Reducing complexity costs

by

implementing a modular design

Master thesis

Some information has been left out due to confidential reasons

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Abstract

Along with the raising demand in customized products, the number of product variants offered by companies has been rising significantly and continue to rise in the coming years. The higher number of products within a company leads to variety-induced complexity and consequently raising costs. In a world driven by competitiveness and profit maximization, it is evident that these variety-induced complexity costs should be as low as possible. CEOs around the world acknowledge the need to control this increase in complexity and react in order to lower the costs, whereas nearly half of them do not feel ready for it.

Currently, there is no comprehending, empirically tested process that aids managers in reducing the complexity costs that their company is facing. Hence the goal of this paper. This paper introduces a process which has been tested in a medium-sized manufacturing company, and with that proven its worth regarding lowering the complexity costs significantly within the company. This process has been established through an extensive literature review and interviews with employees throughout the organization, with as a starting point using modularity as a way to reduce complexity costs.

It has been found that, next to saving costs directly in the way of cutting out unprofitable or unnecessary product components, the indirect cost savings of reducing variety are higher as they occur at multiple areas in the organization: planning, production, communication, warehouse management etc. This means that money is saved constantly instead of only one time. This enhances the profitability of the company.

Moreover, the process forces a company to analyse their product portfolio, consider the wishes of their customer and think about the future. Surprisingly, unexpected results were found such as discovering an unprofitable product line and a customer wish to reduce lead times. Also, a potential area for new product development has been found which can be subjected to future research.

Table of contents

List of figures

List of tables

1. Introduction

1.1 Situation and complication

The recent increase in demand customization (Closs, Jacobs, Swink & Webb, 2007) has led towards an increase in the number of products offered. Executives reported that their firms offer on average an increase of 1.7 new products for every product retired (Hoole, 2006), consequently leading towards an increase of complexity of their product portfolio (Berman & Korsten, 2010). This means that the main source of complexity is the number of products and the components within these products (Myrodia & Hvam, 2015). It is expected that this megatrend continuous, resulting in more complexity.

As complexity is expected to rise, so are the costs associated with it. Nearly eight out of ten CEOs anticipates on the complexity that lies ahead, half of the 1,500 CEOs that were participating in this study do not feel ready for it (Berman & Korsten, 2010). "*The world's private and public sector leaders believe that a rapid escalation of complexity is the biggest challenge confronting them" – Samuel J. Palmisano, CEO of IBM Corporation* (Berman & Korsten, 2010, p.3). This means that finding a way to reduce complexity costs in this world driven by profit maximization is of great value for companies. Also because managers in general expressed their concerns that this increase in complexity undermine the future profits of their company (Hoole, 2006; Berman & Korsten, 2010). Complexity costs are the costs that come from offering a multitude of products (Hansen, Mortensen & Hvam, 2012).

To meet customer demand, multiple variants of products and components are necessary. Following this reasoning, not all complexity is bad, and some complexity can be even considered as a competitive advantage (Scheiter et al., 2007). The important task is to identify the non-value adding complexity, and transmit this complexity into certainty. By tackling complexity costs, organizations can reduce its cost by 15% to 30% in significant portions of their business (Wilson, 2009). Kraft, owner of the famous triangular shaped Toblerone bar, estimated a result of $400 million a year due to its reduction in complexity. Reducing complexity costs is not just about reducing the level of complexity within the organization, it is also about reducing the cost of delivering complexity (i.e. making complexity less expensive) (Wilson, 2009).

The conflict between the external pressure from customers pushing for unique applications/ and the internal standardizations due to cost reductions/ can be solved by introducing a modular design (Martin & Ishii, 2002). A modular design standardizes different product components, which then can be configured into a wide range of end products to meet customer demands (Tu, Vonderembse, Ragu-Nathan T.S. & Ragu-Nathan B, 2004). By developing the ability to produce a wide variety of products through developing standardized modules, manufacturers can significantly reduce complexity costs (Sanchez, 2000). Thus implementing a modular design is a way to lower complexity costs. Simon illustrated this already in 1962 with an example, however, with the current trends (i.e. digitalization, globalization, customization) complexity became more evident and raises the attention of bigger companies. The example given by Simon (1962) can be found in Appendix A.

Current literature acknowledges the fact that complexity costs that comes from the diversified customer demands can be reduced by implementing a modular design (Martin & Ishii, 2002; Blecker & Abdelkafi, 2006; Huang, 1999). However, it lacks both empirical research and a validated model concerning this relationship. This research aims to develop a clear and comprehending process, which is validated and tested in a medium-sized manufacturing company, which currently has a large product portfolio due to the diversified customer demand. This company is hereafter referred to as the pilot company. Also, this research sheds some light on the concept of portfolio management, combined with complexity costs and modular design, where current literature mainly focus on the relationship between two of these concepts.

1.2 Problem definition

The increase in diversity in customer demand results in a challenge for the companies. Not only do they have to articulate the needs into suitable products, but they also need to have the competences to make the products. Moreover, this has to be done as cheap as possible.
By implementing a modular design, the diversified customer needs can be met while lowering costs (Sanchez, 2000; Tu et al., 2004; Martin & Ishii, 2002). By developing a process, a company can follow certain steps that help to reduce complexity costs through implementing a modular design. The process is developed with the help of scientific literature and applied in a medium-

sized manufacturing company to identify potential gaps and to validate the value of the process.

The company has no profit maximization, due to high costs and low selling prices. The high costs results from human errors, high complexity and an inefficient working environment. The company offers a wide range of products for its customers, resulting in an extensive product portfolio. The expectation is that due to the diversified product portfolio and the low number of sales of some product (groups), there is space for optimization. The scope of this research is limited according to an analysis of their current product portfolio, considering the number of sales and accordingly the revenue and profit. Figure 1 is a graphical representation of the problems the company currently faces. The boxes marked in red show the problem that this research aims to solve.

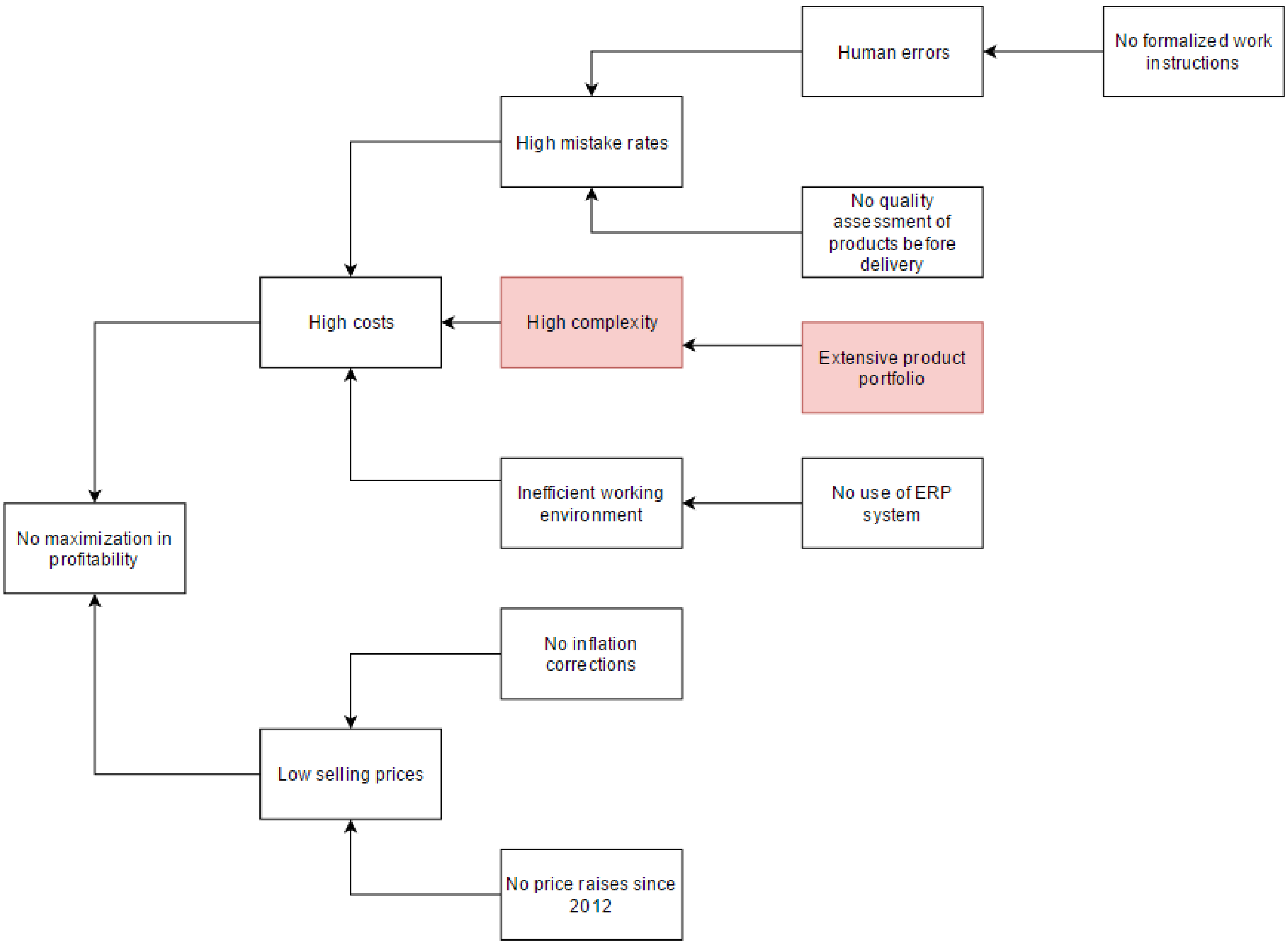

Figure 1. Ishikawa-diagram

1.3 Research goal

The goal of this research is to develop, validate and apply a process through which company X can reduce its complexity costs by assessing their current product portfolio and discovering potential fields and/or products that are suitable for modularization. The process consists of several steps which the company can follow in order to reduce its complexity costs, while aiming at one specific product family. The process is visualized in a flowchart.

1.4 Research lay-out

1.4.1 Research question

How can variety-induced complexity costs be reduced through modularising the product portfolio?

1.4.2 (Sub)questions

1. What is the consequence of variety induced complexity?
2. Which modularisation methods exists?
3. Which method is most applicable for reducing variety induced complexity?

1.4.3 Academic relevance

The academic relevance of this research lies within the fact that this researches proposes a process that is based on relevant literature and is empirically tested in a manufacturing company. The result is that the extensive literature that is out there concerning complexity costs is brought together in one comprehensive chart. In other words, this research combines different methods into one comprehending process that aids a company in lowering variety-induced complexity and with that enhances the profitability. Moreover, this research temps to give the relationship between three concepts (i.e. product portfolio, complexity and modularity), whereas current literature focuses mainly on the relationship between two concepts.

1.4.4 Practical relevance

The practical relevance of this research is that the theory is transmitted into an empirically tested process. Organizations can use this process as a way to reduce their complexity costs and also, as an extension to it, map their variety and assess their current product portfolio.

Moreover, the process forces the organization to map out the current demand in the market. Therefore this process is useful for companies through considering multiple important aspects for a company, but mainly for reducing complexity costs. The reduction in complexity costs are shown in both direct and indirect costs savings, however, the indirect cost savings contain a multitude of the direct cost savings as this reduction in inefficiency occur over and over.

2. Research design

This study aims to develop and test a process in which complexity costs can be reduced by influencing the product portfolio. In other words, this research entails a design oriented research where the current product portfolio is redesigned. This process is presented in a flowchart, which consists of different steps. Both a qualitative and quantitative study has been conducted in order to gather the right information. This study follows a deductive approach, where a particular situation is analysed and then used to validate the process. As a basis for the interviews that are conducted, background information about the company and the gained knowledge from literature review are used. Next to that, information is gathered in an informal way. However, in order to ensure reliability of the research, written pieces are read in order to check for inconsistencies or misinterpretations. Information as sales, revenues, prices and product offerings are gathered through the use of the Enterprise Resource Planning system (ERP-system) in place. The research design starts with the empirical context, and is followed by the data collection method and an explanation on how the data. The research design ends with a detailed description on how the different concepts are measured.

2.1 Empirical context

The pilot company is a medium-sized Dutch manufacturing company which develops and manufactures drive systems and components for a wide range of industries within the agricultural sector. The pilot company currently offers full-time jobs for 25 employees, with a revenue of roughly ***€ million in 2015. The pilot company addresses both the national as well as the international market, with operating in countries such as the Netherlands, Germany, Belgium and the United States. Currently, the pilot company produces a wide range of products that are specially made for the customer and therefore has an extensive product portfolio. The pilot company changed ownership in April 2016, and consequently has a new day-to-day management. The owners/management is aware of improvement possibilities and has the ambition to optimize business processes. This research aids their ambition. The benefit of conducting the research in a medium-sized company, is that it is easier to get a clear and comprehending picture of the whole company which opens the opportunity to entail in an embedded study as multiple sub-units of the company are analysed. To get a clear and comprehending picture of the company, the researcher has been present at the company 40 hours a week in the period of April ’16 till February ‘17. Note that during this time, there was no engineer available in the company that could aid in the design and implementation of a modular design. The quotes throughout these reports has been disguised, in order to ensure confidentiality.

2.2 Data collection method

The data has been collected through a combination of both qualitative and quantitative approaches. As a qualitative approach, semi-structured interviews has been conducted with different employees throughout the company. It is likely that, in order to ensure the reliability and the completeness of the information, multiple interviews with the same persons are conducted over the time period of this research. An advantage is that qualitative research, in this case semi-structured interviews, give rise to the opportunity to gain a deep insight of the company (Babbie, 2010). By using a semi-structured approach, the possibility arises to diverge from the topic when interesting and valuable answers are given. No interview transcript is added to this research due to confidentiality reasons. Different people throughout the company will be interviewed, for example current management, salespersons and the coordinator of manufacturing. Also, questions are asked in an informal way with people throughout the organisation. To ensure the reliability of the research, the answers were validated once written down.

In order to get a clear picture about the market and the customers, questions were asked to the customer at an international fair as well as through a questionnaire via e-mail. The information gathered from the customers is used directly in the form of quotes, and indirectly as background information to get a profound picture of the company as well as the products that are sold.

As a quantitative approach, a primary and secondary literature review has been conducted in order to uncover patterns within for example the industry and the market. This succours the research into different concepts as customer demands and inventory assessment.

2.3 Analysis

After the data was collected, the qualitative data has been analysed through coding. Coding refers to “the process whereby raw data is transformed into standardized form suitable for analysis” (Babbie, 2010, p. 338). Coding makes it easier to compare data generated from multiple sources, or to look for inconsistencies within answers from one respondent.

