Cost analysis of robot families

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Summary

During the last decades, the production enterprises have gone through a strong global change in terms of shorter product life cycles, fluctuations in the order income and increased demand of customized products. Basically, a company needs to develop appealing products in terms of cost and quality that are brought to the market in timely manner. As many studies show that over 70% of the total life cycle cost of a product is determined at the early design stage, this thesis work are focused on analyzing how the total cost of robot families can be affected in the early design stage through changing the component commonality level. More specifically, a cost estimation model in excel has been built to see how the total costs of robot family IRB 6640 are affected when choosing different gears for joints one, two and three. Also, a more general analysis has been done where it is investigated how ABB can take benefit of a product configuration system integrated with a robot platform and cost estimation model.

The result of this study shows that the traditional opinion on "higher commonality means lower costs" is not applicable in all cases. For instance, considering the commonality of gears within a robot family, the optimal solution out of a cost perspective do no longer exists at the highest commonality possible but at a slightly lower commonality level, lying between $0,7 < CI < 0,9$ using the measurement commonality index (CI). This is because the gears tend to be over dimensioned, and thereby more expensive for certain joints when commonality increases. The analysis also shows that fix and variable costs are not linear to each other, which complicates the situation when trying to describe the change of total costs with one commonality index. Consequently, two different commonality indices are needed: CI to describe the fix costs and CIC (component part commonality index) to describe the variable costs.

Preword

With these words, the writer would like to thank especially Marcus Pettersson (supervisor from ABB Corporate Research) for the information and support needed to accomplish this thesis work. Also many thanks to Johan Ölvander (supervisor from Linköpings Universitet), Xiaolong Feng (project leader at ABB Corporate Research) and Leif Pind (ABB robotics).

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1 Background, purpose and method

1.1 Background

During the last decades, the production enterprises have gone through a strong global change in terms of shorter product life cycles, fluctuations in the order income and increased demand of customized products (Reinhart, Wiedemann, & Rimpau, 2009). Within saturated markets, the customers' demand are especially high regarding short delivery times, better quality and technical functions at the same time as low prices. Mass customization is a strategy that supports the changes of these basic conditions.

Basically, a company needs to develop appealing products in terms of cost and quality that are brought to the market in timely manner (Asiedu & Gu, 1998). Research shows that the earlier in the product development phase these aspects are taken into consideration, the likelier it is for the company to achieve them. Dowlatshahi, among others, states that over 70% of the total life cycle cost of a product is determined at the early design stage, where designers are in good position to reduce the life cycle cost of the products (Dowlatshahi, 1992).

1.2 Purpose

The objective of the thesis work is to analyze how the total costs of a robot family is affected when the component commonality is changed. A part of the objective is also to investigate how ABB could take benefit of a product configuration system integrated with a robot platform and cost estimation model, supporting the consideration of cost aspects in the robot family design process. The work is connected to an ABB project running at the moment, where the author's part is to investigate how the total costs for robot family ABB IRB 6640 are affected when the individual and family design is changed. More specifically, a cost estimation model will be built to see how the total costs of robot family IRB 6640 are affected when choosing different gears for joints one, two and three in the robots. Other aspects such as quality and time will be discussed briefly in the thesis work but not taken into consideration in the cost estimation model.

1.3 Theoretical approach

The theoretical approach will be from three perspectives: product configuration system, product platforms and families, and product life cycle costing. The aspects of product variety optimization will also be discussed briefly as it is closely related to the objective of the work. The product configuration system supports the connection between product and process specifications to restrict and speed up the development of customized products (Hvam, Mortensen, & Riis, 2008). Product platforms and families enable the company to provide as much variety as possible for the marketplace with as little variety, i.e. as high commonality, as possible between products to keep the costs down (Thevenot & Simpson, 2006). Product life cycle costing lies as foundation when estimating total costs of individual products and product families (Fixson, 2004).

1.4 Method

The method used for acquiring information involves workshops, meetings, interviews and internet research. A cost estimation model is built to do the costs analysis, where the actual cost figures come from a prior study at ABB.

2 ABB

2.1 The company

ABB is a Swiss-Swedish global power and automation technology company that delivers products, systems and services to customers worldwide. 2009 they had operations in around 100 countries, with approximately 117,000 employees, and reported global revenue of $31.8 billion (ABB, 2010). Its products range from household circuit breakers to industrial robots, systems ranging from simple plant automation applications to substations installation and commissioning, and services from breakdown repairs to life cycle and complete plant maintenance. ABB Corporate Research (CRC) is a support organization within ABB that introduces product technology as well as business process innovation for all ABB companies (ABB, 2010). ABB Robotics is a business unit within the discrete automation and motion division that develops and manufactures industrial robots i.e. marketing, sales, procurement, assembly, logistic and finance.

The manufacturing process can be described as Figure 1. The robot parts delivered and put into stock. Then the parts are assembled together to finished robots that are put in stock until they get delivered to the customers.

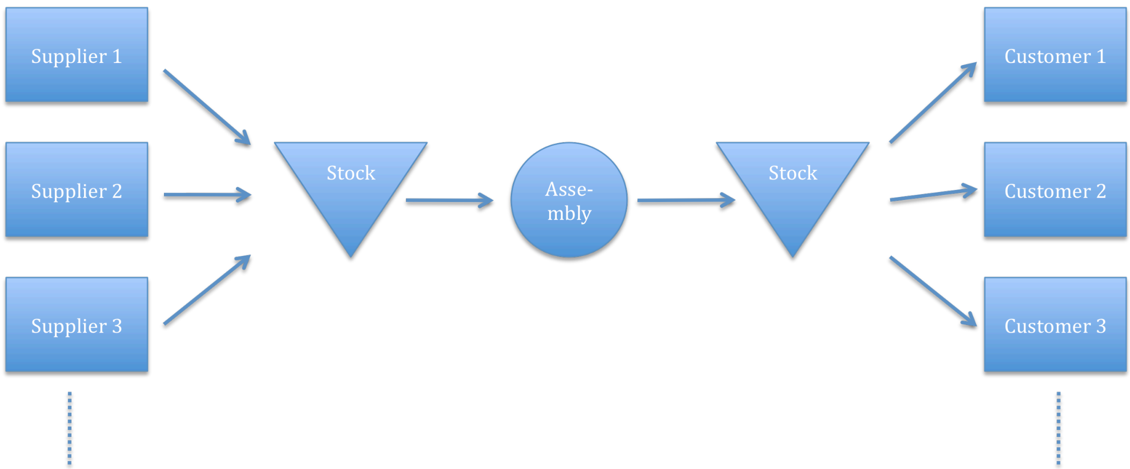

Figure 1: Flow chain at Robotics

2.2 The development process of Industrial robots

The robots operational lifetime is between seven and eight. An industrial robot consists of a mechatronic system with a mechanical structure, usually referred to as robot manipulator and robot controller. The robot manipulator consists of a base, stand assembly, lower arm, arm house assembly, upper arm, tilt house assembly and a tool flange, see Figure 2 (Ölvander, Feng, & Holmgren, 2008).

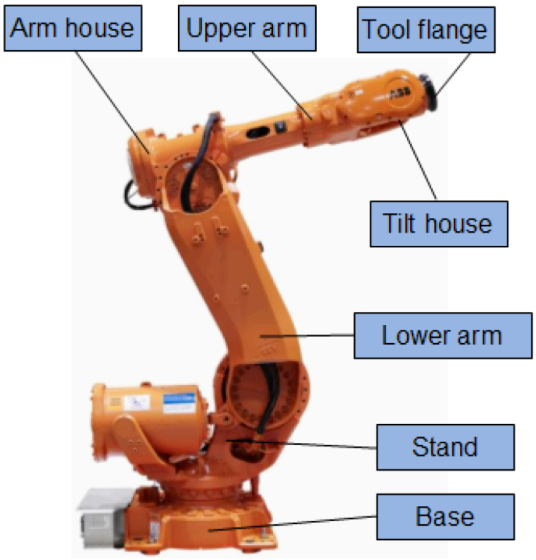

Figure 2: ABB IRB 6640 – 185/2.8 robot (Ölvander, Feng, & Holmgren, 2008)

The robot manipulator also consists of drive-train components such as magnet electric motors and gears. The most common robots, like the IRB 6640 in Figure 2, have six rotational joints giving it six degrees of freedom:

- Joint one between base and stand
- Joint two between stand and lower arm
- Joint three between lower arm and arm house
- Joint four between arm house and upper arm
- Joint five between upper arm and tilt house
- Joint six between tilt house and tool flange

The robot controller consists of power units, rectifier, transformer, axis computers and a high level computer for motion planning and control.

The most common performance measurements of a robot are:

- Reach and shape of workspace
- Payload handling capacity
- Axis speed and acceleration (or cycle time when measuring some typical cycles)
- Position and path accuracy
- Number of degrees of freedom

According to Ölvander et al., designing an industrial robot is complex process involving a lot of modeling and simulation. When designing the robot manipulator, the major steps are kinematics design, dynamics design, thermal design, and stiffness design, shown in Figure 3. Due to the complex issues, the design process is of an iterative nature (Ölvander, Feng, & Holmgren, 2008).

