superficial level, the research objective provide a choice between quantitative or qualitative studies. The tasks were decided to be closer to ”examine **How** SBCE elements are present” rather than ”examine how present SBCE elements **are**”. It was formulated with an open end because practices similar to those of SBCE can appear without knowledge of SBCE as a concept. SBCE can also be introduced without the respondent knowing the name of it. Hence a deeper investigation is needed to try and uncover these potential elements, and also to try and understand where they come from. This is information that is not easily obtained through quantitative methods. It was also not clear what would be uncovered during the study. These arguments are fitting with a qualitative approach (Yin, 2014).

3.1.2 Science ideals

The purpose of qualitative research is to describe a phenomenon through how participants experience it Orb, Eisenhauer, and Wynaden (2001). A foundation for the research is the ontological (view of reality) and epistemological (view of knowledge) perceptions of the researcher, because these perceptions can influence conduction of the study (Savin-Baden & Major, 2013). The extremes of ontology is realism (distinction between how the world actually is and our human perception of it) and idealism (reality is how we interpret it to be) Ritchie, Lewis, Nicholls, and Ormston (2013). On the subject of epistemology, Ritchie et al. (2013) argues for two main stances: Positivism (social science is governed by strict and predictable laws in a similar manner to natural sciences) and interpretivism (social world is not governed by strict regularities). The research was conducted on a basis of idealistic interpretivism. In other words: The respondents hold the truth, and the reason for why they see or do things a certain way is subject to an influence of social context.

3.1.3 Semi-structured interviews

Exploratory research was chosen for the case study, which is typical for a "how"-question (Yin, 2014). This can be done in-field or from desktop. Considering the lack of available resources on how the PD process is carried out in various Norwegian companies (it is in some cases a company secret), field research is a natural choice. In this domain, one can choose between experiments, observations or different kinds of interviews (Yin, 2014). Considering the time constraint related to thesis work (20 weeks), interviews was deemed a well-fitting way of extracting much information from a large set of selected informants.

The chosen method for data collection in field was semi-structured interviews. In this interview form, a protocol is followed, but a researcher can ask follow-up questions to remarks made. This was so that unforeseen details emerging during the interview could be accommodated, as it was not clear what would be the reasons for why the PD process looks like it does in each case. This flexibility is important according to Yin. Here are basic attributes that are important for a case study researcher conducting interviews, according to Yin:

- Ask good questions - and interpret the answers fairly.
- Be a good "listener" not trapped by existing ideologies or preconceptions
- Stay adaptive, so that newly encountered situations can be seen as opportunities, not threats
- Have a firm grasp of the issues being studied, even when in an exploratory mode.
- Avoid biases being sensitive to contrary evidence, also knowing how to conduct research ethically

3.2 Reflections on methodological choices

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3.2.1 Ethical considerations

Ethically (from a scientific point of view), qualitative research can be problematic as it is somewhat more unstructured than quantitative research, and therefore harder to replicate (Yin, 2014). Careful considerations of validity and reliability is important, as maximizing these is important for high quality research.

Regarding personal privacy of the respondents, the project was reported to Norsk Senter for Forskningsdata[1] (NSD). NSD highlights the importance of keeping any directly or indirectly identifying data about the participants separate from the actual data, and treating this data as sensitive information. Recordings are included in this category, as the sound of a persons voice combined with specifics that emerge during the interview can be identifying, and can be compromising in certain settings.

The NTNU ethical guidelines were used and complied to throughout the project (NTNU, 2018).

3.2.2 Reflections on validity

Validity refers to the ability of the study to measure what was intended, and is subject to some dispute especially when it comes to qualitative research Johnson (1997). According to Johnson (1997), validity has 5 components:

- **Descriptive validity** - refers to correct referral of time, place and action. What was reported actually happened, and the researcher reported it accurately.
- **Interpretive validity** - refers to how well the researcher is able to interpret what is communicated correctly, and how accurately this is reported.
- **Theoretical validity** - refers to how well academic theory resonate with results.
- **Internal validity** - refers to how justified the researcher can be in reaching a conclusion, based on data collected.
- **External validity** - refers to how well the knowledge produced in this study can be generalized through replication.

In general, the researcher should have a the mindset of a detective; systematically working through data to build arguments for cause and effects and work on eliminating rival explanations until a final case is build with undeniable evidence (Johnson, 1997). This, coupled with reflexivity (the ability to reflect on potential biases coming from personal views, affecting observations or interpretations) is the basis for good research (Johnson, 1997). In general, validity was pursued throughout the project by being keeping a detective-mindset and staying unbiased.

To increase descriptive validity, investor triangulation can be used (Johnson, 1997). This means that another researcher is present in the study, confirming the observations and findings. Although this was not possible in this case (considering this was a solo project), data extracted from interviews increases the credibility of the study.

To increase interpretative validity, the participants can be asked to repeat points or answer any questions regarding matters that were unclear for various reasons, to better ensure correct interpretation. This is called *participant feedback* (Johnson, 1997). Many inaccuracies are eliminated this way.

Peer review can be used to ensure good theoretical validity (Johnson, 1997). This was done in collaboration with the project supervisor, who has experience in the field of LPD. The results of the study can be compared with other studies to look for theory replication.

[1] English: Norwegian Center for Research Data

Internal validity can be pursued using e.g. data triangulation (meaning data points with common factors are used) through including companies in similar areas, size, industry, etc. (Johnson, 1997). Not being biased in participant selection is important to ensure good internal validation (Johnson, 1997).

Probably the most problematic type of validity in this type of research is the external validity (Johnson, 1997). The research is from one instant in time; it is natural to expect product development processes to develop in the future, as companies will keep competing in ways of efficiency to keep up profitability. Many respondents will have interests in being a participant from the fact that the project contains information about academically recognized efficient PD processes. Naturally, companies are interested in learning about this. After the deadline for the project, this paper will be distributed to the companies who express interest. This may affect their PD processes, and therefore the future study including these companies will return different data than this one. Interviewing other companies should return the same results as this study, although it is important to remember how quickly ideas can spread socially or professionally through people now familiar with the methodology.

3.2.3 Reflections on reliability

”Reliability is the consistency and repeatability of the research procedures used in a case study” (Yin, 2014, page 240). By this, it is meant that a later investigator should be able to arrive at the same conclusions based on the approach of the original research design. A way of ensuring this is to make the steps as procedural as possible (Yin, 2014). Reliability is relevant in both design of the study, and in the analysis of the data. For the design, it is important to use a protocol follow this. In the analysis, it is important to present as much data as possible to back the solution up.

The interviews will likely take around 2 hours each. Between 20-30 companies makes for 40-60 hours of recorded data. Full transcriptions (based on training interview) take around 4-5 hours per hour. Full transcriptions was therefore seen as unrealistic given the time-frame of 20 weeks. The level of transcription is limited to the extraction of only the relevant quotes (relevant in that they say something about performance in the SBCE elements identified), lowering the time used transcribing interviews to around 2-2.5 hours per hour. This hurts reliability in that not everything is transcribed, but that of relevance is still included.

3.3 Data collection

3.3.1 Interview guide

The interview guide was designed so that it was easily identifiable whether or not the company employed elements of SBCE (identified in section 2.5). The following questions about the companies were raised as relevant to the research objective:

- Do they develop many prototypes/alternatives?
- Do they systemize innovation?

- Is there parallel work on systems/production/suppliers?
- Are trade-offs explored?
- Do developers have a clear perception of customer value?
- Are suppliers/manufacturing involved at early stages?
- Are decisions purposefully delayed?
- Are decisions knowledge-based?
- Is the PD-process front loaded?
- Do developers employ engineering checklists or something similar?
- What is the origin of current system?

These questions formed the basis for the shaping of the interview guide. These were the types of questions I wanted answers to, but the guide was designed with mostly open questions (with occasional yes/no with the intention of asking participants to explain further if anything of interest appeared). The interview guide in itself was not presented to the respondents, but indications of topics for questions were included in the invitation. The full interview guide can be seen in appendix A. A training interview was conducted and areas for improvement were evaluated (this data point was not included in main dataset).

3.3.2 Finding and approaching respondents

The type of companies considered were discussed in section 1.2. Relevant companies were found through:

- Previous knowledge
- Information gained from friends, professors, other companies
- Websites of industry clusters, Lean forums, local newspapers
- Job postings
- Google maps
- etc.

The companies were chosen within somewhat defined geographical areas so the research was more practically possible. Companies closer together allowed a higher number of meetings in a day without too much travelling.

The companies were researched through their webpages, and if they seemed to be a company with development in-house, they were contacted by phone. A pre-screening was conducted, to see if they were in line with requirements. After a discussion with the potential respondent(engineer with experience from development projects at the company in question), talking about what the study is about and what it means to be a respondent, an email with an official invitation to participate in the study was sent (seen in appendix B). Correspondence could go three ways; either an appointment was decided, the invitation was declined, or replies would stop.

The study did not require the participants to be familiar with SBCE from before. The attached invitation document contained a very brief introduction to SBCE, but this was however not seen as something that would affect the responses. A potential pitfall would be that the respondents felt they did things ”wrong” and would emphasize the areas where they did things ”right”, but this was disregarded, as there was simply too little information in the invitation to get a clear overview of the methodology, and have this shape responses.

To enhance the value gained from the interviews, it was decided to visit companies for an in-person interview. This way, it is easier for the participants to illustrate or demonstrate certain aspects, or show relevant facilities. Phone or video correspondence is limited in fidelity; body language and facial expressions can be a lead to more or higher quality data, as one is better at ”reading between the lines” when nonverbal communication is part of the picture (Knox & Burkard, 2009).

3.3.3 Interview

During the interview, the respondents were asked to give a presentation about themselves, the company, and their PD process. Questions were asked during this introduction. If information was not answered, the interview guide was consulted (see appendix A). The guide was not necessarily strictly followed in the sense that the questions were formulated as written, but served as a directory of relevant topics and details. The order was occasionally mixed up, depending on what the participant had already talked about.

The information from the respondent was recorded with a voice recorder when appropriate and consented to. A notebook was used in some exceptions (typically when touring production zones). Using the recording device, it was easier to focus on cues from the respondent. Immediately following the interview, I recorded myself summarizing the information gained in the preceding meeting. The recordings were then used to write down quotes in a document, so it was easily accessible for a deeper analysis later.

The duration of interviews was dependent on the quality of answers. Some companies had presentations containing relevant information handy, some could illustrate processes when prompted, and some also gave a tour of production and office facilities. The average length was about 78 minutes, excluding tours and discussion on phone.

After the interview guide was sufficiently answered, a brief introduction of SBCE as a concept was given by the interviewer, as to initiate a discussion on a more concrete level whether or not this was something that was familiar to the participant and whether or not this would work in the company in question. This was done to clear up misunderstandings and to briefly discuss perceptions on how it would work in their company.

If there was a need for clarification or interesting details had been left out or was not available at the time of the interview, the person was contacted by phone and asked to provide these details.

3.3.4 Reflections on field research

The project was carried out in best efforts to keep a high level of quality through conscious use of techniques and mindsets already mentioned (e.g. detective mindset). Keeping an open and honest mind is important to avoid confirmation bias.

The questions were not necessarily in order and questions were not necessarily formulated identically each time. This was due to the conversational element and comfort of the participant in the interview. The meaning behind the questions were reached equally across the interviews to a satisfactory degree, so reliability is still in order.

The sensitive data was treated in alignment with NSD guidelines. The names of the companies interviewed have not been disclosed to anyone unless specifically stated, without prompt, that I should feel free to do so. No description of operations, products or other other information that can be perceived as company secrets have been discussed with anyone except the project supervisor. Any additional Non-Disclosure Agreement (NDA) have been agreed to upon request. The data presented in the thesis is formulated in a way that is disconnected to specific companies, to make it impossible to identify any company-specific details about their processes.

The participants were recorded only when clear consent was given[2]. The transcribed data was stored on a password-protected Cloud-system. The notebook was kept in my backpack at all times, and recordings were stored securely on a personal mobile phone. After project conclusion, the sensitive information will be anonymized (deleted), in accordance with NSD guidelines.