As said, the quantitative data has been used to discover certain patterns and key numbers from primary data provided by the company, which is on its turn compared with secondary literature in order to make sense of the data. Also, quantitative data has been used to define the scope of the research.

3. Theoretical framework

Firstly, the theoretical framework gives static definitions which has been used throughout the report. Secondly, a systematic description is presented on how the literature review has been conducted, followed by the literature review itself. The theoretical framework ends with the flowchart that aids in reducing complexity costs.

3.1 Definitions

There are three central concepts embedded in this research: complexity costs, product portfolio and modularity. By comparing and potentially combining current definitions, a profound and comprehending definition is given regarding the three central concepts mention earlier.

The definition of the *product portfolio* of a company is pretty straightforward. Throughout this report, a product portfolio is considered as *all the products offered for sale by the organization in question* (Jacobs & Swink, 2011), where a *product* is considered to be a *physically discrete system sold as a single unit* (Ulrich, 1995). Variety within the product portfolio relates to the amount of products that is offered by the organization in question. For the scope of this research, the product portfolio only concerns the tangible products offered by the organization. This definition has been chosen as it boils down to a simple but comprehending definition, which is used by multiple researchers regarding several subjects (e.g. Jacobs & Swink, 2001; Cooper, Edgett & Kleinschmidt, 1999; Wernerfelt, 1984).

Current literature is roughly agreeing on a definition for *complexity costs*. Hansen, Mortensen & Hvam (2012) consider complexity costs as '*a price that comes with offering a multitude of products'* (p.1). Lechner, Klingebiel & Wagenwitz (2011) see complexity costs as *'the number and variety of product variants …. which influences costs and performance'* (p.2). Another definition, given by Götzfried, (2013), states that *'as product variety increases, companies often experience internal difficulties which lead to higher manufacturing costs, manufacturing overhead, delivery times, inventory levels and component prices (i.e. complexity costs)'* (p. 2-3). As the definitions from Götzfried (2013) encompasses the most extensive definition of complexity costs, for example the definition includes examples of costs that come from a higher complexity, this definition is used throughout the report. In other words, the definition by Götzfriend (2013) encompasses the most complete definition and combines definitions from different researchers (e.g. Hansen et al. (2012); Lechner et al. (2011).

Modularity can be considered as *the standardization of components and processes in an organization that can be configured into a wide range of end products to meet specific customer demands* (Ulrich, 1995). Ulrich and Tung (1991) define modularity in terms of two characteristics of product design: *1) Similarity between the physical and functional architecture of the design and 2) Minimization of incidental interactions between physical components*. Another definition of modularity is that modularity is *a property of a specific view of a system (artificial or natural), where the system can be decomposed into components that have a form of independence—with respect to some properties (Bergmans, 2011, p.1).*
Considering the above stated definitions of modularity, they all have one thing in common: modularity refers to the configuration of components into end products. The research from Ulrich (1995) has been cited frequently by other scientific articles, meaning that his work has proven its value , and therefore modularity within this research is considered as *the standardization of components and processes in an organization that can be configured into a wide range of end products to meet specific customer demands.*
Modularity as a concept is de decoupling of product components including a one-to-one mapping from functional elements into a physical component. For example, if you consider a camera. The lens is changeable and therefore an example of a modular architecture.

Figure 2 considers modular design example on a basic level. Within one component family, there is a certain degree of design freedom. Between the components, there is an interface meaning that not every component is suitable with another component when assembling (Salvador et al., 2002; Ulrich, 1995)

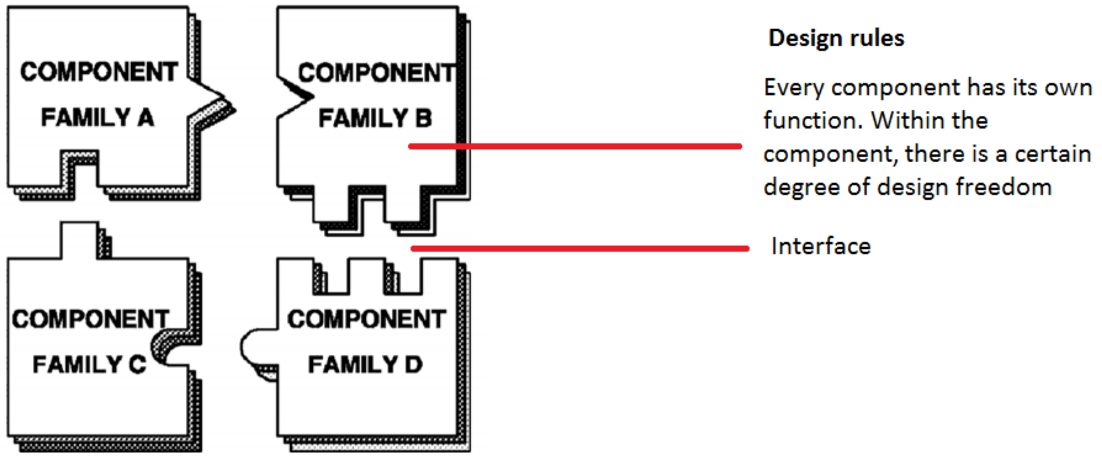

Figure 2. Modular design

3.2 Literature review

Over the past twenty years, the amount of published papers per year concerning the topic complexity costs have increased more than 750%, from 369 in 1995 to 2783 in 2015 (Web of science, sd.). This chapter considers the most relevant papers regarding the central research question, namely how variety-induced complexity costs can be reduced through modularising the product portfolio. Different search engines for scientific literature have been used to discover the published literature, such as *Google Scholar* and *Scopus*. Next to that, the so called *snowball sampling* has been used, where citations within relevant literature give the researcher the name of another interesting study that can be helpful to compound a comprehensive literature review (Vogt, 1999). The generated articles are then sorted by relevance through business application field and in terms of number of citations. The number of citations consider to what extent the scientists perceive the paper as relevant. Also, articles that are published recently (i.e. in the last ten years) are considered of higher value as older information may be obsolete. Around the main theme of this research, three central concepts can be distinguished: product portfolio, complexity costs and modularity. By integrating these concepts into relevant key words, the most important literature was found. When a scientific article encompasses information about multiple concepts, the information is sorted under the relevant chapters. By considering multiple articles from multiple researchers, the trustworthiness of the data increases.

The first sub-chapter considers the relationship between the three central concepts of this research: product portfolio, complexity costs and modularity. This chapter possesses information about what the relationship encompasses and the direction of the relationship. Keywords that has been for finding relevant information are “product variety complexity”, “product portfolio complexity”, “diversified product offerings”, “organizational complexity”., “variety-induced complexity costs”, “value chain complexity costs”, “product variety costs”, “measuring complexity costs” and “modular complexity”.

The second subchapter goes deeper into modularization as a potential solution for lowering complexity costs. It considers how a company can implement a modular design. Keywords that has been entered for finding relevant information are “modular product families”, “modular complexity” and “modular implementation”.

3.2.1 Scientific background

The number of product variants have increased dramatically over the past few years (Hoole, 2006; Wilson, 2009). The provider of the goods or service seeks to achieve more economic benefit and enhance the value perceived by the customer by offering a wider spectrum of choice (ElMarghy H., Schuh, ElMaraghy W., Piller, Schönsleber, Tseng & Bernard, 2013). In other words, due to the increased demand for customization where customers push for unique applications of products, the number of products has risen sharply within companies as they tempt to meet this diversified demand (Hu, Zhu, Wang & Koren, 2008; Hoole, 2006; Closs et al., 2007).

An inverted U-shape relationship exists between product portfolio complexity and performance (Fernhaber, 2012). At some point, the costs (e.g. coordination and communication costs) outweigh the benefits of having a more diversified product portfolio (Closs et al., 2008). At this point, the increase in complexity does not add any value. Identifying this point ensures to have the necessary complexity in order to meet customer demand, but simultaneously rule out non-value adding complexity.

Product variety can potentially increase sales volumes and revenues. However, a higher variety of products is not always good, and may not always offer the extra perceived value that is intended with offering a wider range of products. Evidence shows that customers can get confused when choosing among a wide variety of products (Huffman & Kahn, 1998).
Thus defining the right range of products is an important management issue. There are hurdles from both sides, as the customers' needs may be latent, inherent and difficult for customers to describe. Nevertheless, customers can act as a source of innovation. Therefore, customer demand should be taken into account when establishing a product portfolio (Hutter, Hautz, Füller, Mueller & Matzler, 2011). The other side, the producers, are limited by their technological possibilities and competences. The products a company offers draw upon organisational competences (Danneels, 2002; Prahalad & Hamel, 2006). This often results in a mismatch between demand and supply, which leads the companies saddled with excess inventory and unsold product variants (ElMaraghy H. et al., 2013).

The product portfolio influences the inventory an organization has. When a product has dominant characteristics as short life cycles and high demand uncertainty, or fluctuating sales, inventory levels are adjusted (Langenberg, Seifert & Tancrez, 2011). Consequently, while developing a product portfolio, associated costs like storage costs of inventory have to be taken into consideration. Having an inventory, especially for manufacturing companies, is imperative and therefore cannot be neglected within this process. The interdependence between these two concepts (i.e. product portfolio and inventory) offers an opportunity within the chart to assess current inventory. Thus during the analysis of the current product portfolio, an assessment of the current inventory can be made.

Variant multiplicity may be external or internal. External causes result from factors such as market, competition, suppliers and the technological characteristics of product offerings. Internal causes are organizational and technical deficiencies leading to an unnecessary increase in product varieties, both at product- and component levels (ElMaraghy H. et al., 2013). Schuh and company (2012) shows that both internal and external complexity causes should be taken into consideration.

Figure 3 shows that the effects of high product variety throughout the different areas within the company.

These effects are evident in the pilot company. An example is the high effort in maintenance and documentation.

"There is no or little documentation available of the recent years. Also, the drawings of the different drive systems and components, are obsolete." – Manager 1

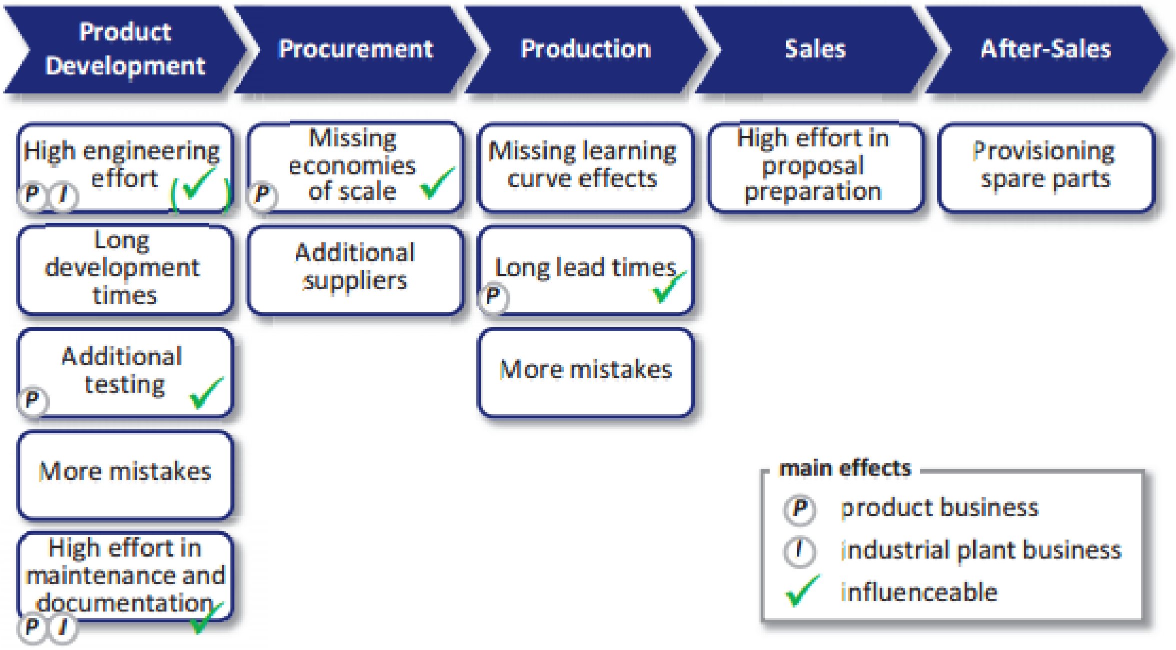

Figure 3. Effects of high variety (Ripperda & Krause, 2014, p.16).

Another example is the missing economies of scale. Product parts are bought and supplied in excess inventory, in order to keep the procurement price as low as possible. However, having a product on the shelf for 2,5 years, has its price too. The lead times in the pilot company are high as well. Of the lead time, around 90% is waiting time of the products before they can proceed production. Also, the number of suppliers are relatively high. Only for the castings that are needed to produce the housing of a drive system, there are 5 different suppliers. Some of these effects are directly nfluenceable, as can be seen in figure 3, however, might take a lot of effort and money to do so. By lowering the variety-induced complexity, these effects are mitigated which saves costs indirectly. The effects of figure 3 are generally adopted by multiple authors (e.g. Hu et al., 2008; Macduffie, Sethuraman & Fisher, 1996; Fisher & Ittner, 1999).

One of the important objectives of variety management is the reduction and management of variety-induced complexity and its associated costs. For example, variety-induced complexity results in human errors and influences both supply chain configuration and inventory control policy (Hu et al., 2008). Variety-induced complexity arises due to the increased number of variants and their features. It is expected that additional product variances raises sales and prices. The consequential profit is often overestimated and does not weight up to the variety-induced complexity costs (ElMaraghy H. et al., 2013). This means that an increased product variety can have a significant negative impact on performance (Macduffie et al., 1996; Fisher & Ittner, 1999).

Variety-induced complexity costs, as opposed to complexity, cannot be easily quantified by traditional cost-accounting methods (Wilson, 2009). The measurement of complexity within an organization has given more attention than complexity cost, as different models has been developed to measure the level of complexity within a firm (e.g. Jacobs, 2013). Recent research into the field of complexity costs stretch the need to develop quantifiable complexity effects on costs (Ripperda & Krause, 2014). Complexity costs come from indirect activities, and therefore cannot be directly associated to a product (Thonemann, 2000). These indirect costs are usually equally distributed among all variants. This results in the fact that different architecture concepts are not implemented very often due to a lack of quantification of the exact complexity costs and the positive effects (or diminishing of negative effects) of a different architecture concept (Hansen et al., 2012).