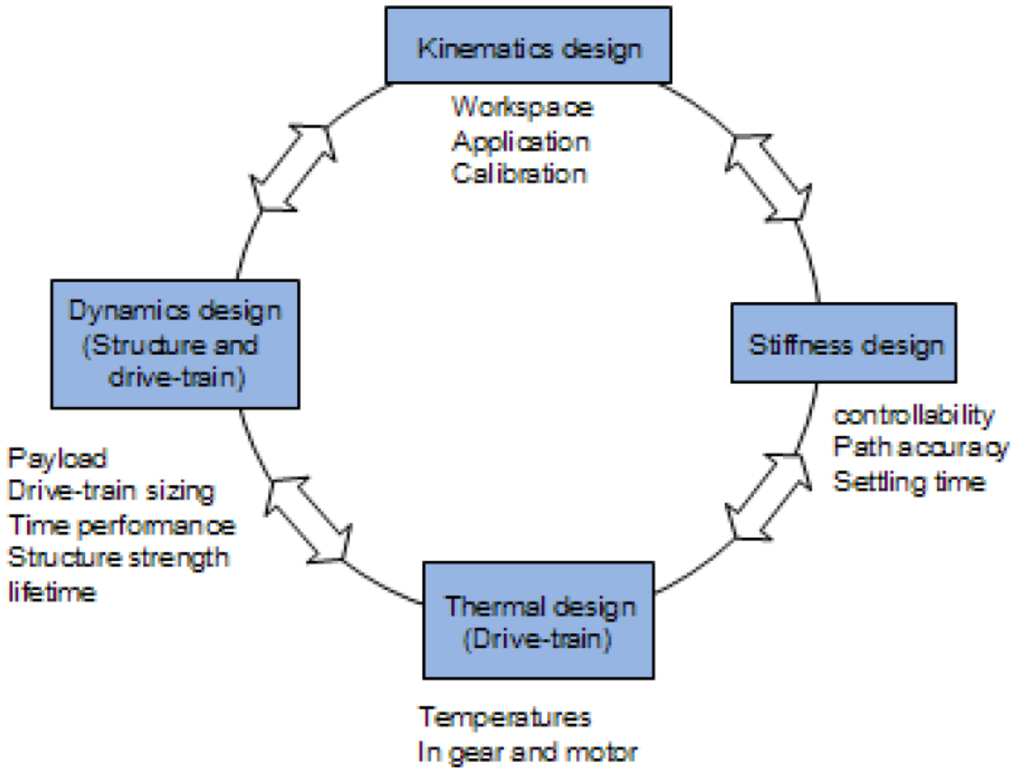

Figure 3: Workflow for industrial robot design process (Ölvander, Feng, & Holmgren, 2008)

2.2.1 Kinematics design

According to Ölvander et al., the first step in the design process of a robot manipulator is the kinematics design. Thereby the manipulator's configuration such as number of joints or degrees of freedom, the link lengths, and the offsets defining connection points between links, is determined. Some of the most common measurements of the performance of kinematics design are (Ölvander, Feng, & Holmgren, 2008):

- The maximum reach of the robot manipulator
- The shape or volume of workspace i.e. the reach envelop of the wrist center point
- The stroke, which is the offset between maximum and minimum reach of the wrist center point, shown in Figure 4.

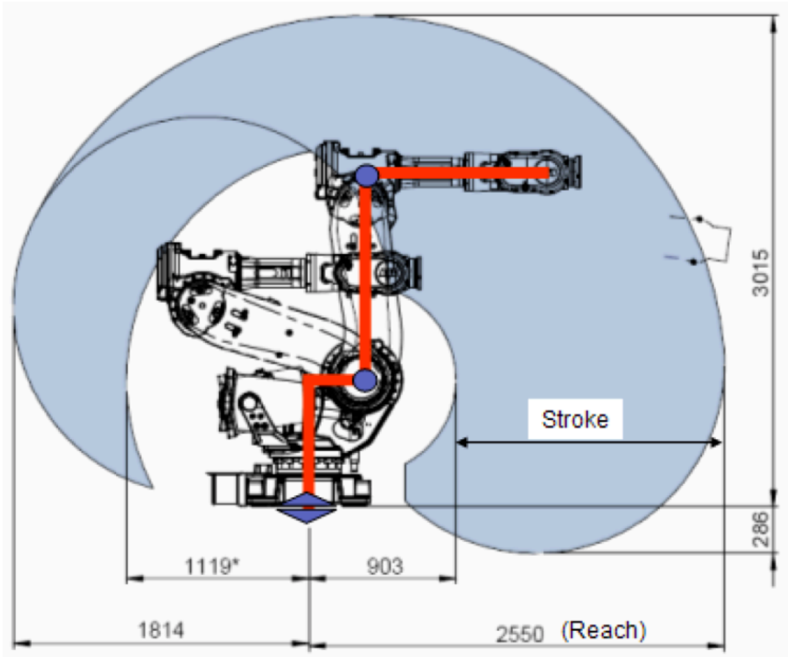

Figure 4: Shape, reach, and stroke for an ABB IRB 6640 – 182/2.8 robot (Ölvander, Feng, & Holmgren, 2008)

Pettersson adds that after the kinematics design additional criteria based on payload, structural behavior, actuation methods and manufacturing must be taken into consideration (Pettersson, 2008).

2.2.2 Dynamic design

There are two critical design steps in the dynamic design: conceptual dynamic design in operational space and detailed dynamics design based on mechatronic design (Ölvander, Feng, & Holmgren, 2008).

In the conceptual dynamics design in operational space the robot configuration, structure components, and drive train components are preliminarily designed. This is done based on time or acceleration performance requirements. The mass data acquired from the initial design is critical for the drive-train dimensioning to achieve the satisfying accuracy. Typical design variables are gear ratio, rated torque, speed of gears and speed of motors. Usual design criteria are tool center point linear acceleration or axis rotational speed and acceleration at a large number of predefined points in the robot workspace. The process is iterative i.e. mass data of drive-train components are updated during the drive-train dimensioning progress. A structure stress analysis for ultimate strength and sufficient lifetime can be conducted when the drive-train components are correctly dimensioned. Consequently, the stress analysis generates a new iterative process as the modification of the components result in change of mass property (Ölvander, Feng, & Holmgren, 2008).

Once the conceptual dynamic design is completed, the mechanical, drive-train and drive electronics as well as the controller is to be simulated in a mechatronic environment. In this design phase, a robot motion program is required. Thereby the performance of the robot manipulator, in terms of accuracy, can be approved (Ölvander, Feng, & Holmgren, 2008).

2.2.3 Stiffness design

To ensure the required accuracy of the robot manipulator, the stiffness of the manipulator needs to be considered. Typical performance measures are path tracking accuracy and settling time when the tool center point approaches a certain posture in the workspace. When executing the stiffness analysis, a multi-body modeling of the robot manipulator is required, where both the flexibility of arm structure components including base, stand, lower arm and upper arm, and the flexibility in the joints are considered. With support of the flexible multi-body modeling, the path tracking accuracy and the eigen-frequency can be simulated and analyzed. The eigen-frequency analysis is dependent on the joint configurations in the manipulator, thus the analysis has to be conducted at a set of tool center point postures, which are predefined in the workspace. To be able to perform the path tracking accuracy analysis, the joint angles are needed as a function of time, which is usually available from the dynamics design (Ölvander, Feng, & Holmgren, 2008).

2.2.4 Thermal design

Thermal design is necessary to constraint the temperatures in motors and gears, so that overheating does not occur. If the analysis is neglected, thermal problems will be discovered first in the prototyping phase. The design is mainly concentrated at structure cooling and drive-train components thermal sizing. As constraints are the number of critical temperatures in motors and gears used, which are not allowed to exceeding their maximum temperature limits (Ölvander, Feng, & Holmgren, 2008).

2.3 The industrial robot (IRB) 6640 family

The IRB 6640 family is a further development of the prior generation IRB 6600, where mostly improvements of strength, weight, path performance, costs and maintenance have been done. The main applications of the family are material handling, machine tending and spot welding. Seven robot individuals belong to the family, where two of them are specially developed for internal dressing, thereby the name IRB 6640ID (Internal Dressing). Table 1 shows the specifications of the different individual robots (ABB AB, Corporate Research, 2010).

Table 1: Specification of IRB 6640 (Robotics, ABB, 2010)

Specification				
Robot versions IRB	Reach	Handling capacity	Center of gravity	Wrist torque
6640-180	2.55 m	180 kg	300 mm	961 Nm
6640-235	2.55 m	235 kg	300 mm	1324 Nm
6640-205	2.75 m	205 kg	300 mm	1264 Nm
6640-185	2.8 m	185 kg	300 mm	1206 Nm
6640-130	3.2 m	130 kg	300 mm	1037 Nm
6640ID-200	2.55 m	200 kg	300 mm	1262 Nm
6640ID-170	2.75 m	170 kg	300 mm	1190 Nm

The first five listed robots are to be focused on the thesis study. The reach and payload for these five are shown in Figure 5.