As this was a qualitative type of research, and what was going to be discovered was unknown, this hurt many chances of extracting numerical data. The respondents had very different circumstances and perceptions, making most parameters hard to normalize for across the sample. Connections and important points could be discovered halfway during field research, and if ten training interviews had been conducted before the study instead of only one, the interview guide would likely include more questions.

[2]No direct quotes from company 2 or 3 were used for analysis, only field notes. This was due to confusion with NSD rules at the time.

Chapter 4

Data analysis

4.1 About the data

4.1.1 Size

85 companies were approached, approximately 50% carried a dialogue, 29 interviews were conducted and 25 ”data points” were considered valid. Some interviews had more participants, so a total of 31 engineers were interviewed in the 25 companies. According to SSB (2018b), 19616 person-years are doing something related to R&D in Norway, of which 34% are connected to industry. Counting development engineers in the companies I talked to, one can say I was indirectly in touch with around 600 development engineers, which makes for around 9% of the relevant pool, given that they were working full-time with development-related activities. However, many reported that they spent time doing other things than development as is likely for their employees as well, so the sample size is likely smaller than 9%.

SSB (2018a) reports 15205 companies related to ”Industry” as a category in Norway. 41% of companies nationwide reported some sort of product innovation within the period 2014-2016 according to SSB (2018c), which makes the 25 companies in this study around 0.4%. The big difference between the engineer-estimate of 9% and the company-estimate of 0.4% is likely due to the relevant companies for this study generally being of mid- to large sizes (startup-companies are included in the SSB-report), and ”product” is defined more broadly (including e.g. IT).

4.1.2 Invalid participants

4 companies were removed from the dataset after the interviews. The reasons were as follows:

1. Company no. 6 was removed as it was a PD consultant, which in hindsight was considered too different from the others in that consultants are service providers.

2. Company no. 9 was removed as they developed products that were not ”concurrent” in nature.
3. Company no. 11 was removed because the interview was unfortunately cut short, too much data was missing, even for a phone interview.
4. Company no. 25 was removed because it had recently transitioned into a software-only company.

Admittedly, case 2 and 4 could have been avoided if a more thorough pre-screen was conducted, but they were hastily contacted after cancellations, and fit with the time and location when out in field. The 25 companies included were considered to benefit from SBCE, from my point of view.

4.1.3 Normalizing the data

The dataset is very broad. Although they all fit within what was described in the scope, very big differences in e.g. new product launch frequency, production-series sizes and the types of products made it difficult to normalize. The respondents individually hold their own perceptions of their surrounding environment, which causes a variety of responses.

In order to normalize the data in the best possible way, the companies were ranked on a scale of one to five in each of the SBCE core elements, based on what they answered. It should be stressed that this is used for a simplified representation compared to the very complex picture drawn from qualitative investigation of 25 companies. The evaluation should be used in conjunction with the qualitative data.

Discreet scales were used, but a scale with a higher resolution could distribute the companies more. This size of scale suffices for the indications of companies scoring low, average, or high on the SBCE evaluation.

The company demography can be viewed in appendix D.

4.2 Data presentation

4.2.1 Evaluation scheme

After collecting the data, company practices were compared to core components of SBCE identified through literature. The companies were ranked on a scale of 1-5 according to alignment with SBCE practice, with 1 being no alignment and 5 being very much in line with SBCE literature (Toyota would score 5 on all). This evaluation scheme was used to better get an overview over promoting and constraining factors by looking at common factors between similarly performing companies. The factors evaluated can be found in table 4.1[1].

Not many knew about SBCE from before, so although some might score low does not mean they perform badly in development. They might use a system that is well-functioning, although not resonant with SBCE. It is unfair to rate their overall performance

[1]The elements can be said to be truncated forms of *customer value focus, knowledge-based environment, degree of set-based design, concurrency, decision timing, resources, supplier involvement,* and *manufacturing involvement*.

Table 4.1: SBCE elements evaluated and score indications

Element\score	**1**	**3**	**5**
Customer	One specification	Some dialogue	Full inclusion
Knowledge	Best guess	Some level	Thorough
SBD	Point-based	Some level	Full concepts
Concurrency	Over-the-wall	Some discussion	Concurrent
Decision	Early decisions	Somewhat	As late as possible
Resources	Backloaded	Even	Frontloaded
Suppliers	Build to print	Seeking input	Cooperation
Manufacturing	After design	Seeking input	Concurrent

based on something that they have not heard of. It is also important to note that SBCE does not carry a patent for e.g. early research or delaying of detailing.

4.2.2 Evaluations

The evaluation results are presented in table 4.2, and average score is presented graphically for each company in figure 4.1.

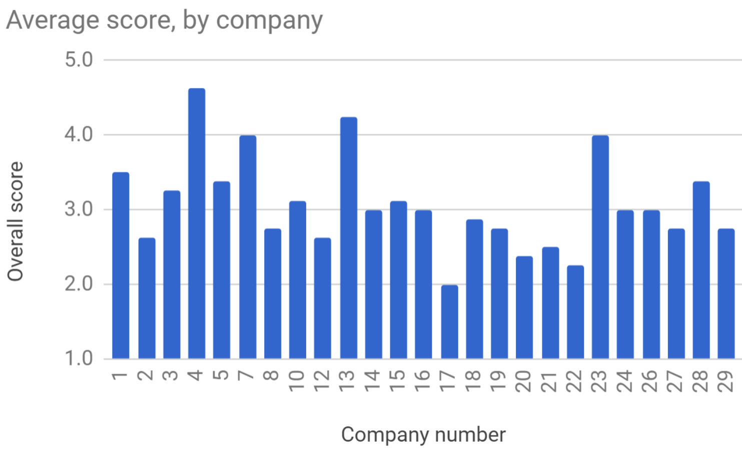

Figure 4.1: Total SBCE-score of each company

4.2.3 General performance in Norway

The average score on the SBCE evaluation scheme across the 25 companies that took part in the study, the average score was 3.08. The median was 3.00. The distribution of the scores can be seen in figure 4.2. From this, we see that most companies actually are sub-average, and reading of the average and median, it is clear that the graph is slightly left-skewed. This means that there is a slight indication of a low numbers actors performing

Table 4.2: Performance of Norwegian companies in elements of SBCE

Company No.	Customer	Knowledge	SBD degree	Concurrency	Decisions	Resources	Suppliers	Manufacturing	**AVG**
1	3	4	2	4	4	3	4	4	3.5
2	4	2	3	3	3	1	1	4	2.6
3	3	5	3	3	2	5	2	3	3.3
4	4	5	5	4	5	4	5	5	4.6
5	4	3	2	3	4	4	3	4	3.4
7	5	4	4	4	4	4	3	4	4.0
8	2	5	4	3	2	3	1	2	2.8
10	2	5	2	3	2	2	5	4	3.1
12	1	4	1	4	2	1	3	5	2.6
13	5	4	4	5	4	4	3	5	4.3
14	3	4	1	4	3	3	3	3	3.0
15	3	3	3	4	3	2	3	4	3.1
16	4	4	2	3	2	3	2	4	3.0
17	2	1	2	3	2	1	2	3	2.0
18	2	3	1	3	2	4	4	4	2.9
19	1	4	3	3	3	3	3	2	2.8
20	4	2	1	4	3	1	2	2	2.4
21	2	3	1	3	3	2	3	3	2.5
22	2	3	1	3	2	2	3	2	2.3
23	5	4	3	4	3	3	5	5	4.0
24	5	4	1	3	3	1	3	4	3.0
26	3	4	1	3	2	4	4	3	3.0
27	2	4	1	4	2	2	3	4	2.8
28	3	4	3	5	3	3	2	4	3.4
29	2	4	2	3	3	3	3	2	2.8
AVG	3.04	3.68	2.24	3.52	2.84	2.72	3.00	3.56	3.08

more in-line with SBCE (raising the average), and that the majority performs under 3.00 (which is the midpoint of a 1-5 scale). This indicates a certain entanglement between the factors, meaning the elements are applied together. This is, however, a small sample.

Following will be an analysis of the overall score of the SBCE elements. The analysis will be based on the graph displayed in figure 4.3. The purpose of this analysis is to find which elements are well-developed, somewhat developed, and not well-developed SBCE practices.

Three elements were noticeably above-average; ”knowledge”, ”manufacturing”, and ”concurrency”. Among the average scoring elements were ”customer value” and ”suppliers”. The element that scored the lowest were ”degree of SBD”, ”delaying decisions” and ”resource distribution”.

Figure 4.2 and 4.3, combined with the promoting and constraining factors found through pattern matching (in the following sections) will be the basis for discussion in the next chapter.

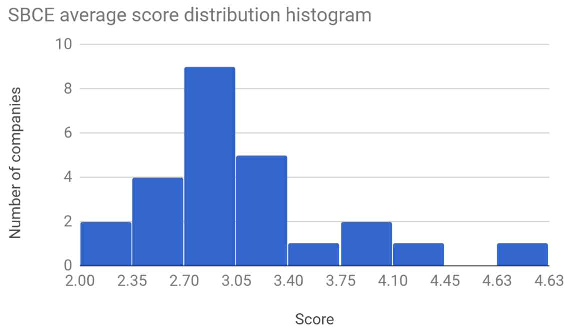

Figure 4.2: Score distribution histogram.

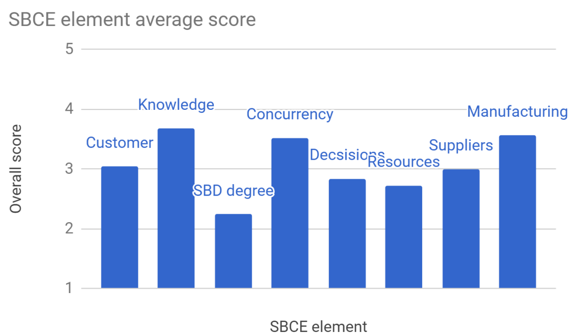

Figure 4.3: Total score for each SBCE element across all companies.

4.2.4 Pattern matching

The purpose of the evaluation scheme was to highlight the alignment of PD practices and the SBCE elements. To complete the research objective, it was necessary to look for factors that promoted or constrained elements of SBCE in the companies. The evaluation scheme made it easier to look for connections, as the data was a lot more structured and clear.

Companies with similar performance were analyzed further, looking for connections in interview data. This type of analysis is called ”pattern matching” (Yin, 2014). The recordings of the interviews were listened to several times, and relevant quotes were noted down according to relevant tags that were predefined. The topics of interest could emerge after listening to an older recording after a new one, as newfound connections could appear.

Table 4.2 and figure 4.1 will be the basis of the upcoming analysis. The results are presented in an honest way, keeping with NTNU’s code of conduct. For a closer rendition of what was actually said and bring interpretation closer to an outside observer, low inference descriptors like quotes were used in the data analysis to make clear points (Yin, 2014). This was to increase the validity of the analysis. The only layer of interpretation is then the translation from Norwegian to English (as the interview was in Norwegian but this text is in English), so great emphasis was put on finding the correct words for correct translation.

The promoting factors identified were:

- Exposure
- Growth
- Levelled organization
- Market tempo
- Certifications
- In-house production
- Modern tools

The constraining factors identified were:

- Instability
- Internal discord
- Developer isolation
- Limitations of current PD model
- Strong project-mindset
- Resistance to change
- Product type

The factors and basis for this analysis is presented in the following sections. When ”some companies” are mentioned, it is meant between zero and three companies. ”Several” are in the range of three to seven, and ”many” are more than that. These are approximate values.

4.3 Promoting factors

4.3.1 Exposure

By ”exposure” it is meant contact with the ideas of SBCE and LPD, through research, academia, consultants, or similar. Among the companies who stated that they knew about SBCE as a concept, were companies 4, 14 and 28. Out of 25 respondents, that makes 12%. Company 4 had learned about it through higher education, in ”market-oriented product development” courses, where they studied PD practices in big firms like Toyota and Phillips. They had also recently started a project of implementing Lean overall in the organization, with the help of a consultancy company, and this led to doing more development activities in parallel.