Established accounting systems (e.g. ERP-systems) focus on direct product costs alone (e.g. standard unit costs), and thus neglect the indirect costs associated with the products (Hansen et al., 2012). Due to the fact that the costs are hard to quantify, complexity costs are generally considered as overhead costs and consequently are fixed costs (Lechner et al., 2011). Volume effects of variants are overestimated, whereas their impacts on costs remain underestimated. This results in the fact that the costs that are assigned to offering a wider variety of products are too low. Therefore are complexity costs considered as hidden costs, and often considered as ‘costs of doing business’ and sometimes erroneously treated as zero (Jagersma, 2008). This increase in complexity raises costs throughout the whole value chain, from product development to marketing & sales (Hu et al., 2008). Meaning that the indirect costs savings will outnumber the direct costs savings as complexity costs cannot be quantified, but nevertheless are present in every company and reduce profitability significantly. This research focuses mainly on the increase in complexity costs at the manufacturing stage, the warehouse & distribution stage and the engineering stage. Examples on how higher complexity increases costs at these stages are among others: more frequent downtime, higher waste, higher WIP, more complex production control, increased space and labor, and higher inventory levels (also, see figure 3). However, Myrodia and Hvam (2015) introduce factors that influence complexity costs. By measuring and altering these factors, complexity costs can be reduced. Among these factors are setup times in production, scrap of materials in setup of machines, sales order handling, inventories of finished goods, and freight of finished goods to warehouses.

3.2.3 Modularity as a way to reduce complexity costs

The trade-off between variety increase and complexity cost is not static, as modular product designs can reduce both complexity and costs. There is a negative relationship between the implementation of a modular design and the complexity costs within an organization, i.e. the higher the success of implementing a modular design, the lower the complexity costs (Blecker & Abdelkafi, 2006). Volkswagen claims to save $1.7 billion annually on development and production costs by effective management of their product architecture. This is mainly done through the use of component commonality within products (Dahmus et al., 2001). Nevertheless, Volkswagen still claims that their products can be effectively differentiated in the eyes of the customer.

Multiple companies embraces product structure optimization as a way to reduce complexity costs as a result from the increased variety in products (Chandrasegaran, Ramani, Sriram, Horváth, Bernard, Harik & Gao, 2013). Modularization as a product structure simplifies interactions by reducing component variation and by unifying component, product, and process specifications (Gereffi, Humphrey & Sturgeon, 2005). Modularity can mitigate the trade-off between product variety and organizational performance (i.e. complexity costs)

(Salvador, Forza & Rungtusanatham, 2002). This means that modularity can be considered as a factor directly influencing the complexity costs (ElMaraghy H., 2013). Figure 4 summarizes the relationship between a diversified product portfolio, the implementation of a modular design, complexity costs and its effect on the performance.

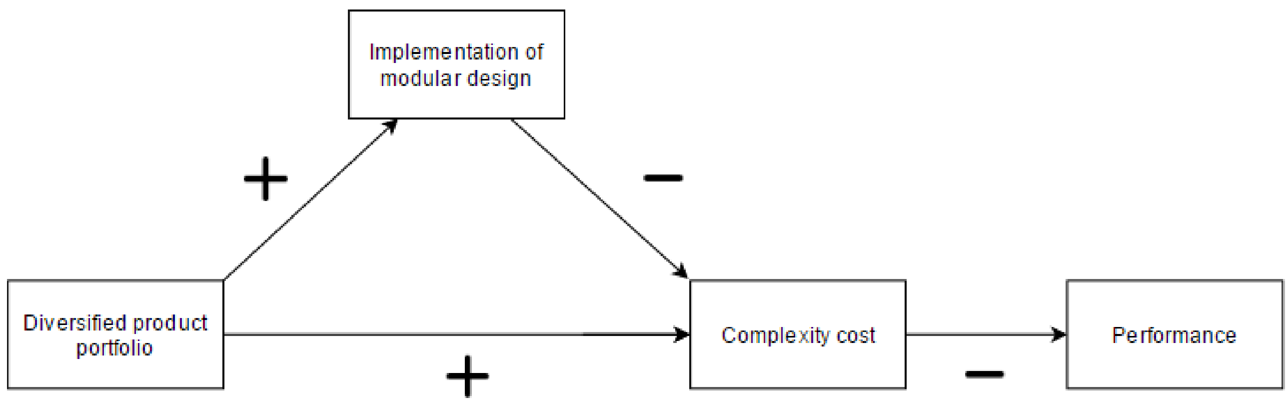

Figure 4. Relationship between diversified product portfolio and complexity costs

A diversified product portfolio has a positive relationship on the implementation of a modular design, as the implementation of a modular design has a higher potential to be more successful when the product portfolio is more diversified. In its way, a higher diversification in the product portfolio results in higher complexity costs, as discussed above. The implementation of a modular design directly influences complexity costs, and thus can reduce the higher complexity costs coming from a diversified product portfolio. High complexity costs leads to a lower performance.

The relationships from figure 4, as explained above, are from here on considered as a given for the rest of this research. Meaning that implementing a modular design is a suitable way to reduce complexity costs in the pilot company.

The development of modular product families aims for the reduction of companies' complexity and of course the reduction of cost (Ripperda & Krause, 2014; Kremer & Gupta, 2012). Thus by identifying and establishing product families, areas for complexity costs savings are ascertained. Krause & Ripperda (2013) characterize a selection of significant method for supporting the development of modular product families. The authors base their selection on relevant criteria that are deduced from literature and project experience. Table 1 shows the different methodologies alongside the criteria. A key element in managing variety is to group and classify similarity within a class of products. Therefore product families are important when dealing with variants which represents individual instances in a class of similar products. Product families help to meet the diverse customer demand, while reusing current assets such as components, modules, processes and knowledge (ElMaraghy H. et al., 2013).

The different articles that are considered in table 1 have been, if available, reviewed. If needed, the table has been adapted.

Different research into the implementation of a modular design has been done by Kremer & Gupta (2012), as they reviewed and compared three well-known modularizing methodologies in order to determine the method that generates the best modular design for a company. The authors base their conclusion on which method offers the highest ease of assembly while offering the variety to meet future customer needs.

The first method is the heuristic approach. Stone et al. (2000) describes a heuristic approach to identify the modules using a function-based decomposition approach. The overall function of the product is decomposed into sub-functions, starting with a so called black-box model which represents the product's overall function. The second task is to develop a chain of sub-functions that operate on the flow. Afterwards, the three proposed heuristics (i.e. dominant flow heuristic, branching flow heuristic and conversion-transmission heuristic) are applied on to the functional model in order to identify the modules in the design problem (Stone, Wood & Crawford, 2000).

Criteria	Variant mode and Effect Analysis - Caesar (1991)	Design structure matrix - Pimmler & Eppinger (1994)	Product development - Ullrich & Eppinger (1995)	Development of modular products - Kusiak & Huang (1996)	Towards a theory of modular design - Stone (1997)	METUS - Göpfert (1998)	Modular function development - Erixon (1998)	Developing product family architecture - Jiao (1999)	Design for Variety - Martin & Ishii (2002)	Produktcomplexität managen - Schuh (2005)	Approach to Product Family Design - Simpson (2012)	Modularizing product architectures using demdograms - Höllta-Otto (2003)	Product Family Masterplan - Harlou & Mortensen (2006)	Structural Complexity Management - Lindemann (2009)	Size Ranges and Modular Products - Pahl & Beitz (2007)	Integrated PKT-approach - Krause (2011)
Product variety	Mainly considered	Not/weakly considered	Partially considered	Partially considered	Mainly considered	Not/weakly considered	Partially considered	Mainly considered	Mainly considered	Mainly considered	Mainly considered	Not/weakly considered	Mainly considered	Not/weakly considered	Partially considered	Mainly considered
Technical-functional modularization	Not/weakly considered	Mainly considered	Mainly considered	Mainly considered	Mainly considered	Mainly considered	Not/weakly considered	Mainly considered	Mainly considered	Not/weakly considered	Mainly considered	Mainly considered	Mainly considered	Mainly considered	Mainly considered	Mainly considered
Product strategic modularization	Not/weakly considered	Partially considered	Partially considered	Not/weakly considered	Not/weakly considered	Partially considered	Mainly considered	Mainly considered	Partially considered	Partially considered	Not/weakly considered	Not/weakly considered	Mainly considered	Partially considered	Not/weakly considered	Mainly considered
Product-related visualization	Partially considered	Not/weakly considered	Not/weakly considered	Mainly considered	Partially considered	Mainly considered	Partially considered	Partially considered	Not/weakly considered	Not/weakly considered	Not/weakly considered	Partially considered	Partially considered	Partially considered	Mainly considered	Mainly considered
Redesign for modularization	Mainly considered	Not/weakly considered	Not/weakly considered	Not/weakly considered	Partially considered	Not/weakly considered	Partially considered	Not/weakly considered	Mainly considered	Mainly considered	Partially considered	Not/weakly considered	Mainly considered	Partially considered	Partially considered	Mainly considered
Integration of interdisciplinary expertise	Mainly considered	Partially considered	Mainly considered	Not/weakly considered	Partially considered	Mainly considered	Mainly considered	Partially considered	Not/weakly considered	Mainly considered	Partially considered	Not/weakly considered	Mainly considered	Partially considered	Partially considered	Mainly considered
Guideline	Mainly considered	Mainly considered	Partially considered	Partially considered	Mainly considered	Mainly considered	Mainly considered	Not/weakly considered	Mainly considered	Partially considered	Mainly considered	Mainly considered	Partially considered	Mainly considered	Partially considered	Mainly considered
Tailored to corporate situation	Mainly considered	Mainly considered	Partially considered	Not/weakly considered	Mainly considered	Mainly considered	Mainly considered	Not/weakly considered	Mainly considered	Mainly considered	Mainly considered	Not/weakly considered	Mainly considered	Mainly considered	Mainly considered	Partially considered
Usability in corporate context	Mainly considered	Mainly considered	Mainly considered	Mainly considered	Mainly considered	Mainly considered	Mainly considered	Not/weakly considered	Partially considered	Mainly considered	Partially considered	Partially considered	Partially considered	Mainly considered	Mainly considered	Mainly considered
Product program view	Not/weakly considered	Not/weakly considered	Partially considered	Not/weakly considered	Not/weakly considered	Partially considered	Partially considered	Mainly considered	Not/weakly considered	Partially considered	Not/weakly considered	Partially considered	Partially considered	Not/weakly considered	Not/weakly considered	Not/weakly considered
Process and company structures	Partially considered	Mainly considered	Mainly considered	Not/weakly considered	Not/weakly considered	Mainly considered	Mainly considered	Mainly considered	Not/weakly considered	Partially considered	Not/weakly considered	Not/weakly considered	Mainly considered	Mainly considered	Not/weakly considered	Not/weakly considered
Costs	Mainly considered	Not/weakly considered	Mainly considered	Partially considered	Partially considered	Not/weakly considered	Mainly considered	Mainly considered	Mainly considered	Mainly considered	Not/weakly considered	Not/weakly considered	Mainly considered	Not/weakly considered	Partially considered	Not/weakly considered
Concept evaluation	Mainly considered	Not/weakly considered	Mainly considered	Not/weakly considered	Mainly considered	Mainly considered	Mainly considered	Mainly considered	Not/weakly considered	Mainly considered	Mainly considered	Mainly considered	Mainly considered	Not/weakly considered	Mainly considered	Partially considered

Mainly considered
Partially considered
Not/weakly considered

Table 1. Comparison of different modular product families (Adapted from Krause & Ripperda, 2013, p.3)

The second method, the B-FES approach, builds upon the heuristic approach by Stone et al. (2000). The B-FES approach by Zhang et al. (2006) reasons that the heuristic approach lacks a reasoning behind the behaviour of the different components. The objective of the B-FES approach is to look for the matching behaviour whose functional output can achieve the desired function (Kremer & Gupta, 2012).

The third method is the decomposition approach. Huang and Kusiak (1998) developed a matrix representation of the modularity problem, which enables the identification of the modules even without sufficient information. Modular products are based on suitability and interaction matrices. The suitability matrices represent to what extent the modules are suitable for the inclusion in a module, and the interaction matrix represents the interaction among components. Then, a decomposition approach is followed in order to transform the interaction and suitability matrices in order to find certain types of modularity.

Based on the review by Kremer & Gupta (2012), the decomposition approach was found to be the best of the three based on their criteria (i.e. highest ease of assembly and the extent to which the method meets the variety in customer demand).

Dahmus et al. (2001) introduce a modularity matrix which gives a framework that can help with designing possible modularity schemes within a company. Architectures that are generated through this model can then be selected through different approaches such as potential profits for a firm or through certain selection methods (Dahmus et al., 2001). The modularity matrix consist of four different steps:

1. Develop separate function structures for each product concepts
2. Union multiple product function structures into a single family function structure
3. Construct a modularity matrix using functions from the family function structure versus products in the family
4. Use the modularity matrix to aid in constructing different possible product and portfolio architectures

Despite the benefits of modularization, modular product architecture has potential issues. Modular products need to be designed with redundant physical components and limited function sharing, so that they are compatible across other products which might result in increased variable costs (Ulrich & Tung, 1991). Also, in case of high-powered mechanical products, modularity is not always desirable. Mainly because with modularity, the product becomes larger, heavier and less energy efficient. Also, it may become harder to control adverse effects such as heat dissipation (Whitney, 2004).

Note that a modular design influences inventory management (Duray, 2004). Also, the possibility for modularization is dependent upon the products a company offers through its product portfolio (Dahmus, Gonzalez-Zugasti & Otto, 2001; Zamirowski & Otto, 1999). In other words, not all products or not every product portfolio is suitable for modularization. Sometimes the variety in products is necessary due to technical reasons, reasons offered by customers or design reasons (i.e. the shape of the product does not allow standardizatoin). Among the factors that influence the possibility to modularize the product portfolio are: traditional market variance, usage variance and technology change (Dahmus et al., 2001). Also, the way a customer uses the product, the extent to which variety is needed within a product after purchase, influences the possibility for modularization (Dahmus et al., 2001). Close interaction with the customer is of key importance when implementing a modular design. A modularized product that have too many features may decrease customer lifetime value (Thompson, Hamilton & Rust, 2005).

The next chapter explains which theory is chosen as a modularization method and the reason for it. This reasoning is followed by the introduction of the flowchart.

3.3 Development of the process: design for variety as modularization method

Based on the above stated literature review, a process is developed in order to lower complexity costs through implementing a modular design.