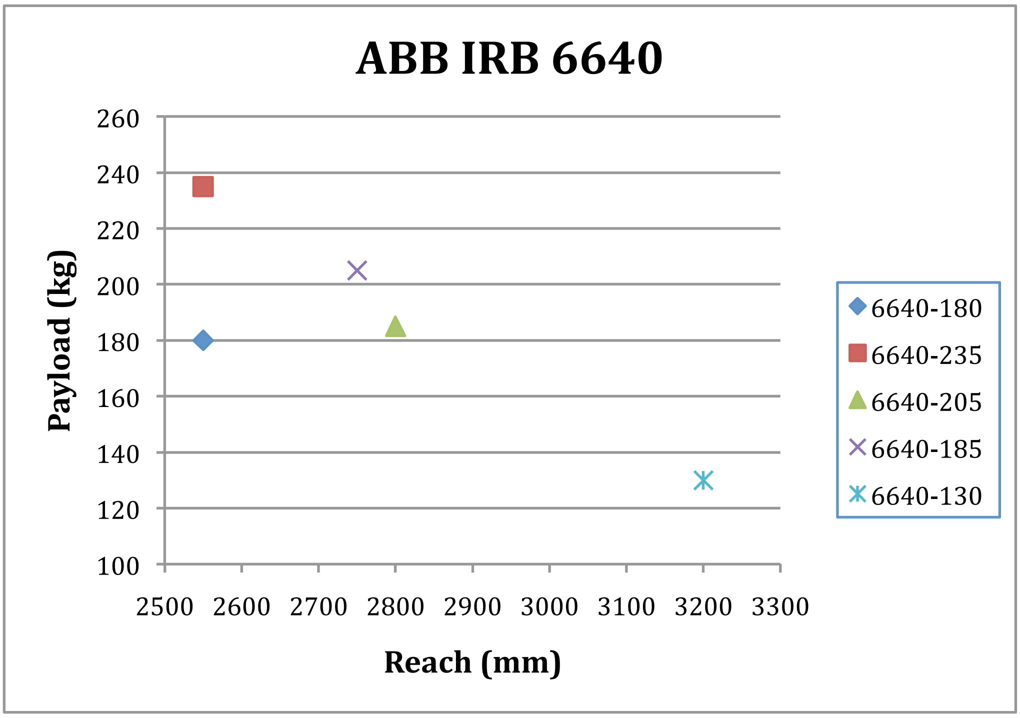

Figure 5: ABB IRB 6640

As already mentioned, the IRB 6640 consists of seven robots. Taking a closer look at the configuration of these robots, they are actually built on hardware of only four robots. More specifically, the robots with the same reach are built on the same hardware.

3 Theoretical review

Since the 1990s, the production enterprises are going through a strong global change in terms of shorter product life cycles, fluctuations in the order income and increased demand of customized products (Reinhart, Wiedemann, & Rimpau, 2009). Within saturated markets, the customers' demand are especially high regarding short delivery times, better quality and technical functions, at the same time as low prices. Due to the change of these basic conditions, strategies such as Lean Production, Agile Customization and Mass Customization have become more and more popular during the last years. These strategies enable a manufacturing company to reach high cost efficiency in the production process as well as fast handling of changes in customer requirements (Piller, 2004).

The strategy of mass customization, shown in Figure 6, combines the two basic elements cost leadership and differentiation, making it a hybrid strategy, which supports the production of individual products to fulfill specific customer needs at the same time as doing it within the principles of mass production at reasonable cost (Reinhart, Wiedemann, & Rimpau, 2009).

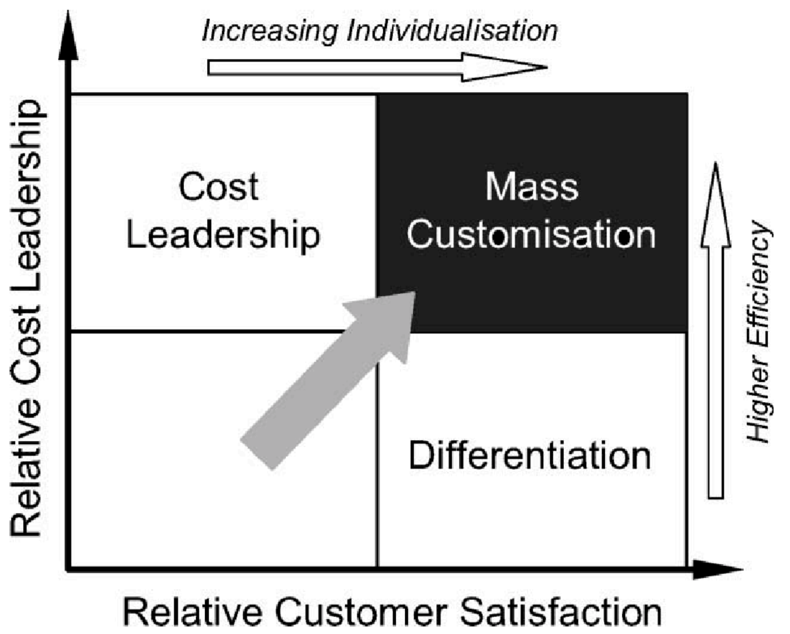

Figure 6: Strategies of competition (Reinhart, Wiedemann, & Rimpau, 2009)

According to Hvam et al., a company has to do a radical revision of its overall business model to be able to adapt to the principles of mass customization, such as (Hvam, Mortensen, & Riis, 2008):

- A focused market strategy answering the question "which customers should be serviced with which products?" Customers lying outside of the segment to be focused on must be refused.

- Offer-, order-, and manufacturing specifications for the customized products with support of a product configuration system.
- A product range based on product families and platforms with standard modules, making it possible to put customized products together by selecting, combining and possibly adapting a set of modules.
- Mass production of standard modules to reduce the overall costs.
- A customer-initiated assembly line suited for the different varieties of putting the modules together.

Reinhart et al. agrees on that mass customization requires a modularization of the product structure i.e. platform based product families, as well as a product configuration system for a quick order processing of customized products (Reinhart, Wiedemann, & Rimpau, 2009).

3.1 Product configuration system

The central elements that are new for most of the companies adapting to mass customization are the development of module based product families and platforms and the use of a product configuration system that includes sales, product design, development and manufacturing specifications for customized products (Hvam, Mortensen, & Riis, 2008).

Before going into more in detail what a product configuration system is, the positive effects that could be achieved with such a system is emphasized underneath (Hvam, Mortensen, & Riis, 2008):

- The time for working out (offer/order) specifications is reduced, sometimes from weeks/months to hours or even minutes.
- Faster response to customer enquiries and less amount of resources needed to make an offer.
- Fewer errors in the specification.
- Fewer occasions where responsibility is transferred.
- Possibility to optimize features and costs related to the customized product i.e. material and production costs.

The task in general is to reorganize the business processes that connect the customers with the production system, formalize their structures and relationships to each other and finally put it into an IT system (configuration system) (Hvam, Mortensen, & Riis, 2008). Thereby the customer needs can be automatically transferred into product specifications, such as offer-, order or production specifications, which show what resources that are needed to fulfill the customer's requirements (Reinhart, Wiedemann, & Rimpau, 2009). The configuration system is typically suitable for component based products and can in some cases be implemented within the company's already existing Enterprise Resource Planning (ERP) system (Helo, Xu, Kyllönen, & Jiao, 2010). A uniform standard configuration system is unlikely to be successful, as enterprises have different organizational structures and different width and variety of product range. In many cases a standard configuration system would therefore be too superficial or, the other way around, too complex, in many enterprises. Consequently, each business process model needs to be adapted to the enterprise's specific boundary conditions (Krause, 2005).

According to Hvam et al., there are some problems experienced in the development and implementation of a configuration system (Hvam, Mortensen, & Riis, 2008):

- If only technically oriented people develop the system there is a risk for lack of commercial focus.
- If there is a lack of support from the management, the system might not be fully implemented and used in the way daily operations are organized. For instance, this could result in that the system is not being continually updated and the data becomes out of date in a very short time.
- The products are not configurable due to the fact that the product families and their possible variations have not been clearly defined. Also, the product range is unstructured and it is not specified which variants should be offered or which market segments should be focused on.
- Lack of an overall description of the configuration system resulting in difficulties when trying to maintain or develop the system further.

3.1.1 Specification and specification processes

A specification can be defined as a description of needs, requirements or intentions that can be transferred from one group of people to another (Hvam, Mortensen, & Riis, 2008). As an example a specification could be assembly instruction for putting an IKEA furniture together, or a baking recipe. Within a manufacturing enterprise, specifications could be customer requirements, product drawings, list of operations, service manuals, etc. In the process of making an offer, which hopefully leads to executing an order, there are several specifications that are needed to specify the product and how the product is to be produced, assembled, transported and serviced. In the case of mass production of standard products, it is possible to determine all specifications regarding the development and production of the product, which can be reused every time the product is ordered. This concept is also the key in mass customization, but has to be modified, since the customer requires tailored products. Some of the specification will change for every new order, but the processes generating the specifications are usually the same. It is therefore sensible to define these so called specification processes that are able to work out the specifications related to a certain customer need. According to Hvam et al., specifications processes can be defined as follows (Hvam, Mortensen, & Riis, 2008):

"Specification processes indicate the business processes which analyze the customer's needs, create a product which is adapted to the individual customer, and specify the activities which have to be performed in connection with, for example, purchasing, production, assembly, delivery and servicing of the product concerned."

In the specification processes, the product related specifications are worked out according to the restrictions and information from the activities purchasing, planning, production and delivery. Figure 7 shows a company's specification process without support of a configuration system (Hvam, Mortensen, & Riis, 2008).