Company 14 and 28 stated that their knowledge of SBCE came from involvement from a research institution that researches knowledge-based development. They initiated the research through applying for grants using their cluster-collaboration. Being in the same industry cluster (i.e. same location) with close proximity to a research institution led to the exposure.

The respondent at company 8 also reported practices well in-line with SBCE, despite not knowing it by name (although the company was known to have collaborated with NTNU on the subject of LPD). Their exposure to LPD has shaped their PD, which show practices well in line with SBCE:

> *When we for instance want a power source, we can investigate 3-4 different ones where we don't know which one is best. If two solutions are technically equal, the next discrimination is on price and availability. (...) We've seen the need for more demonstrators in tests. So even though it costs a little extra in the beginning, we get it back in the end.*
> - Company 8

Company 7 (respondent not familiar with SBCE, although they scored high in almost all elements) believed that the origin for their practices might come from a mix of Lean, defence industry, industrial design and ISO-processes.

4.3.2 Growth

Growth was identified as a promoting factor for establishing a more systematic PD model, often in line with SBCE.

As we can tell from figure 4.1, company 4 scores high overall. They explained an approach of running thorough checklists on new projects, spending time researching unclear matters or new technology, involving both suppliers and manufacturing early, asking for sets of components and creating adjustable prototypes to make trade-off curves for better understanding of performance. They expressed a familiarity to SBCE through exposure in higher education and their recent Lean organization initiative. They explained that the reason for making the PD more Lean was because of growth:

> *We need more structure now, as we've grown to be over 20 people in development. And we're not producing 2000 units anymore, we're producing 20 000. The government wants more documentation too. We just need a well-functioning system.*
> - Company 4

Another well-performing company is number 7, who had a detailed process in place. They had experienced a tough market in the maritime industry, and renewed themselves with their own products in a new segment. The growth they experienced following their innovation led to a need for more systematic thinking. Consider the following quotes:

> *We've made our own internal handbook where we can make notes on suppliers for being "fast but expensive" or "slow but cheap". We also have instructions on how we work on CAD-models. We hired a couple of engineers at a point, and they didn't know why we did things the way we did, and so we saw the need for a manual. (...) We want to describe the process of using it from the perspective of the user. It's good for the engineer to not only look at the specification. This is actually a software-phenomenon, but we figured it fit us too. We have an industrial designer here who is very focused on the design process. We have taken some concepts from Lean. There are two or three here who have taken courses, and one used to be an instructor. Debrief sessions and improvement board are among what we are using.(...) Our process is based on reviews. System requirements review, defining what you want on a system level, getting the customer involved. Preliminary design review answers this, and it can be up to 8 different designs. Before critical design review, we make demonstrators and try and eliminate designs. After that is production readiness review, and that's when the documentation is made. These reviews are the same as in defence industry, so we've been inspired by them through collaboration.*
> - Company 7

Growth is mentioned as a motivation for establishing a system, and the other quotes are examples of how they are thinking, and indications of what they have been inspired by.

There were respondents who expressed similar desires for a system, often connected to growth. They had become too many for what the current system could handle. Company number 12 increased their revenue by 60% in two years before plateauing, and expressed frustration over lack of process:

> *Growth is our worst enemy. (...) We've always used Microsoft Excel. We have no smartness in version control. We're implementing new systems now, but it's heavy work. (...)* ***Q:*** *Do you actively put more resources in the start of a project?* **A:** *We're always a bit behind. We have a tendency to underestimate the need for documentation. That means we have less resources*

in the early phases, and the exact same thing happens in the next project. You make mistakes. ***Q:****Why doesn't that change?* ***A:*** *We've just grown and haven't had the time to get processes in place.*
- Company 12

The critical numbers for where a systematic process is needed seems to be around 50 people in the organization, and 5-6 engineers in development, according to the following quotes:

> ***Q:****Do you have a model you follow in PD?* ***A:*** *Well, in the concept phase we've been strict on keeping it free of formality. Working freely is important to us. That's both bad and good. It's harder for the bigger projects. When we're 1, 2, 3 people, it's fine. When we're 5, 6, 7 it's getting hard, because then the communication must be managed internally. We have a way to go in making that process more efficient.* - Company 24
> *50 and 100 are magical numbers when it comes to size. If you are under 50, you can maintain overview mostly based on relations. You remember the name of everyone, know where people work and what they do, and you can keep a daily dialogue. Exceeding 50 makes for the need of a system. You need more levels in the organization, but you can still do with relatively simple stuff. If the organization grows beyond 100, you need formalized processes. You don't have capacity to monitor everything without one. It's a trade off. If you are fewer, more knowledge is concentrated in the people, and you are at a larger risk overall. But your gain is higher.*
> - Company 10

These viewpoints were strengthened by company 5:

> *We're 45 people and growing. That's the hardest place to be, because when you're 20-30 you're just a small company, but it is problematic being 60-70, because you need the processes of a big company. If you're 70-100, you can defend the processes again. (...) We're doing everything in CAD. That in itself doesn't solve everything. And just being more than one guy is a risk. When you're 5-6 people working in the same assembly, you have to be very careful in order to avoid components colliding. Sometimes you have to move stuff and just get the domino going.*
> - Company 5

Several companies that were very reliant on oil price used their downturn to get new routines in place. The companies shrunk and are using their smaller size to be more nimble. The biggest recent drop in oil price was in 2014 (although effects of shrinking margins could be felt from 2012 and onwards, according to a couple companies), leading to many engineers having to leave the relevant companies the following years. Company 13 had undergone a change in process already, as they are a direct supplier to the oil and gas industry, and had already started their growth again. Company 13 performed well overall. They said this about their change (and also mentioned exposure):

> *We've had a big project throughout the company on improving the organization. We've tried to find areas which we can make more efficient. We've reduced waste, activities that doesn't give anything. (...) We had an executive that said we're going to be as good as Toyota. Maybe that's where the processes come from.*
> - Company 13

Some of the other companies are sub- or sub-subsuppliers to the oil and gas industry, and were currently at a low point (or had recently passed it) in profitability when they took part in the study (company 2, 16, 21, and 29), and expressed interest for new ways of thinking in development, saying they were changing things up. The average score of these companies were 2.72 on the SBCE-evaluation.

Company 1, 18, 22 and 24 (also reliant on oil) were well into development of new products for new markets (averaging 2.91 overall). 1 and 18 (averaging 3.20 overall) had also undergone changes in the PD model, focusing more on structure now than before.

4.3.3 Levelled organization

A levelled organization where everyone had an equally valued opinion promoted higher scoring values in SBCE elements like ”concurrency” and ”manufacturing involvement”.

Many respondents said that they had a very open culture with absence of hierarchy, and believed this was special to Norwegian culture, comparing themselves to countries whom they had interaction with. The competency seems to be pretty evenly distributed, with generally a high level of knowledge in engineers, as company 22 states:

> *A big advantage in Norway is FEA. Here, everybody does it. In Poland, maybe only one person is doing it. Then he does his job and sends it back. It's slow.*
> - Company 22

If pay-grade is an indication of which level they are in a hierarchy, engineers are conversely higher up than skilled workers in that perspective. However, this seemed like a non-issue in the firms interviewed, as they very often humbly sought input from production. Company 10 is one example:

> *Production is most definitely involved. We try to reduce the lead time in production. We also try to maximize what we can get out of the steel, and discuss design for assembly. We walk around and drink coffee with them. We have the same break room and a running dialogue.*
> - Company 10

On the same note as for manufacturing, most companies have found the value in working in parallel across functional departments, distributing power to many decision makers. Having many decision makers helped projects ”flow” through development more easily and thus cutting lead time. Working in parallel (i.e. concurrently) helped reduce the lead time even more. No company scored below 2 in ”concurrency”. Consider the following quotes as examples for views on concurrency and decision-making:

> *We often win contracts on getting faster to market. I think we have more efficient methods for working here in Norway than they do in Germany, for instance. There's a short distance to decisions here.*
> - Company 8
> *Toyota and Lean are positive examples of how Japan is. What surprises me with Japan is how little initiative there is in the individual. Everyone is really scared of doing a mistake. Norwegians don't care if we make mistakes.*
> - Company 20

How the employees are situated affect the level of cooperation. Many of the higher scoring companies in the concurrency element said they had open office areas or an open-door policy:

> *We are pretty synchronized in the process. We're sitting in an open office solution and discuss stuff there.*
> - Company 24

It was believed by many that the Norwegian mindset is pragmatic in nature, which strengthens the notion of distributed decision making. Company 4 had a very close connection to Sweden (they had several Swedes in development, close cooperation across border) and stated the following;

> *I used to work in a different company up until very recently, and I can clearly see a difference in culture. Maybe especially in development, as the Swedes are a lot more production-minded. They're really good at it. Norwegians are more innovative and solution oriented, but without a lot of structure. The Swedes are more organized. You need a system in Sweden.*
> - Company 4

The respondent came from a mostly-Norwegian company, and could clearly see a difference. The pragmatic attitude was also shown in comparison to Chinese suppliers, as company 17 states:

> *We have a project where we probably are buying some things from China. We thought we could include them a bit in development to see if we can agree on something that is OK production-wise and cost-wise. It's challenging though. They're not used to it. They are used to being served drawings and asked "how much will this cost?". They are really eager to send test-series, no problem, but they need all the drawings first. That made us consider other suppliers, but it's too expensive.*
> - Company 17

The last part of the quote from company 17 shows a constraining element in price hunting, to which we will return.

4.3.4 Market tempo

Company 4 has already been presented as a company employing many SBCE practices. They mentioned time-to-market as crucial for success in their industry. The company was subject to ever-changing government requirements, and subsequently needed a high frequency of new product launches to stay compliant and competitive. When this was identified as a ”next step” in business development, an initiative for improving the process and establishing a better system was put in place. They explain:

> *We want to compress the PD-process. Even though numbers are pointing upwards, we're behind in sales. The market life of the products we sell is short. If we are late to market relative to when the need for the product is identified, we lose money. We're trying to get more of the cake. (...) We've had a Lean-project because there's been a negative reputation internally on the PD process. We're taking too long. We've had consultants teach us what to do, but now it's on us to pull it through. (...) We want to do more of the phases in parallel to reduce time in development.*
> - Company 4

Company 27 explained a similar reasoning behind their concurrent practices:

> *We might move towards a different way of executing projects. We recently worked on a project where short lead-time was critical, and instead of doing things in order, we did things in parallel. You had some designers do their thing and tested it immediately in the shop without any verified information. You made an assumption and adjusted after testing. It worked very well time-wise. It's hard to evaluate the resource-use, because we don't have anything to compare it to.* ***Q:*** *But how did the resource-use feel? Was it efficient?* ***A:*** *We felt that we got to market quickly, we could charge a high price, and we've earned good money on it.*
> - Company 27

Although the situations for company 4 and 27 are similar, 27 meant that the example presented was executed as said simply out of necessity from product-specific market circumstances in a one-time occasion. They were unsure if the resources spent was done efficiently or not, but they did ensure success in the market.

Company 1 also practice something similar, where they have realized which parts take the longest to make. Starting on these and freezing them early limits the design possibilities, but cuts the lead time.