Design for Variety is used as modularization method, as it fulfils the criteria that the method is suitable for this research: redesign the product portfolio. Also, it fulfils the criteria set by the pilot company, as clear guidelines are important to reproduce this research for different product families. The associated cost aspect, which also is considered by Martin and Ishii (2002), is an important criteria as well for the company. The pilot company is not looking for a big investment at the moment. The other method that is left after these criteria, the Variant mode and Effect analysis by Caesar (1991), is not suitable since it does not view modularization from a product view perspective, which is evident in this research.

Design for variety is chosen over the decomposition approach introduced by Kremer & Gupta (2012), as the decomposition approach is the best approach fulfilling just two criteria: ease of assembly and meeting future customer needs. The design for variety method fulfils the criteria from Schuh and company (2012) that both internal and external environment should be taken into account. The next subchapter gives a detailed description of the design for variety method.

See figure 5 for an overview of the different steps within the process, presented in a flowchart. Appendix B shows the meaning of the symbols.

After identifying the need for lowering complexity costs within an organization, an analysis is made of the current product portfolio. This analysis is used to define the scope of the research. Information such as number of sales and revenues are used in order to give a profound analysis of the product offerings. The so-called Whale Curve shows that the top 20% to 30% of the product sales to customers, can generate up to 300% of the profits. As profits cannot exceed 100%, the remaining 70% to 80% loses profits (Wilson, 2009; Kaplan & Narayanan, 2001). Unprofitable customers are customers who order custom products and require the company to hold inventory (Kaplan & Narayanan, 2001). By using the Whale Curve, the most profitable products of the company can be identified. In this way, a right scope for the research has been defined in order to get efficient results (i.e. the products are targeted that can enhance the performance the most). Figure 6 shows a graphical representation of the whale curve.

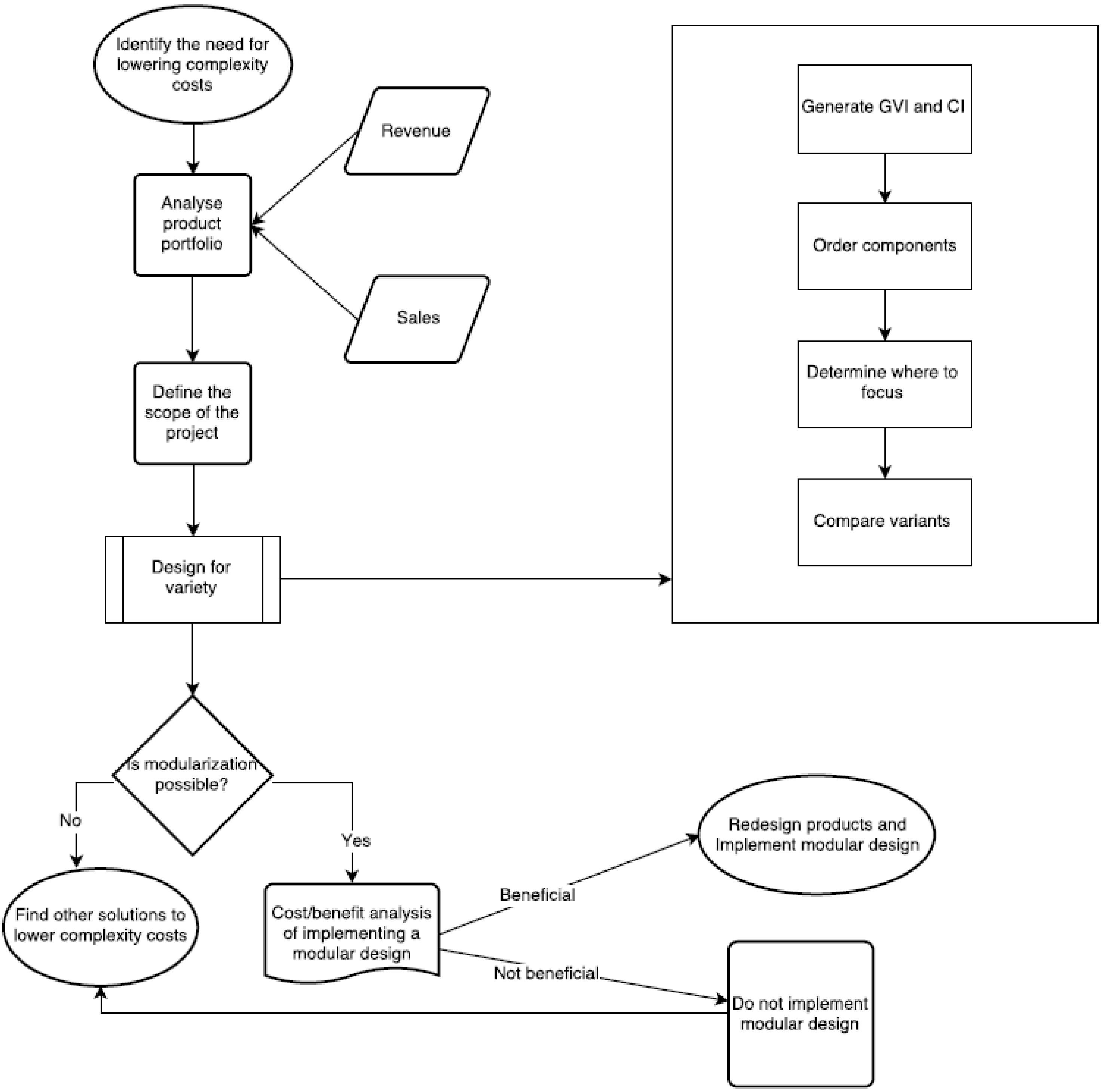

Figure 5. Flowchart to reduce complexity costs

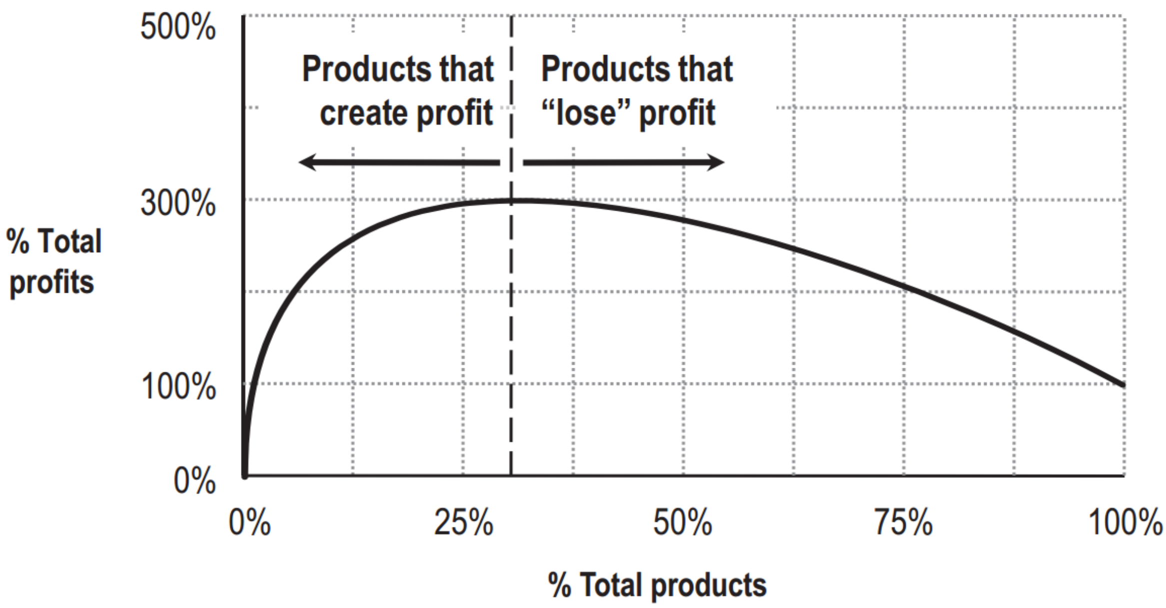

Figure 6. The Whale Curve (Wilson, 2009, p.5).

For illustration purposes, an example is given of the usage of the whale curve. After analysing the current product portfolio, a company can find that 21% of their product portfolio generate 350% of the profit from last year. This means that the remaining 79% of the products destroyed 250% of the profits from last year. By removing or redesigning those 79% of the products, profits can be improved.

The design for variety method shows whether or not modularization is possible for the current product portfolio. If not, other ways to lower complexity costs have to be considered. If modularization is possible, a cost and benefit analysis has to be made in order to see whether or not implementing a modular design is beneficial. Before the implementation, a redesign is made of the products that are influenced by the implementation of the design.

3.4 Design for variety: a modularization method

The design for variety method consists of four distinctive steps. Following these four steps creates a foundation on where a solid and well-considered decision can be made whether or not modularization is possible within the current product portfolio. The article by Martin and Ishii (2002) explains these four steps in detail.

Step 1: generate the generational variety index (GVI) and the Coupling indices (CI) for the design

The generational variety index, hereafter abbreviated as GVI, is an indicator of which components are likely to change over time. The index indicates the amount of redesign that is required for a component to meet the future market requirements (Martin & Ishii, 2002). The GVI index is based on an estimate of required changes in components from external factors. Changes in these factors may cause changes in components over time. To generate the GVI index, seven different steps need to be followed. A graphical representation of these steps can be found in Appendix C.

1. Determine market and desired life of product platform

The first step is to determine the market which the product is targeting. This market may change over time. Also, the desired life time of which the product platform has to operate needs to be determined. As the goal of this research is not to develop a new product platform, this step is limited to determining the market as customer needs differ between markets. These customer needs are listed in step two of the GVI index.

2. Create the quality function deployment (QFD) matrix

The quality function deployment (QFD) enlists two phases. The first phase lists the external customer requirements and their relationship to engineering metrics. The second phase maps the engineering metrics to the components used in the design. An “X” indicates a relationship in phase one, whereas in phase two the “X” indicates that the components can affect the engineering metric (Martin & Ishii, 2002).

3. List expected changes in customer requirements

In the table derived from phase one from the QFD matrix, a column needs to be added to estimate (qualitatively) the range of change for the customer requirements. The range of change is determined with high, medium or low whereas high indicates that this is a rapidly changing customer need.

4. Estimate engineering metric target values

This step determines the engineering metric target values (EMTV) for the period for the desired lifetime of the product. The target values could be based on information from conjoint analysis, trend analysis, expected new markets, or expected competitor introduction of products. The estimation for this engineering metric values in this research is based on expected market developments (i.e. what do the customers expect to change) and previous trends (i.e. amount of products introduced over time). This information is presented in a percentage to which the component is expected to change within the next five years for the current market.

5. Calculate normalized target value matrix

Step five consists of normalizing the target values from step four, and plotting them to visually represent the expected changes. Step five is an optional step within this process of determining the GVI.

6. Create GVI matrix

The matrix is based on the QFD phase two. To determine the GVI matrix, an estimation of the costs is made for changing the components to meet the future metric target values. The GVI matrix uses a 9/6/3/1 rating system for these estimates (see table 2). These costs includes design effort, tooling and testing). These costs are expressed as a percentage of the original costs of design.

Rating	Description
9	Requires major redesign of the component (>50% of initial costs)
6	Requires partial redesign of component (< 50%)
3	Requires numerous simple changes (< 30%)
1	Requires few minor changes (< 15%)
0	No changes required

Table 2. GVI Matrix rating system

7. Calculate GVI

The GVI is calculated by summing up each of the columns of the GVI matrix. The GVI is an indicator of the level of component redesign that may be required to meet the future engineering metrics.

The second index that is calculated is the coupling index (CI). Ulrich (1995) defines coupling as two coupled components whereas change in one component can require the other component to change. The CI in this paper is considered as the strength of coupling between the components in a product. The stronger the coupling, the more likely a change in one component will require a change in the other (Martin & Ishii, 2002). The process of defining the CI index consists of six steps. A graphical representation of these steps can be found in appendix C.

1. Develop basic physical layout for the product

In order to generate the CI, a general layout of the product must be known. From this general layout, linkages in components can be derived.

2. Draw control volume around components

A control volume (CV) is a boundary around a system indicating the flows into and out of that system (Martin & Ishii, 2002). In the design for variety method, each component is considered a control volume.

3. List specification flows required between components

For each control volume, a specifications are listed of what the control volume *receives* from each of the other volumes. Also, a list is made on what the control volumes *supply* to other control volumes. No assumptions of precedencies among the components is made in this stage.

4. Build a graphical representation of the specification flows

The results of step three can be visualized in a graphic manner. This step is optional, however may be useful as a graphical representation makes clear which control volumes supply numerous specifications to other components. These control volumes should be left static, in order to minimize redesign effort.

5. Estimate sensitivity of components to changes

For each specification, an estimation of the sensitivity of each component to a small change in that specification is made. If a small change in the specification requires a change in the component, it is listed as highly sensitive. Sensitivity is presented on a scale of 0/1/3/6/9, see table 3. For this rating system, it is assumed that the "impact" caused by a specification change is equivalent and linear across all components. (Martin & Ishii, 2002).

Rating	Description
9	Small change in specification impacts the receiving component (high sensitivity)
6	Medium-high sensitivity
3	Medium-low sensitivity
1	Large change in specification impacts the receiving component (low sensitivity)
0	No specifications affecting component

Table 3. CI rating system for sensitivity of specifications.

6. Calculate coupling index

From the coupling matrix, two indices are derived. The sum for a column indicates the strength of the information supplied by that component to other components and is referred to as coupling index-supply (CI-S). The sum of a row is information being received by that component, hence the coupling index-receive (CI-R) (Martin & Ishii, 2002).

A high CI-S indicates that the component receives relatively a lot from other components, therefore a change in this components probably results in a change in other components. A high CI-R results in a greater likelihood that a change is necessary due to changes in other components.

Step 2: order the components

The first phase of step two is to rank the components according to the GVI, from highest to lowest. These are the products that are most likely to change due to external factors (Martin & Ishii, 2002). Both the CI-R and the CI-S are added to the list of components.

Step 3: determine where to focus efforts (i.e. where to standardize and/or modularize)

In order to determine where to focus, the components are categorized into high/low categories. A component has a relatively high/low index when compared with other components within the same index. The categorization process is not necessary, however, it may help visually in the ranking process. Next, an estimation of the nonrecurring engineering (NRE) costs are determined. Up until this point, costs were not involved. However, costs can influence the decision on where to modularize significantly.

After adding the costs, a clear picture is given about the consequences of modularizing the different components (e.g. how it influences other components or to what extent external drivers are likely to influence future developments) (Martin & Ishii, 2002). Based on these consequences, a decision can be made on where to focus efforts.