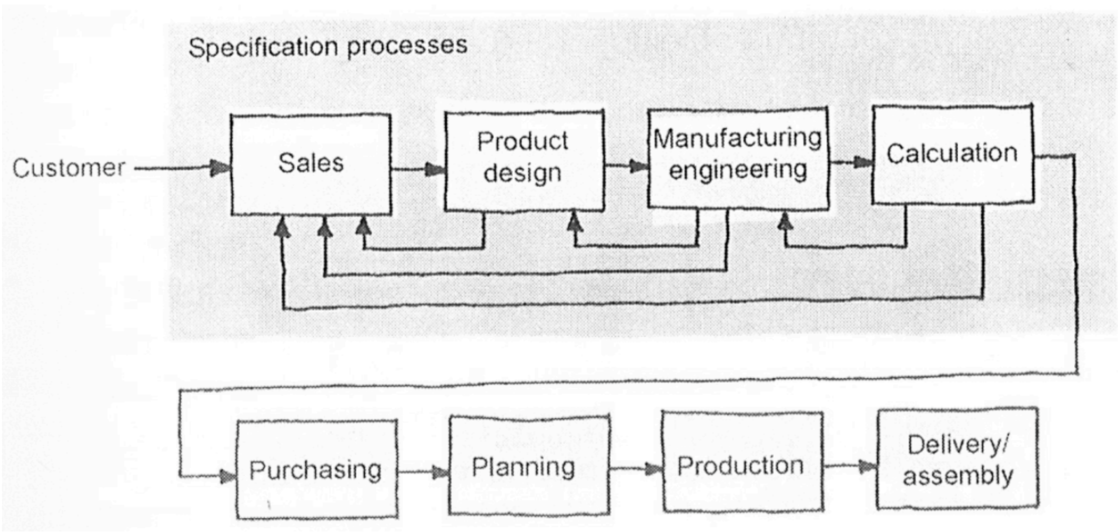

Figure 7: A company's specification process (Hvam, Mortensen, & Riis, 2008)

Looking at all the connections between the sub processes involved in the specification process, a lot of information needs to be sent between the departments before the specification process is done. The result of this is a great risk for many non-value added activities, double work, errors and long throughput time. To improve the processing, a configuration system can be built, which supports and integrates the company's specification activities, shown in Figure 8. The main principle of a configuration system is that the knowledge from an organizational unit is modeled and made available to other organizational units (Hvam, Mortensen, & Riis, 2008).

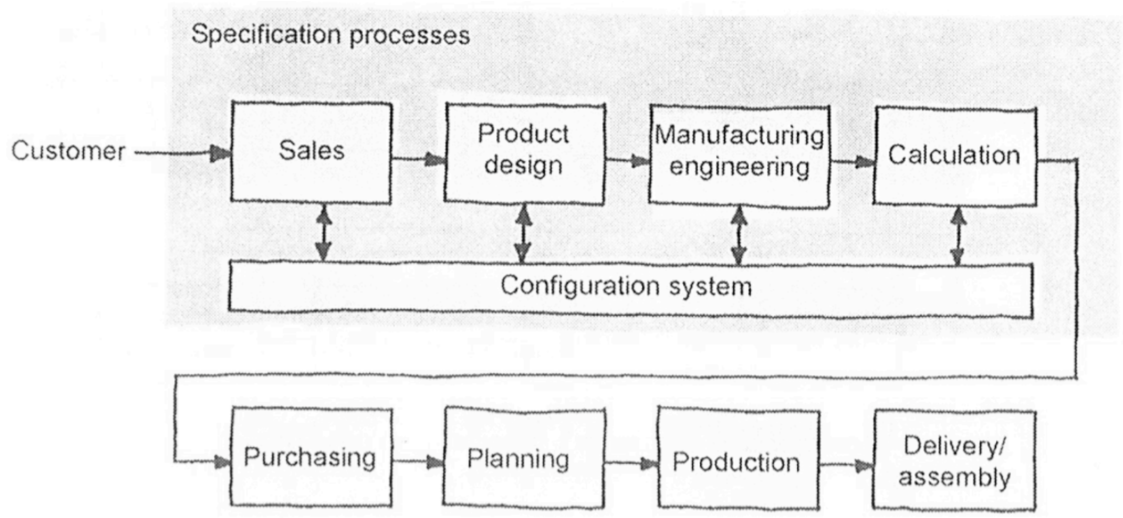

Figure 8: Support of configuration system in the specification process (Hvam, Mortensen, & Riis, 2008)

3.1.2 Modularization and production strategy

When developing a modular based product range that support mass customization, it is important to separate the actual task of development, where the parts of the product are developed from scratch, and the task of operation, where the product is designed in detail to match the individual customer's need. The aim of the development task is to create new solutions, which increase the general value to the customer and reduce the costs. The aim of the operation task, on the other hand, is to fast and effectively work out error-free specifications, which stands in direct relation to a specific customer order. It is crucial to keep these tasks separated in order to achieve a high level of quality in a fast and effective way. An important part of the development task is to develop modules and the configuration system to be used in the operational task. The configuration system makes it easier in the operational phase when designing a customized product based on a set of modules. Thereby a customized product can be designed faster and cheaper on the basis of modules instead of built from scratch every single time. By using this sort of concept, mass customization can be achieved as shown in Figure 9 (Hvam, Mortensen, & Riis, 2008).

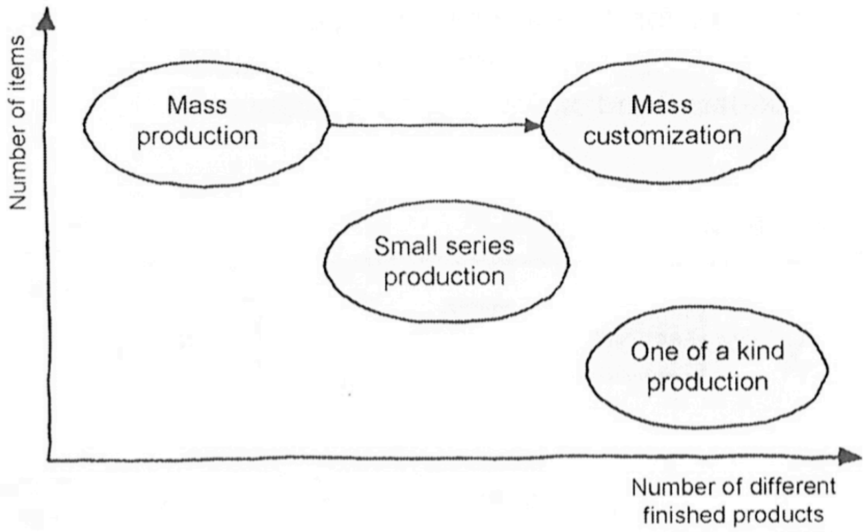

Figure 9: Concept of mass customization (Hvam, Mortensen, & Riis, 2008)

To be able to use modules and a configuration system it is a precondition that it is possible to develop a product range and a set of business processes that are stable over time.

Looking at different types of specification processes, it must first be taken into consideration what production process strategy the company has, Figure 10. According to Olhager, the customer order decoupling point (CODP) divides the production activities in two parts, the activities before the CODP and the activities after the CODP. The activities before the CODP are driven by prognoses, which means that volume and design of product requested by the customer is unknown and therefore produced according to prognoses and then put on stock. This is mainly done to reduce the customer order lead-time by already having a part of the product produced when the actual order comes in. The activities after the CODP are driven by customer orders, which means that the demand is known and each product belongs to a specific customer order that determines what activities have to be done to complete the product. There are four different concepts: make to stock (MTS), assembly to order (ATO), make to order (MTO) and engineer to order (ETO) (Olhager, 2000).

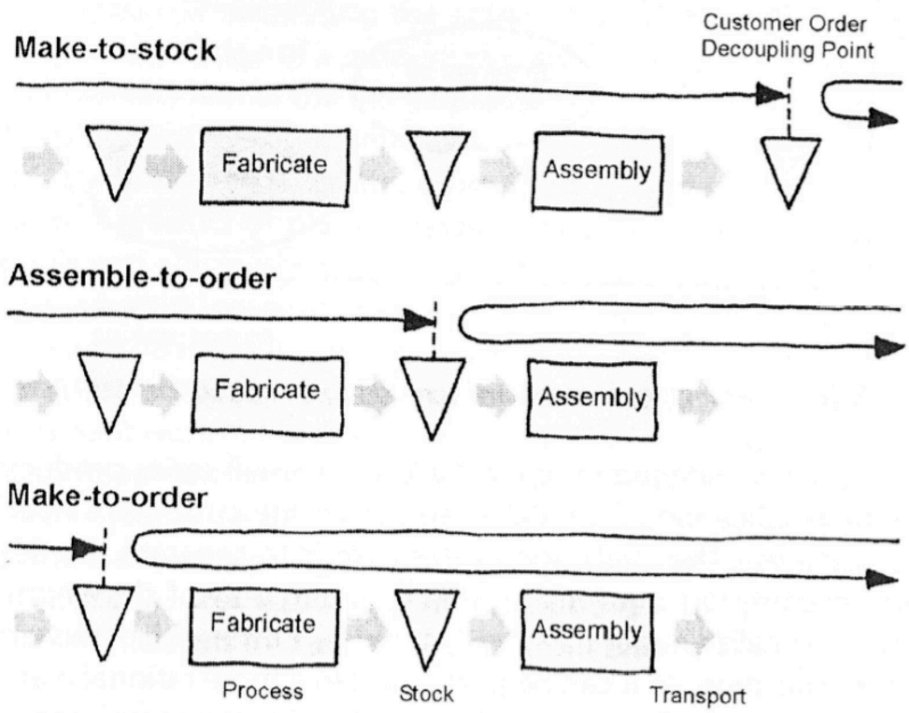

Figure 10: Production process strategies (Hvam, Mortensen, & Riis, 2008)

The strategies differ in where the CODP is located in the production flow. By MTS the CODP is in the finished goods inventory, by ATO in the inventory inbetween production and assembly, by MTO in the rawmaterial inventory and by ETO before the rawmaterial inventory, as the rawmaterial most likely has to be purchased (Hill, 2000).