4.3.5 Certifications

Certifications work by showing that the company complies to a standard. The certification bodies have different types of influences (very often product safety standards), but some also affect internal organization processes. A common type of certification for this is ISO. ISO is an independent non-governmental international organization setting standards for operations within manufacturing, technology, etc. The purpose is to ensure safe and reliable products of good quality across borders. The organization sets standards in which inspectors test compliance with at companies applying for certifications. If compliant, the company is ISO-certified, which works as a quality statement (there are several variants of ISO-certifications, but only the general idea is what is relevant here). Over the years, the standards have started to include development processes as well, with the purpose of minimizing errors and reducing wasteful activities. One example is a mandatory ”lessons learned” session post-project, in which the team has to document what went bad and what went well in a project. Another example is computer directory architecture. Company 1 says their ISO-certification has helped systematize their work:

> *We have one who came from [Swedish automotive manufacturer] who works as a technical and quality manager in production, and he has helped the whole main office to a new level when it comes to the ISO-process and taught us the methodology. I think we could have developed space ships with that guy. With that process, it simply slides through.*
> - Company 1

ISO-certification serves as an outer motivation for establishing a structure. ISO-certified companies generally said their certifications improved their processes, including recording of knowledge. However, there were some occasional deviance from the intention of the certification, as 15 states:

> *We are ISO-certified, and it's not hard documenting lessons learned with our type of development. But you have to put in useful stuff, and you have to be able to access it again. We're struggling to make that work.*
> - Company 15

When discussed with, many of the respondents agreed that recording things learned seem on the surface to be a good idea, but it comes with the price of time. Most companies operated with several projects per engineer (possible instability, to which we will return), meaning post-delivery operations like lessons learned is not prioritized, much less writing down arbitrary information about which bearings they used. Especially when there is no system in place for what information is recorded (high risk of noise) and no standard procedure for extracting relevant information, it is not perceived as value-adding.

Current ISO-certifications requires ”lessons learned” to be saved in project folders. This means that ISO does not require establishment of a central hub of knowledge. Some companies have already started this work on their own, just through realizing that the information is available. Company 7 has a ”best practice” document that started as 2 pages and is now on 60+ pages through the intent of standardizing processes (mentioned on page 52). Company 12 has also started thinking about knowledge documents:

> *We have a ”best practice” document. We are also using checklists for market, sales and logistics. Have we checked everything? Is it probable that development will succeed? Is this high-risk territory? Does it fit with our type of development? Lots of things. That's part of a gate, before it goes to a checklist that we have everything ready on design requirements and so forth. (...) Lessons learned was connected to each project individually earlier, but*

> *in the last year we started gathering it outside of project folders. We've also agreed with [department in another country] on a format that is a bit more streamlined.*
> - Company 12

Many companies who reported knowledge retention practices started with this through certification processes, this is why it is considered to be a promoting factor overall.

4.3.6 High levels of complexity or risk

The data show that high levels of complexity or risk promote more systematic processes, which promotes several SBCE elements (e.g. knowledge, SBD). Company 7 develops products for high-risk operations. They have standardized their PD process, and argued that developing only one solution is not aligned with their approach, as is evident through this quote:

> *We have our process that allows making demonstrators. You're supposed to think broadly. We're not the right company if we're asked only to make one solution. That's not us. You come to us if you need development. (...) We reduce risk, that's what we do.*
> - Company 7

Related to this, company 13 and 23 are both connected to an industry where failure can be catastrophic. Extensive documentation is required to show that risks are considered and mitigated, and naturally a more detailed process is followed to make sure everything is covered. This makes the companies score higher on "knowledge". They both stated other several important points; Transparency with the customer, heavy inclusion of manufacturing to avoid nasty surprises, evaluation of several concepts (often using decision matrices or similar). Company 23 is considerably smaller than company 13, and said they were influenced a lot by their customers, explaining that their thorough approach was an industry norm.

Company 13 have higher complexity in their products and almost ten-fold the amount of engineers, and naturally had more extensive structure compared with company 23. Company 13 described something similar to the V-model, discussed in section 2.6.2.

Company 14 and 21 also used the V-model as their method of choice, neither of which were performing very well overall on the SBCE evaluation scheme, but this might have to do with their types of product. More on this in section 4.4.7.

4.3.7 In-house production

Seen in appendix D, 15 companies had manufacturing facilities on the same location as their developers, and scored on average 3.93 on the "manufacturing involvement" element. 7 companies had manufacturing in the company on a different location with an average of 3.43, and 3 companies did not have dedicated manufacturing in company and averaged 2.3 on emphasizing manufacturing input. This indicates the strength of having manufacturing in-house from an SBCE perspective. However, the sample was small, and 3 datapoints should just be treated as indication (not final evidence). Most of the companies with in-house production said it was ”simply natural” to discuss things over with manufacturing:

> *We're always trying to think ahead. (...) often times, the designers can encounter a problem like ”can we machine it this way?” Then it's really helpful talking to the manufacturing guys. We have defined hubs we talk to, specialists in surface welds, machining, turning, coating, whatever. These guys know how the processes work in detail. Then we ask ”can we make it this way? This is only my thoughts, what do you think?” That's the main advantage of having manufacturing on the same location as the engineering-office.*
> - Company 13.

Several companies named the ability to deliver fast as one of their primary competitive edges, and connected this to their in-house manufacturing. Having the opportunity to talk to production workers and get instant feedback, and possibly ideas for improves manufacturability, is well in line with SBCE. Often times in these companies, production is included in development meetings. General consensus said disagreements between the two sides of engineers and skilled workers enabled products in the end. One of the companies without a dedicated manufacturing department said:

> *We only have a few guys with experience from manufacturing here. If they walk out, we have nothing. Then we just have to trust the manufacturers we hire, but they have their own interests. I think it'll be a huge problem in Norway in the long run, moving manufacturing abroad. We're losing our competency.*
> - Company 22.

Robust design/engineering was mostly an unfamiliar concept (by name) to the engineers interviewed. Many reported that they have learned first-hand what was good design principles for e.g. manufacturing, so at some level robustness was consciously included in development.

The companies who actively used their manufacturing department said this was linked to their levelled organization.

4.3.8 Modern tools

Several of the older engineers interviewed said that the onset of modern technology (tools for analysis, more sensors in machines) had enabled more knowledgeable decisions. Companies 3, 10 and 19 had a routine of building a prototype system, or a research rig if you will, with similar components to what following products for sale will have. They used more advanced components, for instance stronger motors, to collect data on a bigger range. This gives indications of performance of the company's products. This is explained here:

> *We build a prototype that's more advanced in all directions. Gearboxes and servomotors are filled to the brim with sensors today. We run it for a year and log everything we can data-wise, and we get a good grasp of performance. We used the right components, only more expensive. That's something we've*

> *started with, now with the onset of Big Data.*[2]
> - Company 10

Communication tools have also improved over the years. This helps against knowledge gaps and increases concurrency. New communication tools are particularly useful for firms of bigger sizes. Company 13, having around 100 engineers, states the value of standardizing communication:

> *We've found better ways of handling requirements and communicate in development projects. When you have 8-10 people on a project, a big question is how you communicate minor and major decisions during concept development. We've used Office 365*[3]*, for example. It's a nice way of "tasking" others. Before this, you could risk missing important decisions when you were home with a sick child, for instance. Now you can see action lists and live-transcripts during the meeting, so you can follow what's going on.*
> - Company 13.

However, the computational tools are not perfect yet. Company 8 points out limitations with simulations:

> *The simulations aren't perfect. You can't control every parameter, so you have to do some assumptions. (...) Simulations can tell you lots of things, but the answer doesn't show before we've tested the system.*
> - Company 8.

Knowledge of both the limitations and potential of the tools is important in the "knowledge-based environment"-element of SBCE. Company 5 has had situations where CAD only told parts of the truth:

> *You have to build 1:1 models. You can go completely blind in CAD, no matter how many mannequins you put in there for scale. (...) We've had cases where everything looks good even in reviews, and when you're standing there with parts in-hand, you have no idea how you're going to do it.*
> - Company 5.

The use of more advanced modern tools (CAD is considered baseline) used in tandem with tests helped companies score higher in the SBCE knowledge-element.

4.4 Constraining factors

4.4.1 Instability

The most common response to why faulty decisions were taken was "time". This manifested itself in unstable working environments. The respondents told of a pressure on

[2] Big Data is a contemporary trend in business development, referring to the vast expansion of data analysis opportunities. The ever-shrinking computers have enabled more memory for data, and better, smaller sensors enables collection.

[3] Office 365 is a software from the Microsoft corporation with modules for e.g. project planning/handling, and communication.

developers from surrounding environment to deliver swiftly. This pressure can come from e.g. customers demanding short delivery times (through e.g. sales department using time as a negotiating element), engineers having to spend time on customer support, or the company has a culture of rushing through and rely on problem solving as they go along.

The following quotes show examples of reasons why time is limited and therefore become a constraint:

> *Very often it's time that is limited in early phases. We can see we really want to do more analyses, but we're playing ball with the customer, and you know that the customer is probably talking to someone else just after talking to you. There's constant competition.*
> - Company 24

> ***Q:*** *Are you considering more than one concept during development?* ***A:*** *No.* ***Q:****Why not?* ***A:*** *I don't know. We don't really know for sure what works. Even though you get a bright idea, it might not be the best solution. We're focused on things going fast. We don't evaluate more than one solution. It has to do with culture, and short developing time. Get things done. But we do experience a lot of rework.*
> - Company 22

> *Customer support on existing products can interfere. If something is supposed to be done in a year, you don't tell the customer you'll talk to them after that year has passed. Then it's easier to move delivery.*
> - Company 21

> *We have examples of things going wrong in manufacturing, that we actually can't manufacture a part, for instance. The production method wasn't good enough.* ***Q:*** *How could you have avoided that?* ***A:*** *Well, we could recognize that this part could be complicated. People here understand that, but it's hard to take up. (...) We have examples where we've hadn't had enough time before agreed delivery. We squeeze together things in development to make the timeframe as compact as possible. That's typically when we don't pay attention to these things. (...)* ***Q:*** *How do you want the resource distribution to look?* ***A:*** *Ideally, we want to use enough time on the pre-project research, but we usually don't have unlimited time or people available. But when we don't spend enough time on that phase and we start the project regardless, I'll promise you we'll exceed budget in both time and money.*
> - Company 19

Following is a quote from company 28, a company that said they are actively using knowledge-based development as their method of choice. There was, however, a dissonance between saying and acting. Most often their designs were best-guesses. This really shows that it is not easy to change to a fully set-based system, even when educated on the matter, due to lack of stable working environment:

> ***Q:*** *What makes set-based difficult to execute?* ***A:*** *I think it's time pressure from the customers. And when we have the possibility, we don't have the*

initiative. Often you have an idea or understanding about what you are going to do before you're pressured, but then you don't have the resources. You need the customer to get the resources, but that's when you see that you don't have time for it.
- Company 28

Even a high-scoring company like number 7 experience trouble regarding lack of time, and end up having to spend more time and resources because of it:

*Having two demonstrators can make things a bit less streamlined, because you want to eliminate one of them. So you continue testing. That can hurt the timeline. (...) Sometimes you have to make a choice to get on with it. But you can choose the wrong interface, and things can go wrong in manufacturing, and you just go "f***, I should have gone for the other one".*
- Company 7

Company 17 was the unfortunate company that received the lowest score. They had recently undergone big changes in company structure and was still trying to find balance. Parts of their trouble connected to this was being 4 engineers in development, where an unstable environment kept key players having to return to non-development related activities, and this led to the hiring of development consultants. This can lead to worse performance in knowledge retention. Being few also stops the process from being more structured. Company 17 explains their situation:

We are 4 people working with development. But if we're developing something new, it's hard finding the capacity to do so. Much of my time is spent in management and fixing stuff, and we have another guy who do a lot of testing. (...) When we're making new products, we use consultants.
- Company 17

Not having enough engineers available at project start can hinder proper frontloading of projects, as company 15 explains:

Q: *How does the resource distribution look?* **A:** *Ideally it's pretty flat. When developing slows down, the same guys go into test and integration. It's hard to ramp up in early phases, because we don't have people sitting around waiting.*
- Company 14

SBCE practices require stable environments, and not allocating enough time for the process is one way of inhibiting SBCE elements. Lack of stability potentially affects SBCE practices in all areas. Instability is an example of a negative effect of "market tempo". High tempo can lead to good practices, but not if the environment is unstable.

4.4.2 Internal discord

Internal discord refers to misalignment of expectations between management and developers. This typically led to lower scores in the "resource distribution" and "delaying decisions" elements.