Step 4: develop product platform architecture

The last step of the design for variety method is to develop a product platform architecture. However, the goal of this research is not to develop a product platform architecture. The goal is to consider the current product portfolio of the pilot company and point out areas that are suitable for modularization. Step three of the design for variety method determines these areas and its feasibility. Therefore, step four is not taken into account when applying the design for variety approach on the product portfolio of the pilot company.

Nevertheless, the top three components that are most suitable for modularization are compared between variants and questioned why there is a variance between them. Potential modularization within these components between the different variants are then submitted to a cost and benefit analysis. Therefore, the fourth step of the DFV approach is considered as limiting the variation within the components.

3.5 Other solutions

When modularization is not possible, other solutions arise to reduce complexity costs. Other solutions aim at directly influencing the product portfolio. Meaning that by applying these solution, the product portfolio is altered either by cutting out products, changing the assembly process or consider the customer wishes. By considering key numbers from inventory management, like inventory turnover and WIP, potential products can be identified that are not as profitable as the company.

Zhu, Hu, Koren and Marin (2008) point out that a mixed model assembly line is an alternative to reduce complexity cost as well.

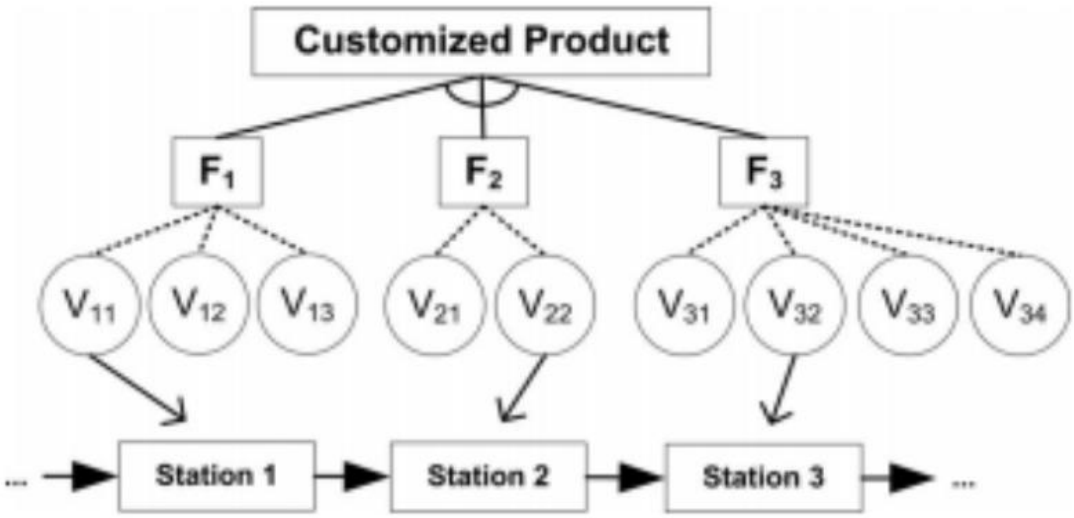

Figure 7: a mixed model assembly line

Figure 7 gives such an example of a mixed model assembly line. The customized product has three features, each with several variants. In figure 7, the possible number of different end products is 24 (i.e. 2 x 3 x 4). In the mixed-model assembly process, one variant is chosen from every feature and assembled along the assembly line. Quite often, this assembly process is accomplished manually where operates at every station must take the right choices considering choosing the right part, tools, fixture and procedure (Zhu et al., 2008).

Companies throughout the world have embraced mass customization as a way to avoid unnecessary costs and complexity that comes from the increasingly diverse customer needs (Gilmore & Pine, 1996). Mass customization aims to deliver products and services that best meet individual customers' needs with near mass production efficiency (Tseng & Jiao, 1996). Mass customization changes the design and production from 'made-to-stock' to 'made-to-order' and thus can also improve inventory and supply chain management efficiency (Tseng & Hu, 2014). Gilmore & Pine (1996) define four approaches to mass customization:

1. *Collaborative customizers* conduct a dialogue with individual customers to help them articulate their needs, to identify the precise offering that fulfills those needs, and to make customized products for them.
2. *Adaptive customizers* offer one standard, but customizable, product that is designed so that users can alter it themselves.
3. *Cosmetic customizers* present a standard product differently to different customers.
4. *Transparent customizers* provide individual customers with unique goods or services without letting them know explicitly that those products and services have been customized for them.

Not choosing the right approach can lead to unnecessary costs and complexity (Gilmore & Pine, 1996). However, mass customization is most beneficial with large quantities and also requires certain technological capabilities (Jiao & Tseng, 1999).

4. Results

The results are structured according to the different steps as proposed in the flowchart (see figure 5).

4.1 Analysis of the current product portfolio

The complete product list of the pilot company, including small product components and material parts, consist of over 8000 different parts. Most of these parts are used to assemble an end-product within the company. Overall, the majority of the revenue comes from their own products:

"I think that around 70-80% of our revenue comes from our own, assembled products, whereas the other 20-30% of the revenue we gather from acting as a supplier for other manufacturing companies" – Manager 2

This means that a filter needs to be added to filter the products that are assembled within the company. Also, the list consists of all the parts the company used till date, including the ones that are not used anymore. Moreover, materials as bolts and nuts are included in the product list as well. Some of the products are also tailored made for customers. After narrowing down the list, 21 mainly generic products remained. These products are all assembled within the company, have different variants, have been sold during the last year and influences the total revenue significantly (i.e. totally over 67% of the total revenue in 2015) (Annual report, 2015). From these 21 products, the total revenue over 2015 and the first half of 2016 are calculated, using updated selling prices and the number of sales over 2016 and the sales of 2016 up until June. The average price per product differs, even within one product line (e.g. ST1, ST2, T1, TW2), due to the fact that:

"Some products are generic (e.g. ST1, STB, T-series) with different prices for different variants. This means that the average price per product (Revenue / # of sales) may vary per month as it is dependent on which variants are sold, in what amount and to which customer due to price reductions. The ERP-system in place within the company does not allow to specify this per variant within a product line. " – Employee 1

The results of the analysis of the sales of these 21 products can be found in appendix D.

4.2 Scope

By identifying and establishing product families, areas for complexity costs savings are ascertained (Ripperda & Krause, 2014; Kremer & Gupta, 2012). The pilot company already thought about several product families:

"In general, we have three product families: Group 1 consists of the ST1, ST2 and the STB. Group 2 of ST09 and ST07, whereas group 3 consists of T1, T2, T3 and T10. Then we have the W1, W2, W3 which can be seen as a group, however, they do not consist of a motor. Also, at assembly, there is one place where the 'rest' is made." – Employee 1

Product family group 1 generated 36,2% of the total revenue in 2015, and 35,3% in 2016. Group 2 and group 3 generated respectively 20,6% and 8,1% in 2015. Taking into consideration these contributions towards the revenue, product family 1 seems most appropriate for further analysis. This is agreed upon by current management:

"Taking ST1, ST2 and STB under consideration for your research seems like a good idea to me" – Manager 2

A name of a product variant has three parts, for example the ST1-5-3. The 'ST1' is named after the market which it targets, namely the stables ('stallenbouw'). The 5 represents the torque, namely 50 Newton meter (Nm). At last, the '3' represents the revolutions per minute. So in short, the ST1-5-3 is the first series of a drive system that can be applied in stables, with a torque of 50 Nm and 3 revolutions per minute.

From the ST family, including all the variants, the cost price and selling price have been validated or recalculated. An example of a calculation of the cost price for the ST2-15-1 can be found in appendix E. The cost price and selling price consequently lead towards a given margin per product. Table 4 shows some key numbers regarding the product group and its variants.

Variant	Cost price	Selling price	Margin	Sales in 2015	Sales in 2016
ST1-5-3	***	***	***	***	***
ST1-10-3	***	***	***	***	***
ST2-15-1	***	***	***	***	***
ST2-25-1	***	***	***	***	***
STB-5-3	***	***	***	***	***
STB-10-1	***	***	***	***	***
STB-10-3	***	***	***	***	***
STB-10-3-24Vdc	***	***	***	***	***

Table 4. Key numbers of the product family and its variants

Giving insights into the margins per product itself is of value for the company, as the margins are currently unknown:

"Our margins are very small, I do not know them exactly. We were planning to rise our prices in 2012, however, due to the economic downturn we decided not to do it. Till date, we still use the same prices" – Employee 2 + Sales 1

"Our margins are very small, some are even negative. However, I do not know the exact ones." – Employee 1

As the selling price is given as a list that is available within the company, the missing information regarding margins comes from the lack of a validated and reliable cost price. Hence, the need for calculating the cost price by hand (Appendix E). This is acknowledged within the pilot company:

"The cost price within the system are likely not up-to-date. I would not trust them" – Employee 1

The given sales prices are the standard prices. Bigger customers do have their own prices, with a given reduction (i.e. usually between 10 and 28%). This lowers the margins even more, hence proving the need for lowering the costs through modularization.

4.3 Design for variety: modularizing the product family

This chapter uses the modularizing method, design for variety, to analyse the product family. It ends with recommendations for the management, based on a cost and benefit analysis. Within this analysis, relationships has been made. For illustration, every (sub-)chapter consists of one or two example of reasoning behind these relationships. For a full view of the reasoning behind the tables and figures of the GVI, see appendix F.

4.3.1 DFV step one: generate GVI and CI for the design

The first step is to generate the GVI index and the CI indices. To recap, the GVI index is an indicator of the expected amount of redesign required for a component to meet the future market requirements. The CI indices are the likelihood that changing a component will require redesign in other components (CI-S), and the likelihood that a component will change when other components are redesigned (CI-R) (Martin & Ishii, 2002).

4.3.1.1 Generation of the GVI index

The first step is to determine the market where the design is operating in, as well as the future markets. Table 5 consists of the introduction dates of the ST1 and ST2. The development started in April 2006, was first tested in November 2006 and got introduced into the market in 2007. The market it got developed for is still the market till date.

Market	Description	Introduction date
-	Development start	04-2006
	First prototype	11-2006
Current	Storage	04-2007
Current	Stables	04-2007
Current	Ventilation	04-2007

Table 5. Markets and introduction dates ST1/ST2

The STB is developed as a cheaper alternative for the ST1 (budget version). However, as the economies of scale are not there (yet), the components for the STB are not cheaper to produce. Hence the higher cost price of a STB compared to the ST1 variants. Table 6 consists of the introduction dates from the STB.

Market	Description	Introduction date
-	Development start	09-2012
Current	Storage	11-2014
Current	Stables	11-2014
Current	Ventilation	11-2014

Table 6. Markets and introduction dates STB

The potential for future type of markets is low. However, there are other countries where the ST's possibly can be sold.

"*The application for the ST's are at its limit. However, the eastern countries is a market where we can sell our product. This is mainly because our drive system is mechanical, whereas the one from our competitor is more focused on electrical components. You see that the eastern countries prefer our mechanical systems". – Sales 2*

The second step of the GVI is to compose a simplified phase I and phase II QFD. Phase I lists the customer needs and their relationship to engineering metrics (table 7), whereas phase II maps the engineering metrics to the components used in the design (table 8).

The customer wants a working drive system for their application (e.g. ventilation, feeding system). A short-time duty electrical motor is cheaper than an electrical motor which can be

used continuously. After a cycles of roughly 10-15 minutes, the electrical motor has to cool down to room temperature as it is not cooled internally.
Also, the drive system has to be self-breaking as ventilation may not close by itself but only when the electrical motor is activated.

	Engineering metrics						
Customer Requirements	Short-time Duty	Weight	Lifespan	Dimensions	compatibility with standards	Self-breaking	Costs
Working drive system for the application	x					x	
Reliable			x			x	
Compact				x			
Low weight		x					
Easy to assemble/alter limit switch					x		
Easy to replace parts					x		
Low costs							x

Table 7. GVI QFD Phase I

	Components							
Engineering Metrics	Housing	Gear	Pinion Shaft	Worm	Worm wheel	Shaft	Limit switch	Electrical motor
Short-time Duty								x
Weight	x	x	x	x	x	x	x	x
Lifespan				x	x			
Dimensions	x							x
Compatability with standards						x		x
Self-breaking				x	x		x	

Costs	x	x	x	x	x	x	x	x

Table 8. GVI QFD Phase II

The short-time Duty relates to the electrical motor, as the electrical motor is the component that has to cool down to room temperature.
The lifespan of the drive system is mostly influenced by the worm and the worm wheel, as these two components are the first two components that are subject to wear.

The third step is consists of expected changes in customer requirements. These expected changes has been added to the table (table 9) that is already made for step two.

	Engineering metrics				
Customer Requirements	Short-time Duty	Weight	Lifespan	Dimensions	compatibility with standards
Working drive system for the application	x				
Reliable			x		
Compact				x	
Low weight		x			
Easy to assemble/alter limit switch					x
Easy to replace parts					x
Low costs					

Table 9. GFD phase I with expected changes in customer requirements

It is not expected that there will be a change in the reliability of a drive system. Customers require a drive system to be reliable at the moment, and it is expected that this will continue. In contradiction, it is expected that a drive system has to become more compact. Customers on the fair repeatedly said that there is less and less room for the installation of a drive system.

The fourth step is to estimate engineering metric target values. These estimated future values (table 10 for the ST-line is based on internal interviews, questions to customer via the phone or e-mail and conversations on a fair.

	Engineering metrics								
Customer Requirements	Short-time Duty	Weight	Lifespan	Dimensions	compatibility with standards	Self-breaking	Costs		Expected range of change over platform life
Working drive system for the application	x					x			L
Reliable			x			x			L
Compact				x					H
Low weight		x							H
Easy to assemble/alter limit switch					x				H
Easy to replace parts					x				M
Low costs							x		M
EM Target Values									
Current markets	1	3	2	4	3	2	3		

EM Target **Values**							
Current markets	1	3	2	4	3	2	3

Table 10. QFD phase I with EM target values added

As stated in step three, the dimensions of the drive system are very likely to change as there is less and less room for the installation of a drive system. Also, in relation to the easiness of mounting the drive system, the weight has to become lower.

Nevertheless, in general, there are no changes needed for different markets as it is not expected that different markets will be targeted with this product line.

This is in line with the wishes of the customers, as they are happy with the current product offerings of the pilot company:

"The current product range of the company is good"- Customer 1

"For our needs, the company offers the right products" – Customer 2

"The current product range is sufficient for us" – Customer 3

Remarks are made about the lead times the company currently has, however, this is not part of this research. Nevertheless, with the introduction of a modular design, the possibility arises that lead times become lower as it is less likely that components are not in stock. However, more research is needed for this.