According to Reinhart et al., only ATO and MTO are appropriate production strategies in combination with mass customization, Figure 11. As a matter of fact it is quite obvious that MTS does not fit together with customization as the products are already finished and taken directly from the finished goods inventory when the customers order them (Reinhart, Wiedemann, & Rimpau, 2009).

<table>
<tr><th>Criterion</th><th colspan="8">Characteristic</th></tr>
<tr><td>Products</td><td colspan="2">standard products without variants</td><td colspan="2">standard products with variants</td><td colspan="2">products with individualised variants</td><td colspan="2">products with individualised variants</td></tr>
<tr><td>Production Strategy</td><td>make-to-stock</td><td colspan="2">assemble-to-order</td><td colspan="2">make-to-order (framework contract)</td><td colspan="2">make-to-order (single order)</td><td>engineer-to-order</td></tr>
<tr><td>Engineering Effort</td><td>< 10%</td><td colspan="2">10% - 30%</td><td colspan="2">30% - 50%</td><td colspan="2">50% - 70%</td><td>> 70%</td></tr>
<tr><td>Type of Manufacturing</td><td colspan="2">mass production</td><td colspan="2">batch production</td><td colspan="2">small batch production</td><td colspan="2">single-part production</td></tr>
<tr><td>Manufacturing Principle</td><td colspan="2">continuous manufacturing line</td><td colspan="2">series manufacturing</td><td colspan="2">autonomous manufacturing</td><td colspan="2">job-shop manufacturing</td></tr>
<tr><td>Assembly Principle</td><td colspan="2">flow assembly</td><td colspan="2">series assembly</td><td colspan="2">cellular assembly</td><td colspan="2">assembly on site</td></tr>
</table>

Figure 11: Characteristics of products (Reinhart, Wiedemann, & Rimpau, 2009)

With a similar approach as the CODP in the production flow, it is possible to talk about a dividing line for specification processes. The Order Specification Decoupling Line (OSDL) is lying between order-initiated specifications and specifications, which are worked out independently of the individual customer order, see Figure 12 (Hvam, Mortensen, & Riis, 2008) & (Fujita & Yoshida, Product Variety Optimization simultaneously Designing Module Combination and Module Attributes, 2004).

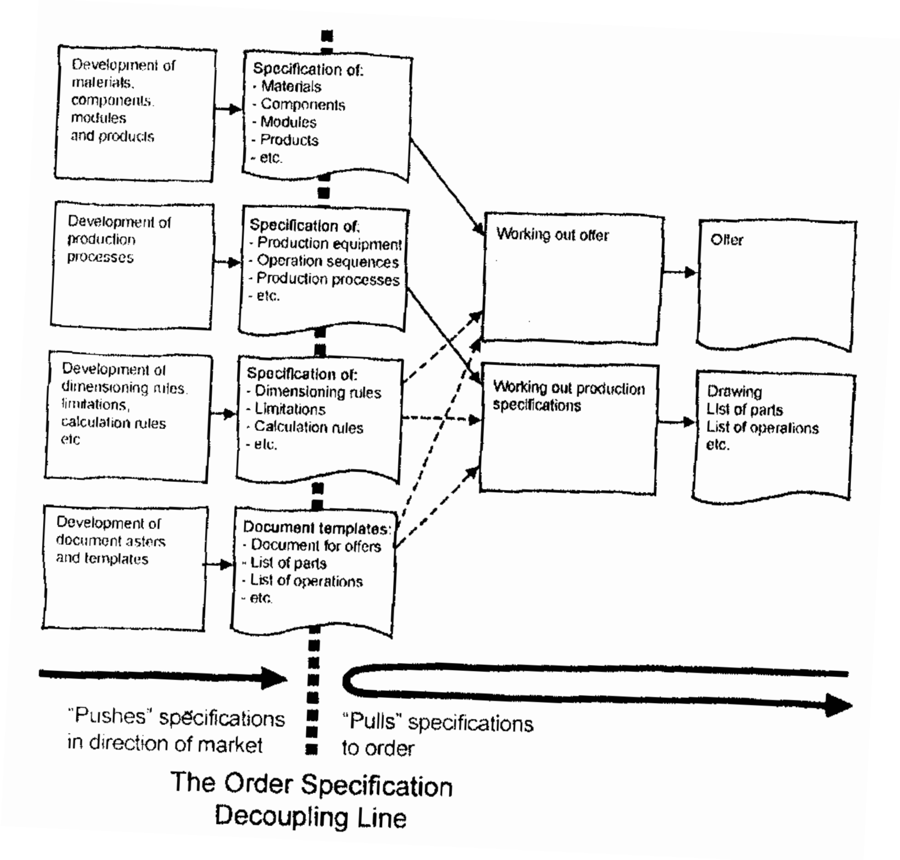

Figure 12:The Order Specification Decoupling Line (Hvam, Mortensen, & Riis, 2008)

On the left hand side of the OSDL, the specifications are worked out independently of the individual customer order. These specifications are usually the result of the development of products, modules and production processes. Such examples can be dimensioning rules, module descriptions, list of parts for a standard component made to stock, setting-up instructions which can be used for all products, and rules for selecting production methods.

On the right hand side of the OSDL, specifications are worked out for individual orders. Examples are offers to the customers, list of parts, drawings, list of operations, assembly instructions and service manuals (Hvam, Mortensen, & Riis, 2008).

In Figure 10 it is showed how the COPD can be "moved" forward and backward to different inventories in the production flow. In the same way, the OSDL can be "moved" to generate different types of specification processes, shown in Figure 13.

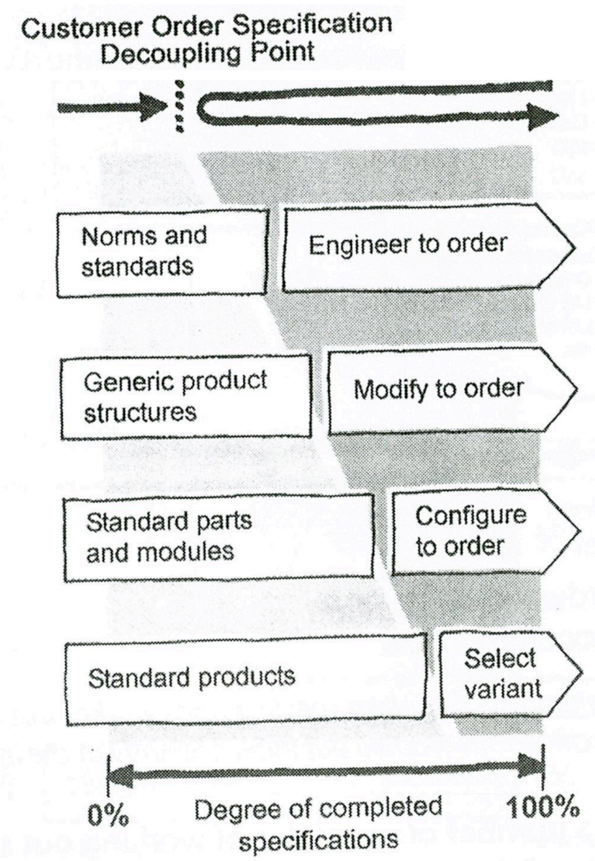

Figure 13: Positioning of OSDL (Hvam, Mortensen, & Riis, 2008)

The "Engineer to order" process is mostly suitable for companies supplying complex products or plants, where a lot of work is necessary for the design and specification of each individual plant.

The "Modify to order" process is aimed to fit companies developing products based on modules with clear rules for how to create a customized product.

The "Configure to order" process is to be combined with a configuration system where the specifications are worked out automatically based on standard products and modules.

In the process "Select variant" the customer is matched an existing product specification which fulfills his/her needs at the best. The seller analyses the customer's needs and with help of the configuration system pick the best fitting product out of product catalogues and databases.

3.2 Product families and Platforms

According to Thevenot et al., many companies today are faced with the challenge of providing as much variety as possible for the marketplace with as little variety as possible between products. Platform-based product development is used in many companies to achieve this. Families of products are developed with sufficient variety to meet customers´ demands while keeping costs relatively low (Thevenot & Simpson, 2006). Meyer and Lehnerd states that a product family is a group of related products that share common characteristics such as features, components, modules or subsystems (Meyer & Lehnerd, 1997). Modular based product family design built on a platform is a common approach when trying to fulfill the demands of mass customization. With the concept of platforms, the product delivery time can be shortened and it is possible to offer the customer a broad product range to meet specific customer requirements while maintaining low development and manufacturing costs. The main drawback, on the other hand, is the reduced performance of the individual products as parts and components are shared within the family restricting the ability to optimal design. The level of commonality, which is measured as number of parts shared among the family members, needs to be traded off towards the performance of the individuals (Ölvander, Feng, & Holmgren, 2008).

A product family is represented by a number of individual products sharing a common platform. The platform usually consists of modules, components, and manufacturing and assembly processes. The total costs for the product family can be reduced due to higher commonality between the variants, but as a result of that the individual performance will most likely decrease (Ölvander, Feng, & Holmgren, 2008).

Designing a product family can be done in three different ways (Fujita & Yoshida, 2004):

- Design of a platform for a specified family
- Design of a family based on a specified platform
- Simultaneous design of both platform and family

3.2.1 Framework

Figure 14 illustrates a decision framework of product family design and development out of a holistic view, i.e. a foundation of five domains: customer, functional, physical, process and logistics. The typical question to answer when mapping the domains together is “what-how?”.