The general expectations by engineers working with development is that failure is part of the process, as company 16 explains:

> *Rework is part of development. It's highly unlikely you hit the nail on the head the first time. It's part of the job. It's not a goal not making mistakes, because we learn from the mistakes too.*
> - Company 16

This is an excellent example of the mindset in most companies interviewed. They said it is impossible to know everything, and you want to try something to test the frontiers of innovation, and this is why mistakes happen. From a perspective outside a PD process (like from management), it is very hard to imagine all the problems that can appear.

The management of a company decides how much resources are to be given to each project, and there often is a dissonance between how much is given and how much is needed for a comprehensive project. Infinite time and resources would be ideal for developers, but management naturally has to limit budget. Company 17 experiences this:

> *I have an example from a meeting not too long ago, where we went through the budget of a development project. We had to use legal help for something, and these lawyers cost several thousand kroners per hour. Management didn't think about it. Later, when we move on to the engineering consultants, who might charge 1400 kroners per hour, a discussion appears on why the engineers need so much time. They don't get what they do, they think they are only drawing drawings. Maybe it's because they are doing something tangible, I don't know.*
> - Company 17

Many developers experienced this type of lack of understanding between them and management. Even when management sees better results, lack of time and resources remains a problem. After a brief explanation of what SBCE was about, a respondent replied the following:

> *The logic is sound. It's very easy to see that it gives advantages, because you'll take decisions based on more information. But it's extremely difficult getting the organization to put heavy resources in early. Getting the top levels of corporate and finance in on that idea is really, really hard. They will rather have us quickly get a rough concept up so that we can show potential customers. (...) But we do see that the times we do go broader, the rest of the project is a lot swifter and we do fewer mistakes. But even then, it's a battle.*
> - Company 15

The quote from company 15 is similar to that of company 19 earlier (under section 4.4.1) as well, that despite going slower returns better results, there is a tendency to keep doing things the same way as before (i.e. over-loaded, unstable). Company 12 strengthens this notion:

> *Management says the current type of situation is only for a 2-year period, then it plateaus and gets better. It never happens.*
> - Company 12

Company 12, as explained under section 2.7.2, has experienced rapid growth, and the engineers feel over-worked. Company 12 jokingly said they had always been "Lean" in that they had always been too few developers.

4.4.3 Developer isolation

Aligning operations internally can be difficult on its own, but there is even a greater discord between external actors, like e.g. customers and suppliers, and the developers. Company 19 has a distance between developers and customers:

> ***Q:*** *How are the customers involved?* ***A:*** *They are distanced from us. They should be included a lot more. (...) Even though you have a specification, you're not really sure if they really want what is said. They could have just said something during a meeting, but after thinking about it, maybe it wasn't right after all. Often you have a trade-off between properties of the product, but you can make the wrong choice of focus because you don't talk to the customer.*
> - Company 19

This distance is also relevant in relationships to manufacturing and suppliers. Generally, suppliers are naturally in touch with developers, but the type of communication matters. Just ordering something based on a drawing can give surprises, as experienced by company 28:

> *We have some examples where we messed up, not asking how things can be done. It ended up being incredibly expensive, low quality product with long delivery time. They came to us after and suggested an improvement. We've learned from this, so now we ask first.*
> - Company 28

Even when the price has been communicated from suppliers, it can cause problems:

> *Suppliers are a risk. We can get a price estimate and go for it, and when we are paying it costs 3 times as much. At that point, it's too late to do anything about it.*
> - Company 5

The use of suppliers was divided. Some had realized the notion that suppliers were knowledgeable and could provide valuable input (some even used them almost as consultants on more advanced products like e.g. motors). On the other hand, many were reporting that price is what mattered the most (in most cases), and often simply ordered what they had worked out they needed. It depended on what was practical for the different companies, and the type of product in question. Most reported that they had at least two suppliers on each type of product, so as not to be too dependent on one. This is a common strategy for risk mitigation, as because if the one supplier that the company relies on goes out of business, it can be an unpleasant surprise. It is also to avoid one supplier becoming too comfortable. Company 7 explains their standpoint on suppliers:

We are aware of the concept of ”playing your suppliers better”, but we are more focused on ”shopping” a bit.
- Company 7

The majority had mixed practices, depending on circumstances, and scored 3 on the evaluation scheme. SBCE promotes actively seeking knowledge about design space (i.e. what the suppliers are able to do) and customer value, and the top scoring companies had supplier involvement as a strategy.

4.4.4 Limitations of current PD model

Related to the ”internal discord” section, management can suggest sub-optimal processes for development. For example, company 19 is developing products in an environment with lots of innovation happening. The maturation of product the product type is ongoing, growing in acceptance, but is still competing with a traditional form of product. A few years ago, they were bought by a big actor in the traditional products segment, and they experience a pressure from corporate level on how to shape their PD model. The respondent in company 19 shares their view of their model:

Stage-gate works really well if you know the market and product. If you know what you are working with and what you are making; it's familiar landscape. But if you're going out in either new market or technology, there's a challenge.
- Company 19

Company 17 has experienced something similar:

We have forms and stuff that you are supposed to fill out and a manual for how things are supposed to be at the different gates, but when I look at them, I don't feel the forms cover what you should cover. I don't care about them. I also think it just weighs down the progress.
- Company 17

Company 15 also experienced limitations in their model, despite it generally working fine. Consider the perspective of 15:

There are weaknesses in our model. We are now in a system phase where I know that, in two months, the product is not going to be like we've described it now. It's stupid spending time on it. We have some main concepts we need to find out if works before we design the rest of the system, so it doesn't make sense doing that job first. The systems architect has done exactly what our document says, but the model demands something that shouldn't be asked for at this point. It's worked nicely for other projects, just not this one. Unfortunately, there's no room in the system for breaking that process.
- Company 15

In the ”delaying decisions” element, none of the companies scored 1 (argued through almost all solving concepts on a rough level before starting detailing). However, many were still reporting a need for everyone agreeing on what they were doing before moving on. Having to decide something for the project to progress is the general perception. This is similar to rigid PBD stage-gate thinking processes, which company 16 uses:

> *We have contracts in the transitions between the phases. Each phase has its own delivery. Project schedule is made and commented. Then the project manager, technical sponsor and marketing sign and say that everything is done and that they are happy with the transition to a new phase. This is to avoid the risk of getting far into the project and someone saying ”why didn't we do it like this?”, on material or processing being different. This way, everyone is sure how we are developing it. And when you develop, things change, so you are sure that everyone developing are up-to-date. It's important to us to get everyone onboard from early phases.*
> - Company 16

The current system of PD model in the companies could also be limited in ability to estimate cost, which nearly every company said they struggled with to some degree. Sometimes it is just hard hitting the nail on the head, as the following companies explain:

> *Ideally we invest a lot in the start of a project, but when you get to delivery or test, the cost goes up anyway.*
> - Company 13

> *It's hard to estimate a project this big cost-wise. You can have an idea, but might have to multiply by pi.*
> - Company 29

Finally, some respondents answered that that they intentionally kept the PD process unstructured, to encourage free thinking. There was a concern that a system would replace innovation.

The PD model of the companies could affect scores in all SBCE elements, depending on their experiences.

4.4.5 Strong project-mindset

Related to ”developer isolation”, another problem with a distance between development and sales can be the focus of the sales department to satisfy the customer on specifics based on very strong project approaches. This one-off focus can hurt standardization (knowledge-building) efforts in the development department. Company 22 delivers exclusively project-based products, each time specific for the customer in question:

> *When standardizing, you can look at different solutions, spend time and choose the best. It's not a good idea going with the first thing you come up with that seems to work. We're not thinking about the consequences. (...)* ***Q:*** *What made the approach like it is today?* ***A:*** *It's a combination of many things.*

> *Sales department, maybe some of the old engineers dictate a bit, especially this project-focus. Sales do everything they can to sell. Rather than adjusting it to something we've done before, they adjust it specifically to the customer.* ***Q:*** *How much is the sales department affecting what you do?* **A:** *Close to a 100%. They sell it first, and then we develop it.*
> - Company 22

This project-focus was familiar to several of the companies producing small-series or one-off products. Company 1 had their own way of moving around the problem of project focus from the sales department:

> *In order for the products to be as flexible as possible, we have to be really thorough when we are making a design specification. This is to avoid that we're making something specific for that particular customer, and having to do something similar next year, but all over again. Sales know that the broader the design specification is, the more expensive the product is. They try and make a narrow specification, and they're good at it. But then we in Technical have to think "what is it that they actually want?"*
> - Company 1

Here, company 1 talks about internal discord, i.e. misalignment between functional departments. The strong project focus removes the ability to form knowledge through standardization.

4.4.6 Resistance to change

Many companies explained an inertia in humans, hindering continuous improvement (relevant across all elements). Company 28 is familiar with how set-based thinking should work, but still experience trouble:

> ***Q:*** *What do you think is the reason why you do what you do, despite having a system that is supposed to work against that exact problem?* **A:** *I think it's ignorance. The process gives you a good overview, but it doesn't run deep enough. The development process isn't generalized enough. We kinda know what we want and how it'll work. We don't want to look at everything else, after all we know what we want. It's old habits.*
> - Company 28

This attitude is common in development. One knows what is to be developed, and does not acknowledge the need to spend time on other things than that one solution. This human inertia also affects changes in working environment. Company 8 describes a slow acceptance of new practices:

> *We've had a Lean-project on the electronics-lab too. There wasn't much enthusiasm in the beginning, but it's been very beneficial. Most think it was for the better now.*
> - Company 8

A related problem is to this human inertia is a personal investment in concepts, and a reluctance to ”kill your darlings”. Several companies explained that a bright idea can make the engineer believe in it so much that letting it go, changing the perception of what is believed to be the solution becomes hard. This promotes a ”best guess”-approach. Company 28 explains:

> *Another problem is that sometimes when you've chosen something, you stick with it. You get an inner conviction that this is right. Ownership. And you can't admit it doesn't work. We've had examples where we work several months on a cool idea, before just giving up.*
> - Company 28

They explained that it became increasingly hard letting go the longer the project was kept alive, as more and more fixes were put in, common for a PBD approach.

4.4.7 Product type

Company 14 chose specifically *not* to use set-based practices, despite knowing about it. In a department of 100+ engineers, they had found their system of choice to be the V-model. More engineers constitutes a need for a system, and for them, the V-model worked fine. They considered set-based to be unnecessarily expensive for their application. They meant that the solution was too obvious mechanically, and was focused more on the software and electronics. They explained their reasoning like this:

> *We've had a lot of Lean influence in the company. We actually did research on it in the cluster. (...) I don't feel set-based fit us that well, because we're basically just modifying what already exists. (...) The functional groups on our new project have discussed solutions over longer periods of time, sometimes longer than desired. But it's still not set-based in that we progress with more than one solution. It's unrealistic cost-wise. We're pretty sure what the solution should be. The errors are small things that don't work, for example the supplier not providing what they said they were going to. Of course, we could have an alternative solution to reduce risk, but it's rare, and wouldn't make much difference.*
> - Company 14

The V-model was also reported to be used in company 21, who had learned about it through EX certifying bodies (safety certification for electronics in hazardous environments). Common for 14 and 21 was that the main focus of innovation was in software and how this was deployed in electronics hardware.

Company 13 described something similar to the V-model, but had a very different type of product. They were decidedly more in-line with SBCE in their mindset as well, likely because of the modular nature of their products, making different combinations of components an instinctive discussion. They had a lot more focus on the mechanical aspects of the product, which seem to promote set-based thinking, compared to electronics.

4.5 Correlations

Based on the factors identified and the connection to the elements discussed, a table showing correlations were made. This is a simplified presentation of the qualitative data, but gives an overview. The table is shown in 4.3 ”Corr” means correlation, meaning expected effect (i.e. ”corr” on a constraining factor means that the factor is constraining). ”Inv” is short for inverse, meaning the opposite effect of what is expected. For example, a high market tempo could make PD teams take decisions earlier.