The fifth step is an optional step. In step five, the normalized target value matrix is plotted to visually represent the changes. A histogram (figure 8) has been made to visually plot the expected changes is the engineering metrics for the current market. The higher the bar, the higher the expectation that a change is required.

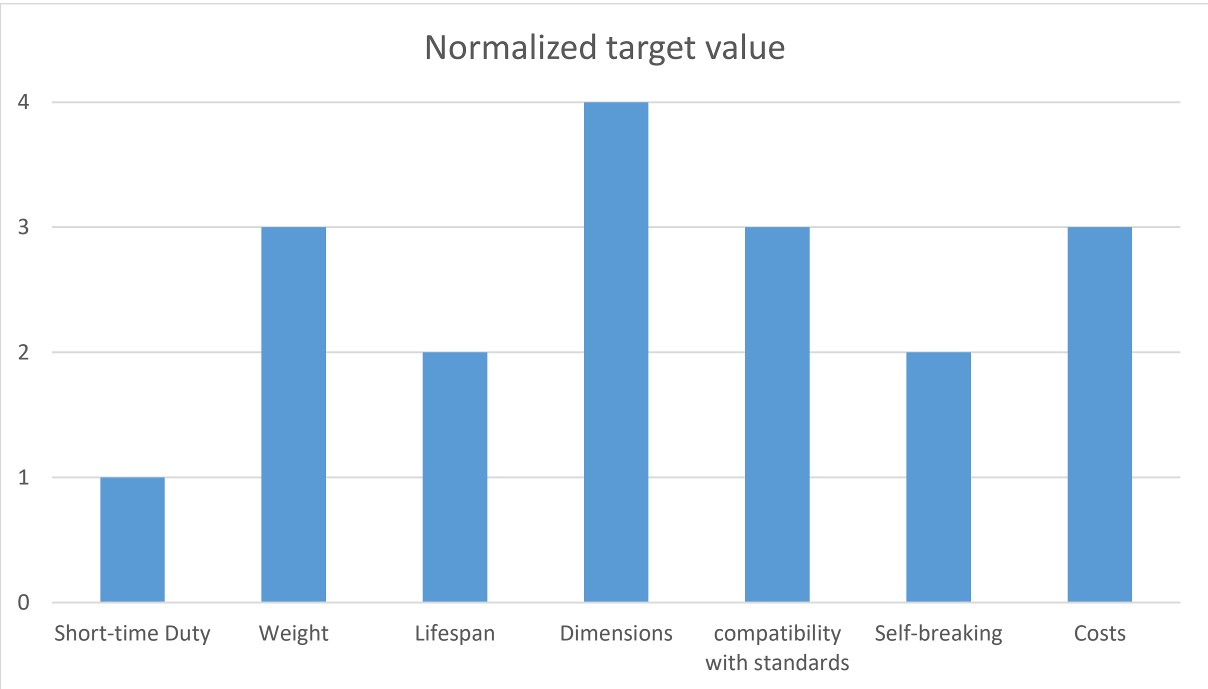

Figure 8 Expected change in EM normalized target values

Step six is to create the GVI matrix (see table 10). The GVI matrix is based on a 9/6/3/1 rating system, based on an estimation for the cost of changing to components as explained previously.

	Components							
Engineering Metrics	Housing	Gear	Pinion Shaft	Worm	Worm	Shaft	Limit switch	Electrical
Short-time Duty								3
Weight	9	3	6	3	6	9	6	9
Lifespan				6	6			
Dimensions	3							9
Compatability with standards						6		3
Self-breaking				3	3		9	
Costs	9	3	3	6	1	6	9	1
GVI	21	6	9	18	16	21	24	25

Table 11. GVI calculation

The costs of redesigning the limit switch in order to get it cheaper is more than 50% of the initial costs, as the redesign will be from a mechanical limit switch towards a technical limit switch. This will involve drawing, testing and gathering competencies from outside the company.

The costs of redesigning a worm wheel in order to get it cheaper are not high, as you can think of different materials or a different way of manufacturing (e.g. different programming to produce it faster).

Step seven consists of calculating the GVI. This is added to table 11. Based on the GVI, the three highest are the electrical motor, the limit switch and the housing and shaft.

4.3.1.2 Generation of the CI index

The first step is to develop a basic physical layout for the product. This layout can be found in appendix G. This is a detailed description of the drive system, and what component comes where on a detailed level.

Step two consists of drawing control volumes around components. It is important that every control volume is of roughly the same level of complexity. For the drive system, a control volume is draw around the housing, gear, pinion shaft, and so on.

Step three is about listing the specification flows required between components. In this step, information is given about the information the components supply and receive. Table 12 consists of this information. The numbers are on a scale from 0-9, and state the impact on the receiving components. These numbers are based on personal perception, and are discussed with multiple people throughout the organization in order to reduce bias.

The housing supplies and receives all the dimension and location of the different components, as the components only fit in one place. In the next step, a graphical representation of these flows is given.

Step four is a graphical representation of the specification flows. Figure 8 shows a basic layout of a drive system (i.e. ST1). The electrical motor (1) rotates the worm (2) when switched on. The worm in its turn, rotates the worm wheel (3). There is a low efficacy, as a lot of efficacy is lost with this abrasion. The pinion shaft (4) is flatted in the worm wheel, and therefore has a high efficacy and rotates when the worm wheel (3) rotates. In its turn, the pinion shaft rotates the gear (5) with a high efficacy. The shaft is flatted in the gear, and therefore rotates at the same speed. The limit switch is coupled to the shaft, and limits the number of rotations the shaft can make before turning off the electrical motor. Meaning that after the limit has been reached, the power is switched off and the electrical motor stops.

Components supplying information

Components requiring information

	Housing	Gear	Pinion Shaft	Worm	Worm wheel	Shaft	Limit Switch	Electrical motor
Housing		X dimension 3 Y dimension 3 Z dimension 3	X dimension 3 Y dimension 3 Z dimension 3	X dimension 3 Y dimension 3 Z dimension 3	X dimension 1 Y dimension 1 Z dimension 1	X dimension 3 Y dimension 3 Z dimension 1	X dimension 6 Y dimension 6 Z dimension 6	X dimension 1 Y dimension 1 Z dimension 1
Gear	X dimension 3 Y dimension 3 Z dimension 3 X location 3 Y location 3 Z location 3		Rotation, high efficacy 9					
Pinion Shaft	X dimension 3 Y dimension 3 Z dimension 3 X location 3 Y location 3 Z location 3				Rotation, high efficacy 0			
Worm	X dimension 3 Y dimension 3 Z dimension 3 X location 3 Y location 3 Z location 3							Rotation 1
Worm wheel	X dimension 3 Y dimension 3 Z dimension 3 X location 3 Y location 3 Z location 3			Rotation, low efficacy 9				
Shaft	X dimension 3 Y dimension 3 Z dimension 3 X location 3 Y location 3 Z location 3	Rotation, high efficacy 0						
Limit Switch	X dimension 3 Y dimension 3 Z dimension 3 X location 3 Y location 3 Z location 3					Moment to stop 1		
Electrical motor	X dimension 3 Y dimension 3 Z dimension 3 X location 3 Y location 3 Z location 3							

Table 12. CI matrix with specification flows

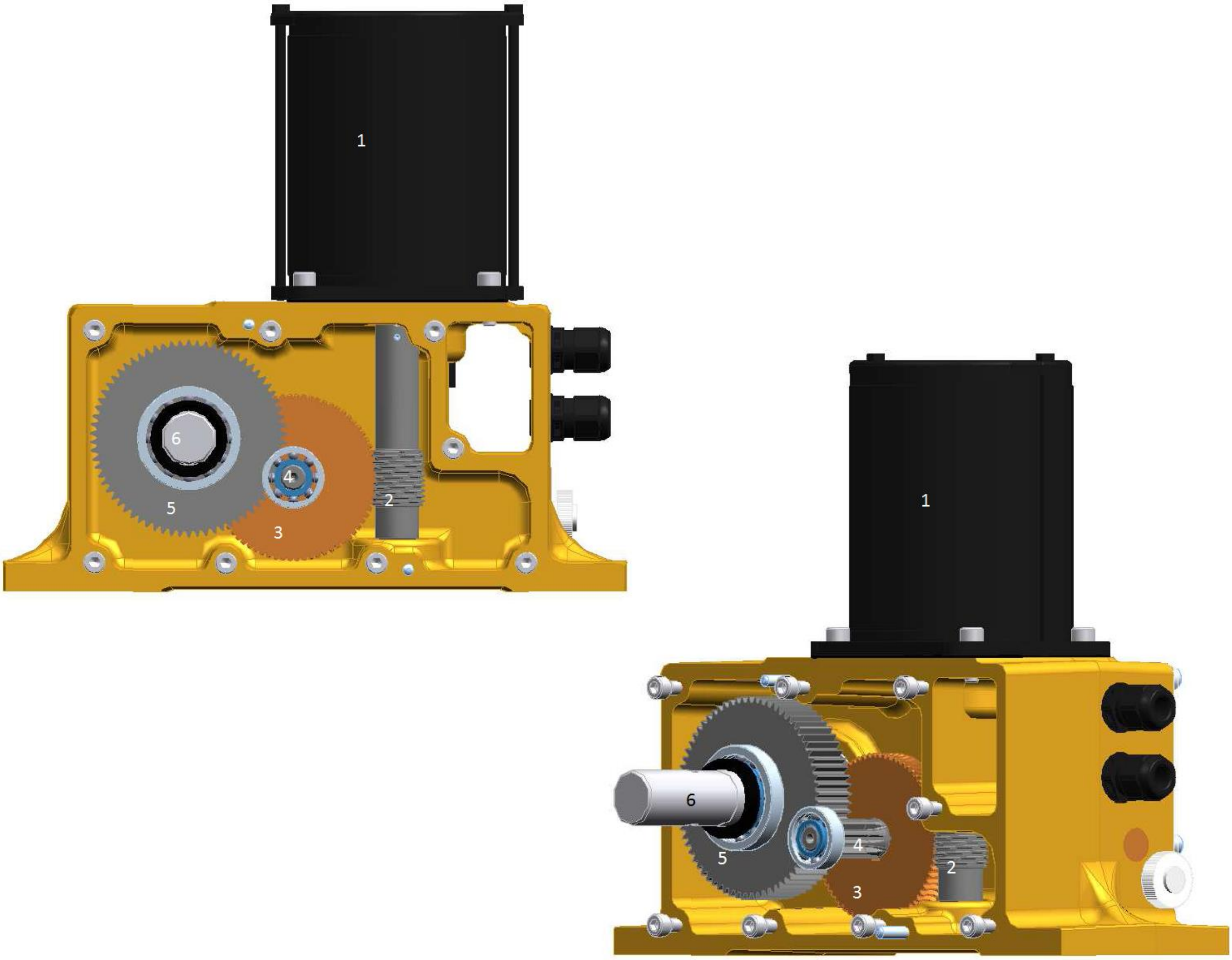

Figure 9 front and side view of a ST1

Step five of the CI index is to estimate the sensitivity of components to changes. This is a rating from 0-9, with 9 being a high sensitivity and 0 being a low sensitivity (table 13).

The gear and the shaft have a low sensitivity, as a change in for example the diameter of the shaft will not affect the gear (much), as you can only make the end of the shaft a bigger diameter. However, changing the worm will require significant change in the worm wheel as these two components are linked to each other and together are responsible for the self-breaking of the drive system.

Step six is calculating the CI. This step is added to table 13, by summing up the rows and columns.

Components supplying information

Components requiring information (rows)

	Housing	Gear	Pinion Shaft	Worm	Worm wheel	Shaft	Limit Switch	Electrical motor	CI-R
Housing		X dimension 3 Y dimension 3 Z dimension 3	X dimension 3 Y dimension 3 Z dimension 3	X dimension 3 Y dimension 3 Z dimension 3	X dimension 1 Y dimension 1 Z dimension 1	X dimension 3 Y dimension 3 Z dimension 1	X dimension 6 Y dimension 6 Z dimension 6	X dimension 1 Y dimension 1 Z dimension 1	58
Gear	X dimension 3 Y dimension 3 Z dimension 3 X location 3 Y location 3 Z location 3		Rotation, high efficacy 9						27
Pinion Shaft	X dimension 3 Y dimension 3 Z dimension 3 X location 3 Y location 3 Z location 3				Rotation, high efficacy 1				19
Worm	X dimension 3 Y dimension 3 Z dimension 3 X location 3 Y location 3 Z location 3							Rotation 1	19
Worm wheel	X dimension 3 Y dimension 3 Z dimension 3 X location 3 Y location 3 Z location 3			Rotation, low efficacy 9					27
Shaft	X dimension 3 Y dimension 3 Z dimension 3 X location 3 Y location 3 Z location 3	Rotation, high efficacy 1							19
Limit Switch	X dimension 3 Y dimension 3 Z dimension 3 X location 3 Y location 3 Z location 3					Moment to stop 1			19
Electrical motor	X dimension 3 Y dimension 3 Z dimension 3 X location 3 Y location 3 Z location 3								18
CI-S	42	10	18	12	10	8	18	4	306

Table 13. CI-S and CI-R calculated

4.3.2 DFV step 2: order the components

Table 14 shows the ranking of the components based on the GVI index. The CI-R and the CI-S index are added.

Component	**GVI**	**CI-R**	**CI-S**
Electrical motor	25	18	4
Limit Switch	24	19	18
Housing	21	58	42
Shaft	21	18	8
Worm	18	19	12
Worm wheel	16	27	9
Pinion Shaft	9	18	18
Gear	6	27	9

Table 14. Ordering the components

As can be seen, the electrical motor, the limit switch and the housing have the highest GVI index, where the housing has both a high CI-R and CI-S index. The electrical motor has the lowest CI-S index. In order to get a clearer picture of the indices, table 15 divides the indices into high or low. The GVI is high when it is over 20, according to Martin & Ishii (2002), whereas the CI-R and CI-S indices are also high when they are over 20. This number is based on the average CI-index for this product family.

Component	**GVI**	**CI-R**	**CI-S**	**NRE**
Electrical motor	H	L	L	€ 15.000,00
Limit Switch	H	L	L	€ 12.000,00
Housing	H	H	H	€ 10.000,00
Shaft	H	L	L	€ 500,00
Worm	L	L	L	€ 2.000,00
Worm wheel	L	H	L	€ 3.000,00
Pinion Shaft	L	L	L	€ 2.000,00
Gear	L	H	L	€ 3.000,00

Table 15. Ranking the indices into high and low

The last column adds the non-recurring engineering costs (NRE). The pilot company is not looking into high investments at the moment, however, in order to keep up with the market, these investments may be necessary.