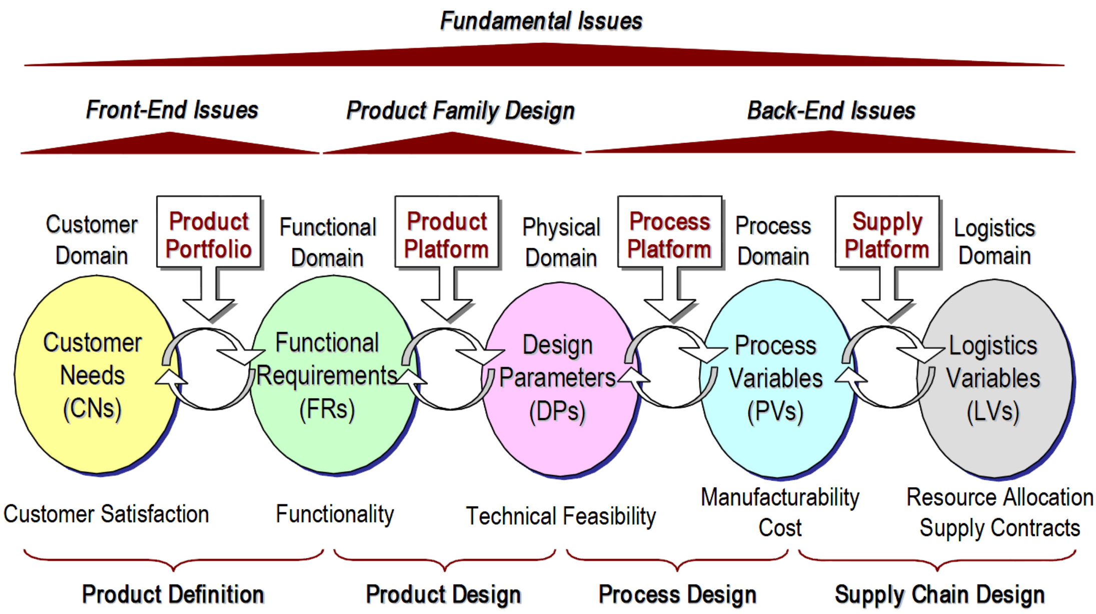

Figure 14: Framework of product family design and development (Jiao, Simpson, & Siddique, 2006)

The customer needs in the customer domain, representing segmentation of markets that demand for product families, are first translated into functional requirements in the functional domain. The mapping between customer and functional domains constitutes the front-end issues, involving development of product families within an existing product portfolio. The functional requirements are then mapped to the design parameters in the physical domain. This is done on basis of a shared product platform (Jiao, Simpson, & Siddique, 2006).

The back-end issues involve process and logistics domains, i.e. process and logistic variables. The mapping form design parameters to process variables demand a process design task to generate manufacturing and production planning of processes as well as tooling, setup, equipment and routings. The production processes can be organized as a process platform with standard routings, facilitating production configuration for different product family design solutions (Tseng & Jiao, 2000).

According to Wortmann et al., more and more companies are moving towards the production strategy assembly-to-order to meet the requirements of mass customization. In combination with outsourcing, this is a promising strategy where resources and capabilities are delivered from around the whole world at the same time as the company can focus on their core competence. Consequently, to support this strategy it is crucial with good supply chain network, which is coordinated to product and process design of product families. The logistics domain addresses the supply chain related issues of product family fulfillment, which are mainly about supply chain configuration, resource allocation, supplier management and supply contracting. With help of a supply platform, the process variables can be mapped to logistic variables (Wortmann, Muntslag, & Timmermans, 1997).

3.2.2 Fundamental Issues

When mapping the five domains together, there are some fundamental issues related to the product family design decisions needed to be taken into consideration i.e. product family, product platform, product architecture, product variety, modularity and commonality (Simpson T. , 2004).

3.2.2.1 Product family

A product family is a set of similar products in terms of features/functionality that are based on a common platform. All product individuals in a family share some common structures and product technologies. While a product family targets a certain market segment, each product variant/individual is developed to address a specific customer need of the market segment. The definition of what the individuals in a product family have in common might differ depending on the observer's perspective. The marketing and sales perspective is naturally the commonalities in functional features and structures in the product family. For an engineer, a product family involve similar product technologies and manufacturing processes, which are characterized by the design parameters, components and assembly structures (Simpson T. , 2004).

3.2.2.2 Product platform

A product family is represented by a number of individual products sharing a common platform (Ölvander, Feng, & Holmgren, 2008). The platform usually consists of modules, components, and manufacturing and assembly processes. Many authors have stated their own definition of a product platform. Here are two of them:

"A product platform is a set of subsystems and interfaces developed to form a common structure from which a stream of derivative products can be efficiently developed and produced." (Meyer & Lehnerd, 1997)

"A product platform is a collection of the common elements, especially the underlying core technology, implemented across a range of products." (McGrath, 1995)

Baldwin and Clark define three aspects that characterize a product platform (Baldwin & Clark, 2000):

- its modular architecture
- its interfaces
- its standards that provide design rules that the modules must obey

Zamirowski and Otto emphasize three different types of product platforms: modular platforms, scalable platforms, and generational platforms. In a modular platform the variants are created through configuration of existing modules. A scalable platform facilitates variants that possess the same function but with varying capacities. A generational platform supports the development of product life cycles for the next generation (Zamirowski & Otto, 1999).

Corresponding to the scalable and modular product platforms, there are two types of approaches to platform-based product family design. One common approach is called scalable (parametric) product family design, where scaling variables are used to "stretch" or "shrink" the product platform in one or more dimensions to satisfy a variety of customer needs (Simpson, Seepersad, & Mistree, 2001, 9). The other approach is referred to as configurational product family design, which aims to develop a modular product platform, from which product family members are derived by adding, substituting, and removing one or more modules (Du, Jiao, & Tseng, 2001).

3.2.2.3 Product architecture

In terms of product design is the product architecture synonymous with layout, configuration, and topology of functions and their embodiment. It can be described as the way in which the functional elements of a product are arranged into physical units and the way in which these units interact. The architecture can be either integral or modular, where modularity can be divided into five categories; component swapping, component sharing, fabricate-to-fit, bus and sectional modularity (Jiao, Simpson, & Siddique, 2006). Cutherell et al. have done research showing that modular architectures are often driven by variety, product change, engineering standards, and service requirements. Integral architecture, on the other hand, is often driven by product performance or cost (Cutherell, Rosenau, Griffin, Castellion, & Anschuetz, 1996).

3.2.2.4 Product Variety

The product variety is the mixture of products that a production system can provide the customers. The variety itself is usually divided into functional variety, most related to customer satisfaction, and technical variety, most related to manufacturability and costs. Looking at it from a strategic point of view, the functional variety strategy aims at increasing the functional variety, so that different customer needs can be satisfied. It is closely related to product line structuring and product positioning. To the contrary, the technical variety strategy aims to reduce technical variety to gain cost advantages, and is closely connected to reduction programs, postponement of the customer order decoupling point, function sharing, modularity and reconfiguration (Jiao, Simpson, & Siddique, 2006).

3.2.2.5 Modularity

When constructing product architectures, modules and modularity are central concepts. A module is a grouping of components that share some characteristics. Modularity is to separate a system into independent modules that can be treated as logical units (Newcomb, Bras, & Rosen, 1996). The interaction of modules is very important when characterizing modularity. According to Jiao et al., there are three different types of modularity associated with product families: functional, technical and physical modularity. The functional modularity focuses on the interaction of functional requirements across different customer groups i.e. each customer group is characterized by a particular set of functional requirements. Technical modularity is determined by the technological feasibility of the design solution. Basically, the interaction is determined by the design parameters ability to satisfy the functional requirements. Physical modularity is based on the physical interactions derived from manufacturability, out of a structural point of view (Jiao, Simpson, & Siddique, 2006).

3.2.2.6 Commonality

A product platform, around which the family is developed, is the key to a successful product family design. The challenge, on the other hand, is to determine the optimal trade-off between commonality and distinctiveness. If commonality is too high, the individual product performance is non-optimal due to the lack of distinctiveness. If commonality is too low, manufacturing costs will probably be too high (Simpson, Seepersad, & Mistree, 2001, 9). Thevenot et al. propose that commonality is best obtained by minimizing the no value added variations across the products within the family without limiting the choices of the customers. Simply, the aim is to make each product in the family distinct regarding what the customer can see and identical in all other ways that the customer cannot see (Thevenot & Simpson, 2006).

There are many different kinds of commonality indices. The commonality index indicates the degree of commonality within a product family based on different parameters, for example, the number of common components, the costs of the components or the manufacturing processes, etc. When designing or redesigning a product family, the commonality indices pose a good foundation for the framework. Thevenot et al. especially points at 6 different commonality indices that considers commonality from a component perspective, i.e. the similarities or differences between the components within the product family. Consequently, aspects such as functionality and performance are not taken into consideration. Table 2 presents a brief description of the six different commonality indices (Thevenot & Simpson, 2006).

Table 2: Commonality indices (Thevenot & Simpson, 2006)

	Name	Developed by	Commonality measure for	Zero commonality	Complete commonality
DCI	Degree of Commonality Index	Collier (1981)	The whole family	1	$\beta = \sum_{j=i+1}^{i+d} \Phi_j$
TCCI	Total Constant Commonality Index	Wacker and Trelevan (1986)	The whole family	0	1
PCI	Product Line Commonality Index	Kota, Sethuraman and Miller (2000)	The whole family	0	100
%C	Percent Commonality Index	Siddique, Rosen and Wang (1998)	Individual products	0	100
CI	Commonality Index	Martin and Ishii (1996, 1997)	The whole family	0	1
$CI^{(c)}$	Component Part Commonality	Jiao and Tseng (2000)	The whole family	1	$\alpha = \sum_{j=1}^{d} \sum_{j=1}^{m} \Phi_{ij}$

3.2.2.6.1 Commonality Index (CI)

The Commonality Index is a modified version of the DCI and provides a measure of unique parts, shown in Equation 1 (Thevenot & Simpson, 2006).

$$CI = 1 - \frac{u - \max p_j}{\sum_{j=1}^{v_n} p_j - \max p_j}$$

Equation 1

u is the number of unique parts, p_j is the number of parts in model j, and v_n is the final number of varieties offered. CI ranges from 0 to1 and is basically the ratio between the number of unique components in a product family and the total number of parts in the family.