Table 4.3: Correlation between promoting and constraining factors identified and SBCE elements

Promoting	**Customer**	**Knowledge**	**SBD**	**Concurrency**	**Decisions**	**Resources**	**Suppliers**	**Manufacturing**
Exposure	Corr	Corr	Corr	Corr	Corr	Corr	Corr	Corr
Growth		Corr						
Levelled organization				Corr				Corr
Market tempo				Corr	Inv	Corr		Corr
In-house production		Corr		Corr				Corr
Modern tools		Corr		Corr				
Constraining								
Instability		Corr				Corr		
Internal discord			Corr	Corr	Corr	Corr		Corr
Developer isolation	Corr	Inv					Corr	
Limited PD model	Corr	Corr	Corr		Corr	Corr	Corr	
Project-mind	Inv	Corr	Corr					
Resistance to change			Corr				Corr	
Product type			Corr					

These connections between the factors and elements are complex. Qualitative data is debatable, as respondents can give examples that have opposite meaning in the same sentence. The data presented in table 4.3 is the general impression. The matters will be further discussed in the next chapter.

4.6 Summary of analysis

25 companies have been evaluated in how well their PD processes resonate with SBCE. The evaluation criteria were how well the companies’ practice was aligned with SBCE literature in the identified core elements of the methodology: customer value focus, knowledge-based environment, degree of SBD, concurrency, decision timing, resource distribution, supplier involvement, and manufacturing involvement. The companies scored from 1 to 5 points, where 5 was top of the scale and very well-aligned with how SBCE

literature describes best practice. Performance was identified based on the analysis of interview data.

Overall performance of the sample across all elements was investigated. The elements were divided in well-developed, averagely developed, and low development areas. The developed areas were manufacturing, concurrency, and knowledge. The average scoring areas were customer value and suppliers. The poorly developed areas were set-based, decision delay and resource distribution. Degree of SBD returned the lowest score of 2.24.

Next, the overall score of each company was investigated. The average score was 3.08, and the median score was 3.00, implying a slight left skew of the distribution (note that it is a small sample size, n=25, and a small difference between mean and median), which implies correlation in SBCE elements. Pattern matching was used by looking at common characteristics between similar scoring companies in each SBCE element and overall. Furthermore, promoting and constraining factors were identified based on this analysis. Among the promoting factors were exposure, growth, levelled organization, market tempo, certifications, high levels of complexity or risk, in-house production, and modern tools. The constraining factors identified were instability, internal discord, developer isolation, limitations of current PD process, strong project-mindset, resistance to change, and product type. A table highlighting correlations between elements and factors was made, forming the basis for discussion.

Discussion will follow in the next chapter on how these promoting and constraining factors affect implementation efforts of SBCE, in accordance with the research objective.

Chapter 5

Discussion and conclusion

5.1 Comparing findings to other studies

There are similarities in the interview data and the findings of the survey by Welo et al. (2013), which was a study done on LPD practices. From the Welo-study, ”stability” and ”standardization” are low-scoring categories, which are related to the identified constraining factors of ”stability” and ”strong project-mind” found as factors affecting SBCE alignment in this project. Knowledge as a category also performs above midpoint in both studies. A surprising find is the high performance of ”customer value” in the Welo-survey compared to the average-scoring finds of the interview data of this project. This deviation can be explained by the slight difference of perspective in the two, as this project put more emphasis on the aspect of ”Team member knows product characteristics related to customer value”. This statement was included in the LPD-survey, and scored lower than the other three making up the ”customer value”-category, narrowing the gap between the two studies.

The previously mentioned case study of D. Raudberget (2010) explained hesitation for SBCE implementation with engineers in resisting change, and also time restrictions (manifested in lack of stability), which is in line with the findings of the constraining factors in this study. The article also points out a perception of how rework is a part of development (supported by Fricke et al.), a find that is in line with the interview data.

Ringen and Welo (2013) mention the necessity of having event-driven processes, rather than a rigid progress-oriented approach. The interview data supports this claim, as there were companies who struggled with lack of flexibility in their current system.

These previous studies support the validity of the findings of the interview data.

5.2 Overall performance in SBCE elements

5.2.1 Performance partition

The overall performance in the SBCE elements in this study were divided into developed areas, mid-level areas, and low-scoring areas. The developed areas were found to be knowledge-based environment, manufacturing involvement, and concurrency. The common denominator in these is that they are related to internal relations and practices (the majority of the companies had in-house manufacturing).

The mid-level areas were supplier involvement and customer value focus, which have external relations in common. This indicates that Norwegian industry is doing well in some areas, but have room for improvement, by including up- and downstream actors more (here downstream is considered what goes beyond manufacturing). These mid-level elements are related in ”developer isolation” as a constraining factor.

The low-scoring areas were degree of SBD, resource distribution, and decision timing. What SBCE offers in these areas (i.e. what must be in order to score high in the elements) is connected to the more counter-intuitive parts of the methodology. These areas is where SBCE is the most counter-intuitive, comparing to traditional approaches (PBD, stage-gate). The reason why these areas are under-developed is likely due to lack of exposure (only 12% reported familiarity), as the counter-intuitive nature of the ideas lowers chances of appearing in isolation.

Following will be a discussion on the three levels of development. In each category, there will be comments on how the related factors affect implementation efforts, in accordance with the research objective. The promoting and constraining factors had interplay with each element in various ways.

5.2.2 Developed areas

Knowledge

The companies generally scored high in knowledge, despite the occasional internal discord and limitations in current PD model.

Norway is a high-cost country with quality as a common selling-point, as reported by many of the companies interviewed. Certifications are often important as a metaphorical badge for communicating this quality. The certification bodies, like e.g. ISO, emphasize structure and ”lessons learned” in development processes, which makes knowledge retention easier. This is one of the reasons why most companies were scoring high in this category.

A lot has happened technologically since the days when SBCE was first introduced. The vast increase in computational power has enabled many new tools. Computational fluid dynamics, FEA, etc, gives analysis of product behaviour and structural integrity. Today, it is also possible with variation in load cases or geometry, for a bigger spectre of information. This makes trade-offs easier to map, and enable a knowledge-based environment. The onset of Industry 4.0[1] and Big Data as concepts enables easier access

[1] Industry 4.0 is a term used to describe the accelerated use of automation, due to sensor and communication technology maturing. Related to Big Data, explained earlier.

to numerical data through the abundance of sensors. Several companies explained their R&D approach as making an expensive version of later products, putting lots of sensors in it and investigating the interplay between parameters. Switching components around to different combinations allowed for a different picture, and this way, they could understand trade-offs. Several companies mentioned advancement in technological tools as the biggest change over the years. Technology has also enhanced communicative tools, which affect concurrency and knowledge retention as well. The companies were generally well trained in the capacity of the tools.

Having routines for capturing knowledge (often introduced through certifications) also help enhance the knowledge-based environment. Having quality related certifications is commonplace in Norwegian industry, and this affects knowledge retention in a positive way from the perspective of SBCE.

The inclusion of practices like knowledge-based processes and the use of tools for analysis help implementation efforts for SBCE, as this is in line with the methodology.

Manufacturing

Parts of the reason why the ”manufacturing” category receives high scores have been discussed under section 4.3.7. 15 companies had in-house manufacturing, and most were emphasizing the importance of including manufacturing in the development process, and using the department as an asset. The companies reported that levelled organization was unique to Norway, comparing to e.g. Japan and Eastern Europe.

Having a manufacturing department in-house helps companies perform more in line with SBCE. However, the decision on having a manufacturing department in-house or not is a strategic decision that depends on more than just the type of PD. The most deciding factor is likely resources available, but others like location, type of product, series size, etc. matter too. The companies are not reliant on having an in-house manufacturing department to implement SBCE, but inclusion is easier this way. The important point for SBCE is that manufacturing is included, which can also be achieved in other types of organizational structures.

Concurrency

Many respondents explained that their levelled organization and informal work processes helped collaboration. Open door/office solutions where the engineers could meet on demand helped remove the need for meetings as well. Of course, too many interruptions can cause a problem, but the companies seemed happy with their open arrangements.

Market tempo also increased the level of concurrency, as the functional departments increased their collaboration. Working concurrently across functional departments are in line with SBCE practices. Concurrency was acknowledged as important by the customers to cut lead-time and increase understanding across functional departments.

5.2.3 Mid-level areas

Suppliers

The reasons for not including suppliers in development can be many: level of confidentiality, in-house expertise, type of supplier, etc. Price was often identified as the most important factor when choosing suppliers. The suppliers know more about their products than the developers using them, and some companies had realized this themselves. Not knowing what the suppliers are able to do makes for expensive parts or potential rework. The developers have to interact with influencing actors in order to make something that suits the surrounding environment.

Including the suppliers by involving them early, approaching by asking ”what can you do for me?” rather than ”can you do this?” can increase the quality or lower the prices, and keep sets open. This can possibly help build the supplier as well.

The reasons for not including were typically developer isolation or limitations of current PD model (in that they did not have it as a point in their system).

Customer Value

Only one company scored 1 on the customer value-element[2]. It comes to show that most developers have some connections to their customers, although for many it was mostly change in requirements that was the reason for contact.

The open scope of the project allowed differences in type of customer, which might have affected the company sample to score average in this element. Some of the companies produce in series directly for a private person end-user, while others make colossal one-off systems for industry. The vast majority however, reported that their inspiration for new products came from customer feedback, proving input. It was often, however, that the idea was pitched from the sales/market department who had heard something from a customer.

Many of the companies expressed frustration over time restrictions, often provoked by customers. This depends on what the customer desires; if there is a habit of getting a high-resolution prototype quickly, set-based practices can be hard, as the early phases take longer. A proposed fix is to quickly come up with the point-solution, while also working on the rest of the set. However, the problem might be moved to a point where the customer asks for an updated version, but the primary design has been standing still. Fear of this can make companies hesitate to employ new customs. One thinks about Toyota; their customers generally do not count down on delivery times of new models, and does not require a prototype before the final model. Their customers are people that only care about the final design. The private market is in this way different than contract-based development.

The demand from customers can depend on where the company is in the value chain. Being further up means downstream customers might want to test your products. Being a supplier for a company that requires these early versions can inhibit the execution of SBD, as company 28 described. Type of customer relationship in SBCE has not been addressed much in literature, but extrapolation from SBCE literature on inclusion of suppliers and

[2]The company in question explicitly said they were distanced from the customer, and noted that it was hard in their industry (maritime) to know for sure who really was the customer/end user: Shipowner, shipyard, hiring company, etc.

manufacturing, a fix can be transparency and dialogue. Including the customers also ensures heightened customer value. Karlsson and Åhlström (1996) mention the difficulty of establishing relations and maintaining them as a company, as the surrounding environment does not have it as a norm; the general approach is to find the cheapest suppliers (as our respondents also frequently replied). There is support for close collaboration on the customer side according to Von Hippel (1978), which constitutes something of a paradox, as involving a customer means the customer is involving the supplier; so this should benefit both sides.

As mentioned in section 2.3; interviews, focus groups, surveys, observation, market research, or workshops are ways of learning more about the customers and identifying value. However, the current PD system can limit the PD team in not having this as part of their process. The developers might be isolated, which hurts implementation of SBCE.

5.2.4 Low-scoring areas

Decision timing

The ”decision timing” category scored only slightly below midpoint. No company scored 1, which was due to the engineers expressing a ”natural order” when it comes to detailing, i.e. that a rough concept was decided first. This early decisions on rough concepts can, however, in some cases inhibit later design options as design space is constricted by decisions (explained in section 2.2.3).

Many said they had to decide to ”move on”, because they were running out of time. This lack of time is related to instability. One approach to deal with this instability is to load engineers only 70-80% of possible work expected in front of a week, as the last portions likely will fill up due to various unforeseen situations anyway. Company 23 experienced that spending more time planning and dividing the project into many very small activities gave them success in estimating time spent and made them encounter fewer problems. Similarly, company 29 spends 3 whole weeks planning the next 6 months.

The delaying of decisions is one of the counter-intuitive parts of SBCE. For it to be an accepted practice, there must be understanding on all levels of the organization. This is related to internal discord, and also resistance to change, as traditional practices typically do not delay decisions.