4.3.3 DFV step 3: Determine where to focus

Even though the pilot company is not looking to make a big investment, the top 3 of the GVI index as presented in table 14 all require a substantial investment.

The focus is not on the electrical motor, as this is a product that is directly bought from a supplier and placed on a drive system. In other words, the pilot company does not manufacturer or alter the electrical motor. This means that it is harder to modularize the electrical motor. Therefore, the focus of this research is on the limit switch, the housing and the shaft and look for potential places to modularize there. The GVI index here is the most important, as this index comes from external factors (e.g. market) and competitiveness can be reduced if not acted on these market demand.

4.3.4 DFV step 4: comparison of variants

As said, the components where to focus on are the limit switch, the housing and the shaft. Table 16 compares these components across all the variants within the ST product family.

The numbers are the internal article numbers. Where the numbers are the same, the same component is used. Different numbers means different components in the variants.

All the components within the ST1 use the same housing, the same limit switch and the same shaft. This means that the ST1 is already modularized.

The ST2, in contradiction to the ST1, have three different limit switches: 6,12 or 18 revolutions. Two components within the limit switch influence the revolutions. This means that, due to this variance, the limit switch of the ST2 has more different components than the ST1. This leaves space for modularization, as standardizing the limit switch into EB18 reduces the number of goods that have to be produced with 4. Moreover, the limit switch is adjustable. In other words, when an EB18 limit switch is installed, it is possible to adjust it to an EB12. The convenience of the ST1 and ST2 is that the limit switch is adjustable from the outside. This means that you do not have to open the drive system to adjust the limit switch to the preferred amount of revolutions. For the STB, the number of revolutions is not adjustable from the outside but the housing has to be opened to do it. At installation, the number of

	ST1-5-3	ST1-6-5	ST1-10-3	ST2-15-1	ST2-25-1	STB-5-3	STB-10-1	STB-10-3	STB-10-3-24v
Housing	066-0106 066-0200	066-0106 066-0200	066-0106 066-0200	069-0100 069-0200	069-0100 069-0200	067-2120 066-0200	067-2100 066-0200	067-2110 066-0200	067-2100 066-0200
Limit Switch	EB18	EB18	EB18	EB6 EB12 EB18	EB6 EB12 EB18	EB8 EB16	EB8 EB16	EB8 EB16	EB8 EB16
Shaft	066-1200 066-1210 066-1220	066-1200 066-1210 066-1220	066-1200 066-1210 066-1220	069-1200 069-1210 069-1230	069-1200 069-1210 069-1230	067-3200 067-3250	067-3200 067-3250	067-3200 067-3250	067-3200 067-3250

Table 16. Comparison of the product variants

revolutions has to be set. However, here it is also possible to make it less than 8 or 16. Nevertheless, modularization here is not advisable as the limit switch is harder to alter once installed.

The housing of the STB differs across all variants. This is due to the fact that the torque differs, and to ensure the 'cheapest' drive system as possible, different electrical motors from different suppliers have been bought to use on these variants of the STB. All these motors have different worms and with that, different ways to assemble into the housing. This results in the difference of housings in the STB range.
Due to the low number of sales, under 120 in 2015 across all variants, no economies of scale are possible (yet). Hence the low margins on the STB.

4.4 Recommendations for management: Cost and benefit analysis

This chapter offer a cost and benefit analysis of the recommendations, that are derived from the analysis throughout this report and the potential areas for modularization as discussed in chapter 4.3.4.

4.4.1 STB-series

As discussed, the STB series offer a low margin. Taking into account that the selling price offered in table 2 is without potential (customer specific) reductions, number of STB drive systems are sold with a negative margin.
A big customer of the STB in 2015 was ***. *** is accountable for buying *** STB drive system in 2015, for a net price of *** apiece. Considering the cost price, which is ***, a loss of *** per drive system is made in 2015. If, for the same price, a ST1 was sold then the profit would be *** per drive system. This means that, by simply replacing the STB with a (usually more expensive) ST1 and sell it for the same price, a total saving of *** would have been made just on one customer. This would be higher of all the customers buying STB's are considered.

Based on this analysis, I would not sell any STB's anymore and simply replace them with a ST1 if there are no possibilities from 1) re-engineering the drive system in order to get one housing or 2) gather enough sales for the economies of scale in order to reduce the cost price. For the time being, keep on selling the STB-24v version as this is the only 24v version the pilot company is currently producing. Nevertheless, research should be done if the ST2 cannot be equipped with a 24v electrical motor.

The costs savings here are not the direct savings of ***for one customer. The most savings can be found in the indirect cost savings, as cutting out one product line reduces the time and effort being made in multiple areas throughout the organisation. It requires less planning, less maintenance of documents, less warehouse management, more specialization, and so on. The effects of cutting out an unprofitable product line occur more than one time, and therefore reduce complexity significantly within your company.

4.4.2 Housing

The housing of the STB is previously discussed. However, the housing of the ST1 and the ST2 purely differ on the installation of the limit switch. The ST1 has the limit switch at the end of the housing, where the limit switch is built in the middle. As a consequence, the ST2 has an extra hole in the middle of the housing. Also, the limit switch of the ST1 is placed at the bottom, where the limit switch of the ST2 is built at the top of the housing. This results in the fact that the housing of the ST1 and ST2 are not reciprocal. However, as the function of the house is exactly the same and the limit switch makes the housing different, a potential arise for the development of one housing for both the ST1 and the ST2.

My recommendation is to investigate the possibility for one housing for both the ST1 and the ST2. Looking at the number of sales of these drive systems, this can lead to serious economies of scale and rise the margin even higher. A cost reduction is possible in four areas, when one housing is developed for the ST1 and ST2.

Firstly, the set-up costs can be reduced. Over the time period of Januari 2015 untill June 2016, the housing for the ST1 was produced 22 times and for the ST2 24 times. The average set-up costs of the housing equals €***. The average productions of the housing is 23, so a total average savings of €*** could have been made if there was only one housing. Secondly, for every order for the castings of the house, a sum has to be paid to the supplier. The average sum is €***, which leads to a total savings of €*** considering the average productions of 23. The assumption here is that no castings are in inventory. Thirdly, direct inventory costs could have been saved as there is a higher inventory flow if just one housing is produced. Assuming an average inventory of 50 housings, 5% capital demands and 20% savings, €*** could have been saved over 2015. This may not seem as a huge amount, but keep in mind that this is purely the capital demand. It is very likely that the warehouse management becomes more sophisticated as less variants equals less transportation, less handling and so on. Fourthly, the shortage costs are reduced. If an item is not on stock, and longer lead times are necessary, this can lead to a loss of goodwill among customers. The assumption here is that the sale is not lost, therefore there are no direct financial losses. However, if no backlogging exists and the customer goes to a competitor, there are direct financial losses. If an item is not in stock, this can potentially lead to inefficiency as current production or planning needs to be broken down due to shortages. A 1% reduction in inefficiency, leads to a cost reduction of €*** a year. The assumption is made that the increase in efficiency is replaced with sold goods. In short, producing one housing instead of two could have led to a cost saving of over €*** a year.

As with cutting out the unprofitable STB-series, the big money savings are not within these €*** a year. Making only one housing saves money throughout the organisation, as mentioned before.

4.4.3 Limit Switch

For the ST1 the limit switch is standardized to EB18, or 18 revolutions. As the limit switch is easily adjustable for the ST1 and ST2, the number of revolutions can be set lower than 18. For the ST2 this is not the case, as customers can choose for the EB6 and EB12 as well. By standardizing the ST2 to EB18 as well, four articles become obsolete. Table 14 gives an overview of these articles, and the set-up costs of these articles over January 2015 – June 2016.

Limit Switch	Article obsolete	Set-up costs	Prod. ord. Jan' 2015 – Jun' 2016	Total savings
EB6	069-0800	***	***	***
	069-1440	***	***	***
EB12	069-0820	***	***	***
	069-1450	***	***	***

Table 15. EB6 and EB12 articles

Based on the numbers of table 15, the total savings would have been €*** if all the limit switches were EB18.

The assumption is made that there are no savings nor costs for holding inventory and material costs for the EB6 and EB12 components, as these are transferred equally towards the EB18. Also, the components for the EB18 become cheaper, as you have to make more products in one production order. Therefore, the set-up costs are divided among more products. This will result in even higher savings on the limit switch for the ST2.
The limit switch for the STB-line should not be standardized to just one kind, as the limit switch of the STB cannot be adjusted easily from the outside.

4.4.4 Shaft

The diameter of the shaft is not standardized within the market. In other words, the market does not offer a standard diameter of the shaft which is considered 'usual'. Therefore, there is no standardization possible on this component. The standard in the market is the option that can be placed on the shaft, namely the chain coupling. This means that the shaft should be the same diameter as the standard chain coupling. This is in line with the picture the sales department get from the market:

"*There is no standard diameter for the shaft in the market, it differs between customers. Therefore, standardizing the shaft diameter is tricky as every customers has its own personal wishes" – Sal2*

4.4.5 Reduction of lead times

While talking to customers, the current lead times were an issue. Some customers expect short lead times, as competitors of the pilot company have. Some customers go to competitors because of these long lead times. Also, the customers repeatedly said that they wish shorter lead times if necessary, especially for small orders.

My recommendation is to look at a better inventory management, as well as looking at specific orders that customers request. When a customers require a drive system urgently, even a higher price can be asked. This is something that should be taken into consideration.

5. Discussion

The discussion of this research encompasses the key findings, limitations and future research.

5.1 Key findings

During this research, it became evident that there is a lack of insights within the pilot company regarding key numbers such as cost prices of the products, the value of the inventory and the total product offerings. Also, within the pilot company effects of high complexity costs as missing economies of scale, long lead items and a high effort in maintenance and documentation are evident. This research offers some insights into these effects (e.g. insights into the cost price of drive systems) and its consequences (i.e. customers going to competitors because of the long lead items). This evidence shows that, when applying the developed process, other areas for improvement can be found as several parts of the company are under review.

The insights into the cost price of the ST-line showed that the STB has a small positive margin, and when considering net selling prices even a negative margin. This is due to the fact that there are numerous products made for the STB, for example the housing and the worms. By reconsidering the STB as a saleable product, a potential bleeder can be cut out of the organization and has a direct influence of the performance of the company. This means that not only an unprofitable product line is cut out, but also the complexity is reduced significantly. This is followed by a reduction of the complexity cost.

Another key finding was that even though the application for the ST1 and ST2 is the same, the housing differs purely on the installation of the limit switch. Making an uniform housing for both the ST1 and ST2 could potentially save a lot of costs. This reduces complexity costs as it reduces the number of variants within the company.

The limit switch for the ST1 is already modularized to EB18, while the limit switch of the ST2 is not. By modularizing the limit switch of the ST2 as well, over €***,- could have been saved over the last 1,5 year.

The shaft does not have a standard diameter in the market. However, when the market shift towards a standardized shaft, the pilot company should not wait en participate in this change.

The recommendations have a direct influence on the performance of the company. However, they also directly influence the complexity costs the company currently has. However, as previously mentioned, it is hard if not impossible to put a number to this reduction. Nevertheless, by reducing the number of variants and/or product lines, variety-induced complexity is reduced. It is reasonable to state that these indirect cost savings are a multitude of the direct costs savings as previously calculated. This means that the biggest cost saving is not the direct cost savings, but the indirect cost savings. The indirect costs savings save costs at areas as order entry, planning, production, communication efforts, warehousing etc.

These findings show that the model can be applied to medium-sized manufacturing companies with positive results. When such companies use this model, they gain competitive advantage and boost they profits by cutting out costs.

5.2 Limitations

This research has a few limitations. Firstly, the modularization method, design for variety, includes subjectivity. This means that the research is not fully objective. When a different researchers engages in the same research, slightly different results are possible. This limitation is reduced by pointing out the reasoning behind every choice that has been made during this research. Secondly, during the semi-structured interview the employees answered based on their personal perception. This could potentially lead to a bias. Thirdly, a lot of knowledge left the company at the beginning and during this research. This resulted in untrustworthy answers or no answers at all. Finally, there was no engineer available within the company during this research.

5.3 Future research

This research opens up multiple possibilities for future research. Firstly, the model should be tested more often, also in other manufacturing companies as well as different sizes. This leads to the possibility of generalization of the model. Secondly, regarding the pilot company, the potential of the STB should be taken into consideration. There can be a re-engineering to make one uniform housing and worm, or look into the market if there is potential to sell more STB's in order to gain economies of scale. Thirdly, the modularization of products could lead to shorter lead times. More research is needed whether or not this is the case.

6. Conclusion

This paper describes a new process through which complexity costs can be reduced in medium-sized manufacturing companies. This process has been tested in a pilot company and validated its goal. By presenting such an empirical tested model, a gap in the literate has been filled. As a practical contribution, the model can be used by other medium-sized manufacturing companies which are coping with relatively high variety-induced complexity costs. After identifying the need for lowering complexity costs, and targeting a certain product family, the design for variety method can be used as a modularization method to lower complexity cost.

This research shows that both direct and indirect costs savings occur from lowering variety-induced complexity costs. Direct cost savings as a consequence of modularization can be achieved at the limit switch. Moreover, this research raises questions about the profitability of the STB-line. By potentially cutting out a whole product line, and offer a current product line as an alternative, complexity costs are reduced as the variety of products are reduced significantly. In order to achieve these direct cost savings, the reasoning behind decisions has to be validated and submitted to a cost and benefit analysis. Factors that cannot be quantified, such as goodwill from the customers, should be taken into account in this cost and benefit analysis. Also, this research points out that the shaft does not have a standard in the market. Nevertheless, if a market development occurs towards a unified diameter for the shaft, the pilot company should pay attention and react to this development. As last, the customers pointed out some concerns towards the lead time, as well as market developments for example towards the dimensions (i.e. space of mounting the drive system). These signals from the market should be taken seriously and act upon.

Even though the indirect complexity costs cannot be quantified, they are significantly higher than the direct cost savings as these indirect cost savings occur more than once. Cost savings occur at the level of order entry, production planning, communication, warehouse management and so on.

Also, this research points out the effects of a high variety-induced complexity as there is little up-to-date documentation available about the products, there are longer lead times than demanded by the customers and there are missing economies of scale. Also, the numerous suppliers contribute to the higher complexity costs. These effects are affected if the recommendations are followed.

By following the guidelines as presented by Martin & Ishii (2002), and including these guidelines into the developed process, this research offers a good example for one product family. Consequently, if wished for, other product families can be targeted in order to lower the complexity costs even further and potentially finding areas for direct costs savings. Thus following the initially developed model leads to the wished outcome and therefore does not need to be altered.