3.2.2.6.2 Component Part Commonality Index ($CI^{(C)}$ or CIC)

The Component Part Commonality Index is an extension of DCI that also takes product volume, quantity per operation and cost of component/part into consideration, shown in Equation 2 (Thevenot & Simpson, 2006).

$$CIC = \frac{\sum_{j=1}^{d}\left[P_j \sum_{i=1}^{m} \Phi_{ij} \sum_{i=1}^{m} \left(V_i Q_{ij}\right)\right]}{\sum_{j=1}^{d}\left[P_j \sum_{i=1}^{m} \left(V_i Q_{ij}\right)\right]}$$

Equation 2

d is the total number of distinct component parts used in all the product structures of a product family, j is the index of each distinct component part, P_j is the price of each type of purchased parts or the estimated cost of each internally made component part, m is the total number of end products in a product family, i is the index of each member product of a product family, and V_i is the volume of end product i in the family. Φ_{ij} is the number of immediate parents for each distinct component part d_j over all the products levels of product i of the family.

SUM Φ_{ij} is the total number of applications (repetitions) of a distinct component part d_j

across all the member products in the family. Q_{ij} is the quantity of distinct component part d_j required by the product i.

$$\alpha = \sum_{j=1}^{d} \sum_{i=1}^{m} \Phi_{ij}$$

Equation 3

1 to α (see Equation 3) is the variable boundary for the range of CIC. As CIC considers the cost of each component, it generates very useful information. A very cheap part that is different from one product to another has less influence than a very expensive part common throughout the family. On the other hand, the backside of it is the estimation of quantity and costs information needed to compute the index. As manufacturability and costs are the main concerns in the process domain, process design is the clear enabler of mass production efficiency.

3.3 Product life cycle costing

To reach a competitive position on the global market today, a company needs to develop appealing products in terms of cost and quality that are brought to the market in timely manner (Asiedu & Gu, 1998). Research shows that the earlier in the product development phase these aspects are taken into consideration, the likelier it is for the company to achieve them. Dowlatshahi, among others, states that over 70% of the total life cycle cost of a product is determined at the early design stage, where designer are in good position to reduce the life cycle cost of the products (Dowlatshahi, 1992).

According to Asiedu, the cost perspective in the early design phase can be looked at in two ways, design for cost and design to cost. In the design for cost approach, the main objective is to reduce the life cycle cost while keeping the customers' satisfaction by still fulfilling the functional requirements. Design to cost is the other way around, aiming to maximize the customer satisfaction for a given cost target (Asiedu & Gu, 1998).

3.3.1 Conceptual design

In the conceptual design, the basic characteristics of the product are defined. After have chosen a design concept, future decisions tend to be locked in and a large amount of resources in terms of time, manpower and money are needed for bigger changes of the concept. Therefore, it is important that the cost aspect is taken into consideration along with the functional requirements when doing the concept evaluation. Basically, it means that the design team must be able to evaluate (and approximate) the cost performance of each concept alternative in the early design process. The concept development process is shown in Figure 15.

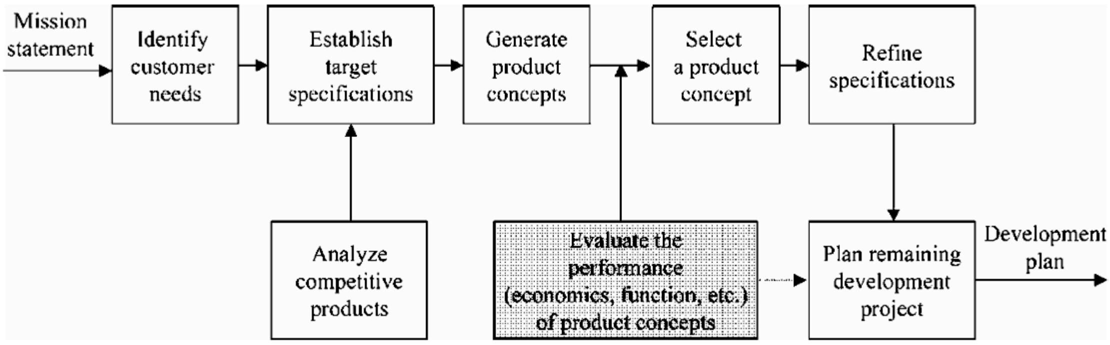

Figure 15: The concept development process (Seo, Park, Jang, & Wallace, 2002)

As the development time is the main factor influencing if a company becomes a leader or a follower on the market, there is usually no time for developing very detailed models for all concepts. Additionally, the lack of information in the early development phase is a barrier when trying to develop a detailed and accurate cost estimation model. The actual cost estimation should be done by cost estimators and not designers, as the designers usually do not have much knowledge about cost estimation. The necessary information is then communicated from the cost estimators to the designers. (Seo, Park, Jang, & Wallace, 2002)

3.3.2 Life cycle approach to design

In life cycle engineering the complete life cycle of the product is taken into consideration in each phase of the product development (Asiedu & Gu, 1998). Every product, regardless of size, value and lifetime, are going through different phases over its lifetime: design and development, production, use and retirement, see Figure 16. Within each of these life cycle phases different processes and activates occur, which create costs (Fixson, 2004).

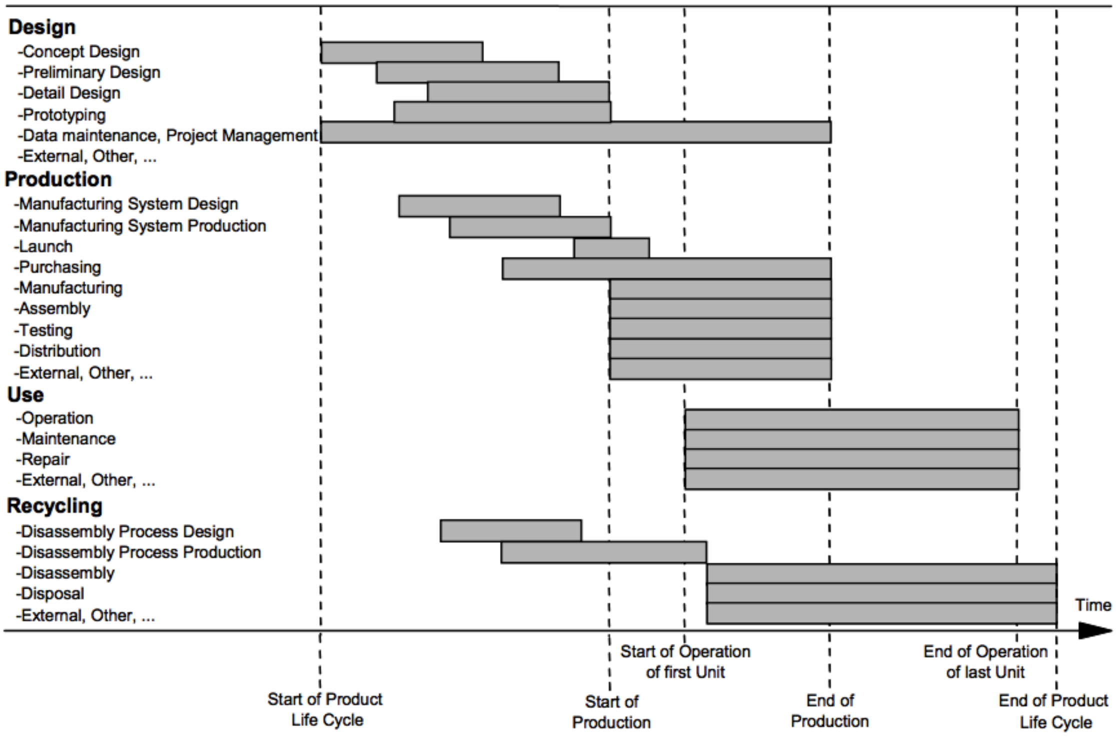

Figure 16: Phases throughout the product life cycle (Fixson, 2004)

3.3.3 Life cycle cost analysis

As different costs occur in different phases of a product's life, the first step is to determine which costs that are relevant for the specific design decision at hand. A product's life cycle cost profile is then determined by absolute cost values, relative distribution of the costs across the life cycle, the duration of the individual phases and the production volume (Fixson, 2004).

Based on the length of the life cycles and the total life cycle costs, products can be grouped into three different categories: large scale, mid scale, and small scale as shown in Table 3 (Asiedu & Gu, 1998).