Resource distribution

Many were familiar with the notion of failing while at lower cost phases (i.e. early in the project), saying it was desired to put more resources in early on to enhance learning. However, most had to work hard to convince management to get heavier funding early for their projects. Often if the price tag is high, they get a no. That can lead to cutting the budget, impairing quality of product and losing trust from management, as they likely have to spend more than what the smaller budget said anyway, as the first draft was closer to reality. This is a vicious circle, leading to internal discord, which was an identified constraining factor. For SBCE to work, management must understand the benefits of the counter-intuitive practices. The understanding can be easier in Norwegian industry compared to elsewhere, based on the expression of benefits of levelled organizations. This helps understanding across the functional departments, which in turn can help implementation efforts.

Degree of SBD

Clearly the worst performance is in set-based practices. This is not very surprising, as the set-based mindset is probably the most counter-intuitive aspects of the methodology compared to traditional development, as discussed earlier. This is would clearly be the greatest paradigm shift when it comes to PD methodology.

Strong project-mindset hurts efforts to implement SBCE, as there is lack of standardization (which helps mapping design space). Product type also affects degree of SBD, as a software-focus is not well aligned with SBCE.

Karlsson and Åhlström (1996) emphasizes the cross-functional integration of LPD, meaning it should be understood at all levels of the organization, and the integration process should not be pressed for time. It is likely a formidable change in operations, and for it to work properly, it should be regularly discussed across functions in organization, both vertically and horizontally in an integration phase. Many of the companies are helped in that they are levelled organizations, which can indicate some promotion in implementation efforts, when these companies are exposed to SBCE.

5.3 Norwegian PD and future potential for SBCE

5.3.1 Example companies

According to my findings, the ideal company for SBCE implementation is one that is currently growing and is exposed to SBCE. It has a high market tempo, and therefore looks at implementing a system that cares for that. They already have a well-working system for capturing knowledge (likely learned through or inspired by a certification body). They have in-house production facilities and are well trained in the use of modern tools and the capacity of these. They are a levelled organization, meaning that everyone are respected equally, and they work together for a solution that works for everyone. Close proximity to a research institution that have knowledge on LPD helps for the exposure and transition. The organization is welcoming of the new system in all levels.

Companies that will have a lot harder time of implementing SBCE are those who have unstable work processes. They have an internal discord between functional departments (and management). The developers have a habit of isolating themselves from customers and suppliers. Their current PD model is rigid, and they are resistant to change this. They think in isolated projects, and do not carry knowledge from one project to another in a good way. They might have focus on innovation in a product category that is not well-functioning for SBCE, i.e. software, which promotes different types of PD approaches.

5.3.2 Reception of SBCE so far

As this study shows, SBCE is not a well-known methodology. Only 12% of the respondents expressed an explicit knowledge of it. Most of the companies were experiencing some kind of trouble with the processes they had in place and expressed interest in improving them. The companies approached were chosen due to the impression that their type of products could benefit from SBCE. Although it was not possible in the short timeframe to look at specific product processes, the impression of relevance still applies to the vast majority of the 25 companies part-taking in the study. After a very brief presentation of the subject and some discussion, some expressed skepticism in efficiency of SBCE for their application, but most were still intrigued.

There were differences in the experiences of SBCE reported in the three companies with respondents who had direct knowledge of SBCE. Company 4 had adopted SBCE, company 14 discarded it, and company 28 was struggling with implementing it properly due to lack of resources (internal discord) and old habits (resistance to change). Those who reported awareness of SBCE said they had learned about it through academic institutions. This indicates that SBCE has not matured beyond the level of research. There are still struggles with implementing the methodology (as with company 28), and fully understanding the benefits. The understanding of SBCE and the value it provides is growing (as per section 2.7.2), but it has not reached the same level of popularity as LM.

It is worth highlighting that some companies (7, 8, 13) were using many elements of set-based thinking without the respondent knowing what the concept is. A question then is if knowing more about the methodology affects approach. This is not unlikely, as a more detailed familiarity of the framework can give ideas on how to shape and elevate practices further.

5.3.3 Culture

The data suggest that the absence of hierarchy in Norwegian companies serves as a welcoming factor for inclusion of different functional departments (levelled organization), promoting concurrency. Whether this absence is unique to Norway remains unanswered. Norway has relatively small companies compared to what is described in many academic papers, where huge corporations are investigated (where a stronger hierarchy might be practical).

The company culture must accompany change and continuous improvement for successful implementation of SBCE to happen. Resistance to change was identified as a constraining factor. The culture must welcome the value of some structure, since working set-based without it can be difficult and expensive. The general feedback from the engineers was a desire for change and improvement, but they also expressed a pragmatic attitude towards structure. Old habits and strong pragmatic attitudes (as e.g. company 28 experienced) can make the organization resistant to change.

Regarding absence of hierarchy and pragmatic attitude, Khan et al. (2013) listed chief engineer as a core enabler for SBCE. As discussed under section 2.8, the point of chief engineer was intentionally left out due to the proposed dissonance with Norwegian culture, as per Welo (2011). As expected, several respondents mentioned that their level organization was important and helpful, making little room for this authoritarian figure. A question left to be answered is if the chief engineer is a very important element of the methodology, or if it was merely an observation of one practice at Toyota made by A. Ward et al. (1995), and subsequently became identified as an enabler. If the responsibility and understanding can be distributed similarly to how it is done today in Norwegian companies, not having a chief engineer might not constitute a problem, but this needs further investigation.

5.3.4 Building from here

Many companies reported that their unique selling point in a global context is high-quality, innovative products. If this should continue to be the case, efforts for maintaining that position should be in place, as global competition increases (Overvik Olsen & Welo, 2011). SBCE implementation is one suggestion that can help maintain that position.

Growth served as an inner motivation for getting a system in place. It is good timing - new employees are immediately accustomed, and the change likely costs money, so it makes sense to change when money is coming in. When these transition phases occur can dictate which systems are put in place. Contemporary research, popular models, and technology are all examples of factors that affect the choice. Many of the companies reported that they were in a growing phase at the time of writing, and considering that this thesis will be distributed to the respondents, it might affect future practices. Exposure was listed as a promoting factor, and this thesis (which will be distributed to the respondents) will be one form of exposure.

In the dataset of my study, 50-60% among the companies with in-house manufacturing stated that they used LM principles (not everyone was clear on this, as there is confusion around what Lean is, and where the border between management and manufacturing goes). The majority of those stated that they were helped by research institutions (e.g. 5, 8, 10, 12, 20) in establishing LM. This familiarity with Lean can open up for further adoption of Lean into PD through association, especially if the experience in manufacturing is positive, given the association between Lean and SBCE. The association can magnify the interest after the effect of exposure.

There was a variation in the level of executive power across the respondent sample. According to literature, it is imperative that the management is on board the change for it to happen throughout the organization. The respondents were very keen to know more about this concept, which can imply a strengthened interest for LPD in Norwegian industry, and some of the respondents were actually in executive positions. If management and PD aligns expectations and see the mutual benefit of SBCE (i.e. no internal discord), chances are higher for implementation success.

As discussed, there are many factors that point to SBCE being a good fit with Norwegian PD. Internal relations in the sample are well-aligned with SBCE principles. On the subject of external relations, although average score overall, many expressed acknowledgement of shortcomings and emphasis on continued improvement. The elements with the biggest room for improvement were related to each other, which helps focusing efforts during potential implementation. The poor performance in the lowest scoring elements is likely related to unawareness of the subject, and the added benefits must be clear for both development teams and management before changes can happen.

SBCE knowledge in Norway is mostly centered in academic institutions as of now, but as the concept matures, people in industry will be exposed to the model and it will naturally spread with change of jobs, cooperation, etc. Bigger companies or clusters are better able to afford extensive research projects, but can also start with companies are more reliant on systemizing (from growth) who are exposed to SBCE.

The immediate low-hanging fruit for enhanced SBCE practice is the bettering of external relations, i.e. work on the constraint of developer isolation. Including customers and suppliers more in the developer environment should, per literature, help the companies make more valuable, high-quality products.

In any case, the choice of adoption of SBCE is ultimately up to the companies. It comes down to need and fit. The company must first acknowledge a room for improvement in their current processes, and an LPD/SBCE system must fit their culture, products, and strategy. There should also be a motivation across the entire organization. The people who introduced Lean thinking, Womack et al. (1990), point out that mass producing companies need a crisis to truly change, which makes them ”wake up”.

5.4 Reflections

Regarding replicability, I am unhappy with the lack of full transcriptions of interviews, but it was unrealistic time-wise in the scope of a master thesis, as more respondents was prioritized to better complete the research objective.

The respondents had each their own personal experience, opinions, and perceptions that have affected their responses. In most cases, only one respondent from each company was interviewed, limiting the general insight they could provide. This hurts the validity of the study somewhat, but was compensated for by the number of companies included. Granted, there is a chance that other people in other departments of the companies visited employed SBCE. This means that the number of companies who know about SBCE might be higher than 12%.

Future studies should narrow the scope for better normalization. Especially size was difficult to normalize for, as one company had over 150 development engineers, and another one had less than 5. It was useful for this broad study, but the type of answers they provided were, unsurprisingly, very different. For future similar studies, it is recommended to focus more on bigger-size companies (20+ engineers), as these put more emphasis on structured processes. Quantitative studies are recommended if a higher number of companies are investigated.

I wanted to find a way of measuring the efficiency of the current systems of the companies to see if there was a correlation between SBCE and higher productivity. This was simply too difficult to normalize for across the sample, but should be an interesting topic for research if companies of similar size and NPD frequency and complexity employ SBCE in one company and something else in the other.

The study showed that Norwegian industry has development potential within LPD. Does this mean that Norway is bad at PD? No, the study has not compared practices to any other country, and the study only evaluated compliance to the SBCE methodology. In any case, all development is good development; it shows a desire of renewal for extended competition and desire for growth. It is also naïve to think that a perfect system is obtainable. There will always be something that goes wrong, but the constant chase is eliminating sources of errors. As one respondent said:

Q: *How can you avoid rework?* ***A:*** *By doing everything right.*

5.5 Implications

The practical implications of this study is that core elements of SBCE have been identified and described, so that future research can look for degrees of SBCE practice using these elements. Promoting and constraining factors for SBCE practice have been highlighted across PD departments in Norwegian product manufacturing industry, and researchers can use these factors to compare the company profile to how fit the company is for SBCE implementation.

Areas of well-developed, averagely developed, and low-developed areas of SBCE elements were identified, helping future research concentrate efforts on the biggest knowledge gaps.

This thesis will be distributed to the companies who have participated in the study. This can affect prevalence of SBCE elements in the future.

5.6 Conclusion

In order to complete the research objective (”to investigate promoting and constraining factors for SBCE, with regards to implementation in Norwegian product manufacturing industry”), SBCE as a product development methodology was studied through literature. Effects from use and implementation efforts were also studied. Core elements of the methodology were identified based on the literature study. To examine the prevalence of these elements in Norwegian product manufacturing industry, a qualitative research approach was decided upon, in which companies with variations in parameters like size, location, and type of industry were interviewed. Respondents from the companies were interviewed using a semi-structured form, following an interview guide that was designed to identify degree of use of the SBCE elements identified in the literature study. The interview data was analyzed, and the companies were ranked in alignment with each of the SBCE elements, providing a score table that was used when looking for patterns between the companies. Using pattern matching, promoting and constraining factors for SBCE practice were identified. These were discussed in relation to implementation efforts, linking them to the SBCE elements.

5.7 Further work

Future focus should couple degrees of SBCE practice with performance indicators to see which are the most defining elements in efficient PD. A study which would indicate which are the most promoting or constraining factors coupled with NPD performance would also be of use. This can be done through surveys, using the work from this thesis.

Another suggestion is to further investigate how well SBCE can be implemented in a Norwegian company climate. The effects of having a strong chief engineer should be compared with more evenly distributed decision making (as is typical of Norwegian companies). Extended field-work is advised to evaluate the onset of SBCE practices over time. Case studies can find where problems might arise, and this information can be used to ease future transition phases.