Concluding, in line with the literature, modularization is a way to reduce complexity costs in a medium-sized manufacturing company. By applying the presented process, and consequently following the recommendations, complexity costs are reduced in the pilot company. More research is needed if this process is applicable for larger manufacturing companies.

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8. Appendix

Appendix A

The below stated example comes directly from the research done by Simon (1962).

There once were two watchmakers, named Hora and Tempus, who manufactured very fine watches. Both of them were highly regarded, and the phones in their workshops rang frequently—new customers were constantly calling them. However, Hora prospered, while Tempus became poorer and poorer and finally lost his shop. What was the reason? The watches the men made consisted of about 1,000 parts each. Tempus had so constructed his that if he had one partly assembled and had to put it down—to answer the phone, say—it immediately fell to pieces and had to be reassembled from the elements. The better the customers liked his watches, the more they phoned him and the more difficult it became for him to find enough uninterrupted time to finish a watch. The watches that Hora made were no less complex than those of Tempus. But he had designed them so that he could put together subassemblies of about ten elements each. Ten of these subassemblies, again, could be put together into a larger subassembly; and a system of ten of the latter subassemblies constituted the whole watch. Hence, when Hora had to put down a partly assembled watch in order to answer the phone, he lost only a small part of his work, and he assembled his watches in only a fraction of the manhours it took Tempus.

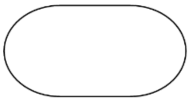
It is rather easy to make a quantitative analysis of the relative difficulty of the tasks of Tempus and Hora: Suppose the probability that an interruption will occur while a part is being added to an incomplete assembly is p. Then the probability that Tempus can complete a watch he has started without interruption is $(1-p)^{1000}$ *—a very small number unless p is 0.001 or less. Each interruption will cost, on the average, the time to assemble 1/p parts (the expected number assembled before interruption). On the other hand, Hora has to complete 111 subassemblies of ten parts each. The probability that he will not be interrupted while completing any one of these is* $(1-p)^{10}$ *, and each interruption will cost only about the time required to assemble five parts. Now if p is about 0.01—that is, there is one chance in a hundred that either watchmaker will be interrupted while adding any one part to an assembly—then a straightforward calculation shows that it will take Tempus, on the average, about four thousand times as long to assemble a watch as Hora. We arrive at the estimate as follows:*

1. Hora must make 111 times as many complete assemblies per watch as Tempus; but

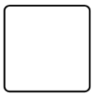
2. Tempus will lose on the average 20 times as much work for each interrupted assembly as Hora [100 parts, on the average, as against 5]; and

3. Tempus will complete an assembly only 44 times per million attempts (0.991000 = 44 × 10-6), while Hora will complete nine out of ten (0.9910 = 9 × 10-1). Hence Tempus will have to make 20,000 as many attempts per completed assembly as Hora. (9 × 10-1)/(44 × 10-6) = 2 × 104 . Multiplying these three ratios, we get 1/111 × 100/× 0.9910/0.991000 = 1/111 × 20 × 20,000 ~ 4,000

Appendix B

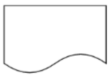


Start/end – this symbol represents the first or last step of a process



Process – this symbol represents a step within the process

Sub-process – used to articulate steps which combined is a process



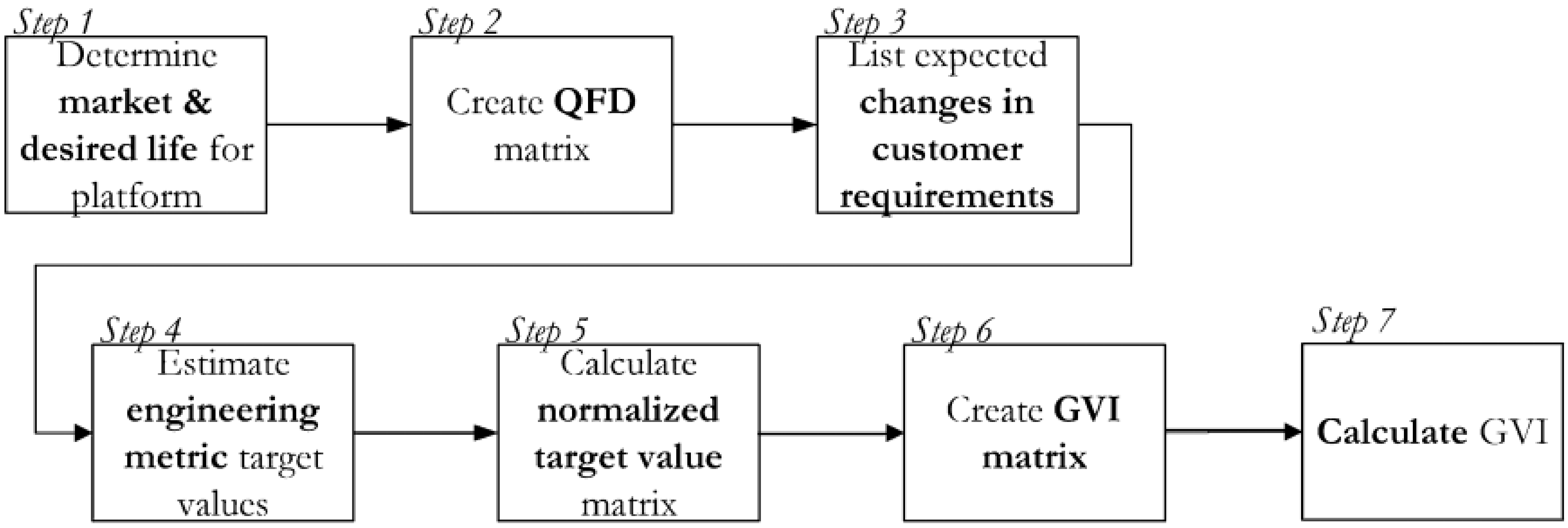
Document – this step results in a given document

Information – this symbol characterizes an information in- or outflow

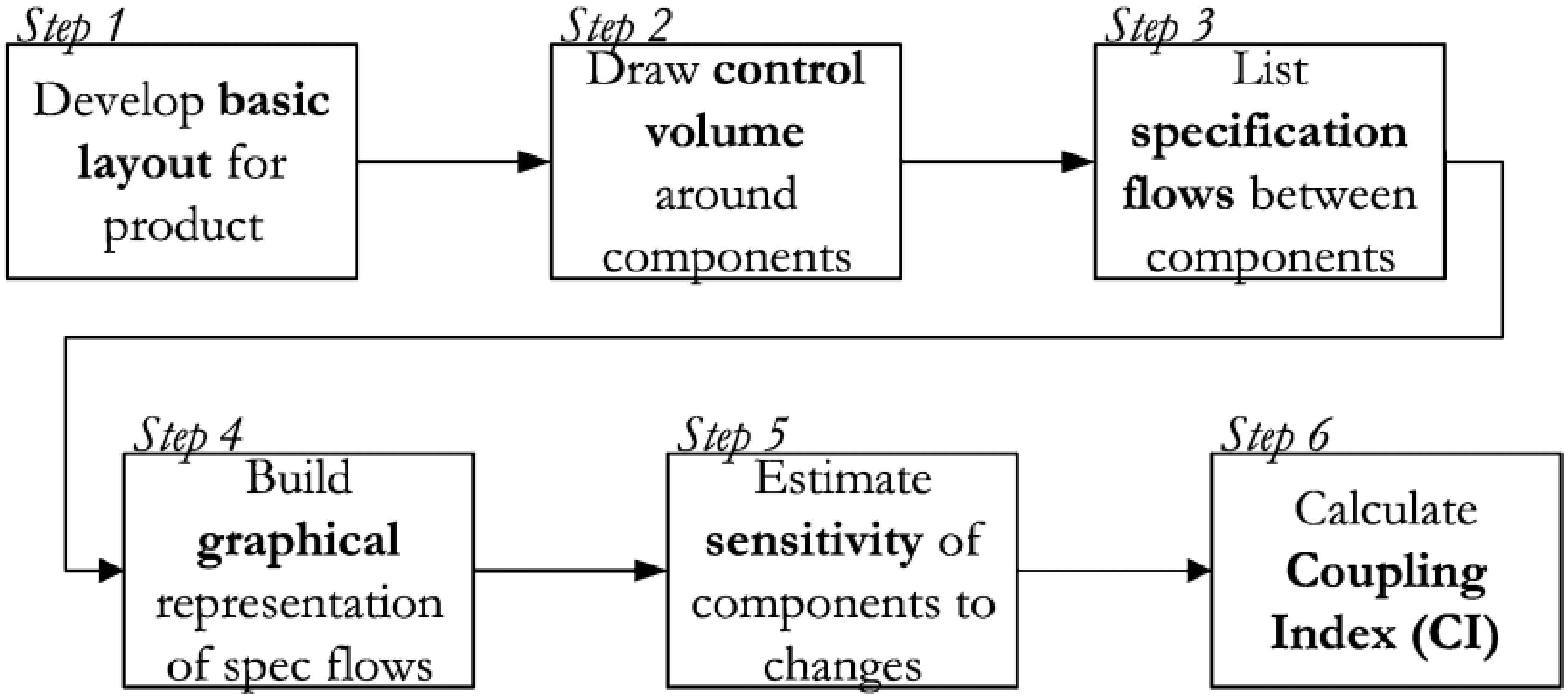
Decision – this symbol means that a decision has to be made

Appendix C

Graphical representation of the steps for establishing a GVI index



Graphical representation of the steps for establishing a CI index



Appendix D

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Appendix E

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Appendix F

GVI QFD Phase 1

Customer requirement	Engineering metric	Argument
Working drive system for the application	Short-time Duty	The electrical motor that is used on the drive systems requires a cool down time, as it is not cooled internally. For this product line, the electrical motor has a short-time duty of 10 minutes after which it has to cool down to room temperature.
Working drive system for the application	Self-breaking	The application requires a certain number of turnarounds from the shaft. After this, the drive system has to stop and the ventilation (e.g.) should not close by itself.
Reliable	Lifespan	The products has to be reliable throughout the lifespan that the drive system is supposed to have.
Reliable	Self-breaking	The self-breaking function of the drive system has to be reliable. It should not be possible that the ventilation closes by itself.
Low weight	Weight	In order to enhance the ease of mounting the drive system in a greenhouse or storage room, the product needs a low weight. The engineer needs to use materials that have the lowest weight while still functioning.
Compact	Dimensions	The dimensions of a drive system needs to be small, as there is less and less room to place a drive system and it may safe costs for transportation.
Low weight	Weight	The lower the weight of the drive system, the lower the transportation costs and the easier it is to assemble the product.
Easy to assemble/alter limit switch	Compatibility with standards	The limit switch of a drive system needs to be easy to assemble or adjust to the wishes of the customer. The closer it gets to the (market) standards, the higher the possibility that the customer is familiar with the limit switch.
Easy to replace parts	Compatibility with standards	Components that comply to the standards (e.g. shaft, electrical motor) are more common and therefore easier to replace and possibly cheaper.
Low costs	Costs	The customer wants to have its drive system as cheap as possible while still functioning according to the customer wishes. In other words, a good price/quality ratio.

QFD Phase 2

Engineering metric	**Component**	**Argument**
Cool down time motor	Electrical motor	Relates to the cool down time of the electrical motor
Weight	Housing	All the components contribute to the weight of the drive system. Reducing the weight in one component of the drive system results in a reduction of the overall weight with the same amount.
	Gear	
	Pinion Shaft	
	Worm	
	Worm wheel	
	Shaft	
	Limit switch	
	Electrical motor	
Life span	Worm	The worm and the worm wheel are the first two components that are worn out.
	Worm wheel	
Dimensions	Housing	The dimensions of the drive system itself are determined by the housing and the electrical motor
	Electrical motor	
Compatibility with standards	Shaft	The diameter of the shaft has a standard, which is set by the market. This influences the chain coupling, which is an option on the drive system.
	Electrical motor	The electrical motor has its own standards, the IEC standards. Complying to this standard results in an easier replacement possibility when needed.
Self-breaking	Worm	The angle between the worm and the worm wheel define the self-breaking of the drive system.
	Worm wheel	
	Limit switch	The limit switch defines when the drive system has to stop. Hence, when the self-breaking has to start
Costs	Housing	All the components contribute to the costs of manufacturing a drive system. Saving costs in either of the components results in a reduction of the overall costs.
	Gear	
	Pinion shaft	
	Worm	
	Worm wheel	
	Shaft	
	Limit switch	
	Electrical motor	

Expected range of change over platform life

Customer requirement	Expected range of change	Argument
Working drive system for the application	L	It is expected that the short-time duty of the drive system will not change much in the future. The application of this product range does not need a continuously functioning electrical motor.
Reliable	L	The product needs to be reliable now, as well as in the future.
Compact	H	Different fairs and customer interviews showed that the available space in order to install the drive system becomes smaller.
Low Weight	H	It is expected that the weight of a drive system has to become lower, as the labour conditions of employees becomes more strict (e.g. one may lift up to 25 kg by itself).
Easy to assemble/alter limit switch	H	Customers find it pleasing that the limit switch is easy to install. As the market changes towards electrical limit switches, from mechanical limit switches, the current ease of assembly should stay intact and potentially should become easier with technology developing.
Easy to replace parts	M	Currently customers appreciate the ease of replacing components within a drive system. It is expected that, considering the current globalization, a component should not have to come from the Netherlands if they are in the United States.
Low costs	M	The customer wants a low price. However, considering the raising competitive pressure, the product has to become cheaper.

EM target values

Engineering metrics	EM target value (1-4 range)	Argument
Cool-down time	1	As the application is not expected to change for this product line, the electrical motor remains a short-duty motor. Therefore, the cool down time is not expected to change.
Weight	3	It is expected that the weight of the drive system has to be lower in the future.
Lifespan	2	Currently, the drive systems in the field last for over 10 years. There are no signals from the market regarding a demand for a longer lifespan.
Dimensions	4	There will be less and less room for the assembly of a drive system in a greenhouse or storage room, this means that the drive system has to become smaller.
Compatibility with standards	3	Currently, the drive systems (partly) do not apply to the standards in the market (e.g. shaft diameter). It is expected that the market is going to demand more standardized parts.
Self-breaking	2	The drive systems are self-breaking at the moment. It is expected that the market demands this to continue. However, the positioning may become more precise.
Costs	3	The customer wants a low price. However, considering the raising competitive pressure, the product has to be designed cheaper.

Appendix G

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