Finally, I suggest more research on the business impacts that SBCE has.

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Appendix A

Interview guide

A.1 Norwegian

Om firmaet

- Hva slags selskap er dere? (leverandører, flere produkter, type of product ...?)
- Størrelse? Antall ansatte, antall i utvikling
- Hvilken type organisasjonsstruktur?
- Hvor mye bruker dere på R&D i forhold til omsetning?

Produktutvikling

- Prosjekt/prosessbasert?
- Bruker dere noen spesifikk metodikk/modeller?
- Hvordan strukturerer dere arbeidet?
    - Tidlig fase utvikling?
    - Valg av konsept? Flere enn ett konsept?
    - Er tidlige avgjørelser viktig? Detaljer?
- Når dere budsjett i tid og ressurser? Hvordan ser fordelingen av ressurser ut?
- Hvor vanlig er rework? Hvorfor oppstår det? Hvordan unngår dere det?

Kundeverdi

- Hva er deres konkurransefortrinn?
- Hvordan intendifiserer dere kundeverdi?
- Hvordan sørger dere for innovasjon? Er innovasjon viktig?
- Hvordan inkluderes kunden i PU?

Samarbeid

- Hvordan jobber dere tverrfaglig?
- Hvordan bestemmer dere kompromisser?
- Hva slags møter har dere, og hvor ofte? Hva diskuteres?
- Hvordan unngår dere kunnskapsgap?
- Hvordan er produksjon involvert? Robust? Når starter industrialiseringen?
- Hvordan inkluderes leverandører? Hvordan bestiller dere? Skifter ofte?

Kunnskap

- Medlem av klynge eller lignende samarbeid?
- Hvordan sørger dere for forbedring? Har det forandret seg over årene?
- Hvordan ivaretar dere lærdom fra PU-prosessen?
- Hvordan kartlegger dere produktenes yte-evne?
- Hvordan lærer dere av andre utenfor bedriften?

A.2 English

About the company

- What type of company? (suppliers, type of products.. ?)
- Size? Overall number of people, people in R&D
- What type of organizational structure?
- How much are you spending on R&D compared to revenue?

Product development

- Project/process-based?
- Are you using specific methodologies or models?
- How are you structuring your work?
  - How does the early phases look? How do you research?
  - How do you choose concept? More than 1?
  - Early decisions important? Why? How about detailing?
- Do you hit targets in time and resource budgets? How does the distribution look?
- How common is rework? Why? How do you avoid it?

Customer value

- What is your competitive edge?
- How do you identify customer value?
- How are you innovative? Is innovation important?
- How is the customer included in PD?

Concurrency

- How do you cooperate across functional groups?
- How do you decide on compromises?
- What type of meetings do you have? How often?
- How do you avoid knowledge gaps?
- How is manufacturing involved? Robust? When does industrialization start?
- How are suppliers involved? How do you order? Do you often change?

Knowledge

- Are you a member of a cluster or other types of collaborations?
- How do you improve? Has it changed?
- How do you capture knowledge, learn from PD?
- How do you know the performance of your products?
- How do you learn from external actors?

Appendix B

Invitation

Forespørsel om deltakelse i forskningsprosjektet: ***"Investigating the Use of Set-based Concurrent Engineering in the Norwegian Product Manufacturing Industry"***

Hva studiet omhandler:
NTNU, og spesifikt Institutt for Maskinteknikk og Produksjon (MTP), forsker på *Lean Product Development*. I den forbindelse vil vi kartlegge utbredelse av en spesifikk metodikk innen produktutvikling, *Set-based Concurrent Engineering* (SBCE), i norsk vareproduserende industri. For øyeblikket skrives det en Masteroppgave på dette temaet av en student som ser etter respondenter som dere. SBCE anses av mange i miljøet som "state of the art".

Kort om SBCE:
Metodikken har rot i *Toyota Product Development System*, og skal ikke forveksles med *Lean Manufacturing*, men omhandler effektivisering av den mer "fuzzy" biten av et produkts liv. Studier viser at hvis man "front-loader" utviklingen kan man få mer innovative produkter både kjappere og billigere. Metodikken i korte drag:

- Kommunikasjon i sett av konsepter, ikke enkelt-konsepter
- Utvikling av flere parallelle løsninger i subsystemer
- Fusjonering av "best match"
- Bedre ivaretakelse av kunnskap
- Operering med spekter av dimensjoner
- Integrering av leverandører tidlig i prosessen

Det høres paradoksalt ut at å bruke mer penger tidlig og å kommunisere mer "tåkete" skal sørge for besparelser og bedre produkter, men disse virkemidlene fører til at man bedre unngår "rework" som ofte er det dyreste i en produktutviklingsprosess. Kravet om flere løsninger gjør at man naturlig er mer kreativ. Metoden/approachen er spesielt aktuell for produkter som krever flere ingeniørdisipliner eller som fusjonerer flere subsystemer.

Hva innebærer deltakelse i studien?
I et intervju med studenten vil vi snakke om hvordan deres produktutvikling foregår; aktuelle spørsmål omhandler:

- Generelle spørsmål om selskapet (størrelse, bransje, type produkter osv)
- Generelle spørsmål om deg/dere (tid i selskapet, erfaring med innovasjon osv)
- Hvordan dere strukturerer produktutviklingen deres
  - Team-sammensetning
  - Idé-henting, innovasjon
  - Metodikk, modeller
  - Hvordan dere bestemmer konsept for utvikling
  - Hvordan dere jobber tverrfaglig
  - Hvordan dere takler "rework"
- Hvordan dere samarbeider med leverandører
- Hvordan dere fordeler ressurser i prosjektene og selskapet
- Hvordan prosessen/metodene har forandret seg over årene
- Hvordan dere ivaretar kunnskap fra prosjekter
- ++

Intervjuet vil vare rundt 2 timer. Studenten vil bruke diktafon under intervjuet for bedre å kunne konsentrere seg om samtalen. I et semi-strukturert intervju er det helst en spørsmålsprotokoll vi vil igjennom, men vi snakker om eventuelle interessante ting som måtte dukke opp. Det må gjerne trekkes frem eksempler i form av dokumenter eller bilder fra intervjuobjektenes side, disse lagres ikke i studien.

Hva skjer med informasjonen om deg?
Alle personopplysninger vil bli behandlet konfidensielt. Kun student og veileder har opplysninger, og disse oppbevares på personlig datamaskin. Navn og data fra intervju oppbevares ikke på samme plass. Selskapene som deltar kan bli gjenkjent i studien ved opplysninger som størrelse, bransje, eller lignende, dersom det viser seg at det er en relevant og tydelig sammenheng mellom dette og bruk av utviklingsmetodikk. Oppgaven vil sendes på mail til de deltakerne i studiet som måtte ønske det.

Prosjektet skal etter planen avsluttes 11/6-2018. Innen 15/6-2018 vil opptak og personopplysninger slettes.

Frivillig deltakelse
Det er frivillig å delta i studien, og du kan når som helst trekke ditt samtykke uten å oppgi noen grunn. Dersom du trekker deg, vil alle opplysninger om deg bli anonymisert.

Dersom du ønsker å delta eller har spørsmål til studien, ta kontakt med:

Student Atle Lycke (+47 97 96 19 53, atle.lycke@gmail.com)

eller

Veileder og instituttleder Torgeir Welo (+47 41 44 00 61, torgeir.welo@ntnu.no).

Studien er meldt til Personvernombudet for forskning, NSD - Norsk senter for forskningsdata AS

Appendix C

LPD Survey

The results from Welo et al. (2013) is displayed in the figure below. The survey received 258 responses from people in 35 companies. The survey asked respondents to put their PD department on a Likert-scale of 1 to 5 where 1 was ”strongly disagree”, 3 was ”neutral” and 5 was ”strongly agree” with the corresponding statement. There were 30 statements, 4 in each of the 6 LPD categories, and 6 statements regarding NPD performance (dependent variable). The companies had minimum 50 employees, had in-house PD department, manufactured physical products, and at least 30% value is added in manufacturing process. The ones highlighted in the right-most column supported self-reported higher performance in NPD through multiple regression analysis.

The NPD statements were:

- Customers are generally satisfied with the true value realized in our new products
- Product development projects are launched on time
- Product development projects are launched at budget
- During the last three years, new product introductions have met profitability targets
- During the last three years, or product portfolio have been extended by introducing (new to us) type of products in the marketplace.
- During the last three years, new product introductions have contributed as expected to our sales objectives

LPD factor	Statements (abbreviations)	Mean	Std. Dev	*Pr* > |*t*|
CV	Customer value in company's mission/vision statement	4.1	0.91	0.820
CV	Customer value drives strategy and activities in PD	4.1	0.77	0.358
CV	Customer is integrated in PD activities	3.7	0.99	0.167
CV	Team member knows product characteristics related to customer value	3.4	0.89	***0.035****
K	Knowledge gaps in PD are identified	2.8	0.93	0.749
K	The company always develops multiple design concepts early in PD	3.1	1.06	0.435
K	Insight and new information is discovered by physical testing	4.1	0.85	0.787
K	Information and knowledge is sought actively from outside company	3.6	0.88	0.141
CI	CI in PD is part of company strategy	3.9	0.92	0.206
CI	Responsibility and roles in PD are clearly defined	3.4	0.90	0.677
CI	Value added work and waste in PD are clearly defined	2.9	1.00	0.683
CI	Plan-Do-Check-Act problem solving cycle is used in PD	2.7	0.90	0.388
S	Holistic approach for project selection and portfolio planning is used	3.0	0.93	0.600
S	Risks and satisfying customer value drives project selection	3.1	0.86	***0.049****
S	Resource planning is used in PD	2.9	0.92	0.357
S	Design for Manufacturing (DFM) is used in PD	2.9	1.09	0.079
St	A formal product realization process is followed	3.3	0.96	0.138
St	Cross training is used to increase resource (management) flexibility	2.7	0.89	0.223
St	The roles of reuse, modularization and customization are defined in design strategy	3.1	0.92	0.956
St	Design strategies are followed and standardization is sought in PD	3.4	0.92	***0.023****
C	Opinions and views are equally respected of all employees	3.5	0.99	0.401
C	Responsibility is delegated to the level closest to the problem	3.7	0.83	0.656
C	Decisions are based on a process of involvement	3.6	0.82	0.928
C	Simple and visual communication is part of company culture	3.4	0.89	***0.042****

Appendix D

Company demography

Details about the sheet:

- The number of developers were reported by the engineer for that office.
- Number of employees gathered from directory of www.proff.no.
- Areas B and E were known to have cluster collaboration, respectively.

Company demography

Comp #	Primary industry	Area	Number of dev	No. of employees	Manufacturing
1	Maritime	A	5-20	0-50	In-company
2	Offshore	A	5-20	100-500	In-house
3	Marine	A	5-20	50-100	In-house
4	Construction	A	20-50	100-500	In-house
5	Maritime	A	5-20	50-100	In-house
7	Defence	A	5-20	0-50	In-house
8	Defence	B	5-20	500-1000	In-company
10	Marine	C	5-20	0-50	In-house
12	Automotive	B	5-20	100-500	In-house
13	Offshore	D	100+	1000+	In-house
14	Defence	E	100+	1000+	In-company
15	Food industry	D	5-20	100-500	In-company
16	Offshore	F	5-20	100-500	In-house
17	Healthcare	C	0-5	0-50	In-house
18	Maritime	G	5-20	1000+	In-house
19	Maritime	G	5-20	0-50	In-company
20	Agriculture	G	5-20	50-100	In-house
21	Offshore	G	5-20	0-50	In-company
22	Maritime	H	5-20	0-50	Out of company
23	Offshore	H	5-20	0-50	In-house
24	Maritime	H	100+	500-1000	In-company
26	Maritime	H	0-5	50-100	In-house
27	Marine	H	5-20	100-500	In-house
28	Automotive	E	20-50	100-500	In-company
29	Offshore	G	0-5	50-100	Out of company