Table 3: Length of the life cycles and total costs (Asiedu & Gu, 1998)

Large scale	Mid scale	Small scale
• Multiple, multi-year, on-going development cycles • Decade length operational life • Customer product cost/unit ≈ $\$10^6$ - $\$10^9$ • Annual unit production volumes ≈ 1 - 100 • Multiple complex subsystems • Large integration effort • High infrastructure development and maintenance • Mid-life upgrades to selected subsystem • Continuing sales value • Examples: aircraft, production plants, power plants.	• 1-5 year development cycles • 1-5 year operational life • Customer product cost/unit ≈ $\$10^3$ - $\$10^5$ • Annual unit production volumes ≈ $\$10^3$ - $\$10^5$ • Critical subsystems • Medium scale integration effort • Low field infrastructure support costs • Replacement by new product models (obsolescence) • Examples: computers, cars electronic instruments.	• Less than 1 year development cycles • Less than 2 year operational life • Customer product cost/unit ≈ $10 - $100 • Annual unit production volumes ≈ $\$10^6$ - $\$10^7$ • Simple subsystems • Incremental design changes • Little or no field support costs • Disposal after failure • Examples: consumer electronics, small appliances.

This categorization is important from a life cycle analysis perspective, as the models suitable for the large scale is probably not as suitable for the small scale (Asiedu & Gu, 1998). In addition to absolute cost and time values, the relative distribution of time and cost over the different life cycles phases plays an important role. For example, a small product, like a watch, requires very low maintenance and support during its use. A navy ship, on the other hand, is a long living and large scale product where 2/3 of the total life cycle costs belong to maintenance and support. In a similar way, a small production volume results in relatively high development cost per unit in comparison to a situation where the cost can be spread over a large production volume. The difference in production volume, total value, total life time and life cycle cost distributions effect the cost incurrence curves according to Figure 17 (Fixson, 2004).

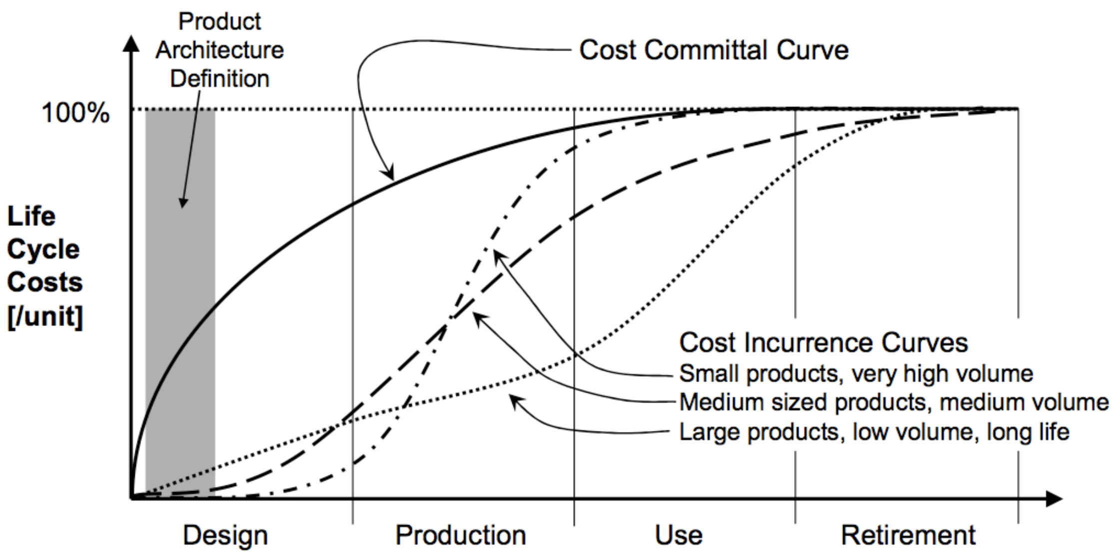

Figure 17: Life cycle cost distribution (Fixson, 2004)

The costs in the different life cycle phases will not necessarily be paid by the company. Table 4 shows how the costs are divided between company, user and society (Asiedu & Gu, 1998).

Table 4: Life cycle stages and costs (Asiedu & Gu, 1998)

	Company Cost	**Users Cost**	**Society Cost**
Design	Market Recognition Development		
Production	Materials Energy Facilities Wages, Salaries Etc.		Waste Pollution Health Damages
Usage	Transportation Storage Waste Breakage Warranty Service	Transportation Storage Energy Materials Maintenance	Packaging Waste Pollution Health Damages
Disposal/ Recycling		Disposal/ Recycling Dues	Waste Disposal Pollution Health Damages

Usually, the company pays for the resources required to bring forth and market the product, and the owner pays for the resources required to deploy, operate and dispose the product.

The total life cycle cost can be decomposed into cost categories, resulting in a cost breakdown structure (CBS), see Figure 18.

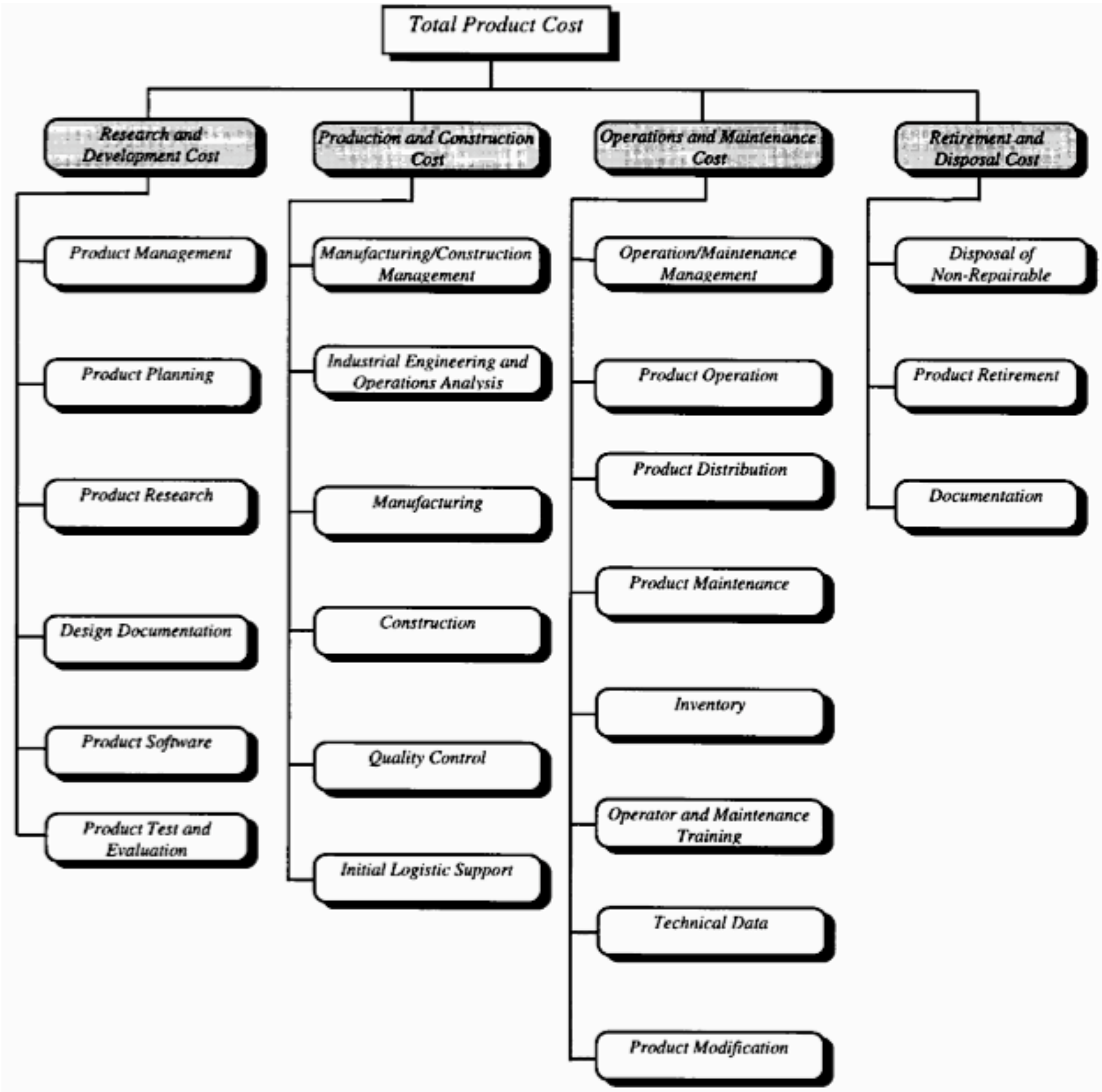

Figure 18: The traditional cost breakdown structure (Asiedu & Gu, 1998)

According to Asiedu, the traditional CBS can be applied on almost any product, but the level of breakdown and the cost categories need to be adjusted depending on the cost estimation model to be built. Nevertheless, the data available as input to the model and the product being designed will also influence the CBS. One cost category that usually does not interest the designer is research and development. This is natural, as the designer only cares for the costs that he/she can influence and control. Therefore, life cycle costs can be divided into management related cost, covering all costs, and design related cost, covering only the costs that the designer can control. The research and development cost in specific is usually not related to the actual design of the product but rather to the kind of product developed.

3.3.4 Product design and development costs

The first phase of a product's life includes the design steps conceptual, preliminary, and detail design as well as prototyping, testing, data maintenance, and project management. For engineered products, these processes are mainly driven by engineering resources, i.e. personnel. Therefore salaries are usually a large cost (Fixson, 2004).

Looking at how different product architectures affect the resource consumption during the design phase, a firm's organizational structure often mirrors the product structure. Simply, the number and sizes of subunits (modules and parts) can, out of a function-component perspective, be translated into the number and size of teams working to develop the product. Looking at it in a tradeoff perspective, Fixson states that one very large team requires many internal iterations in the design process. On the other hand, many small teams produce a long sequence of information transfers. Therefore, a medium number and sizes of subunits is the aim to achieve a medium number and sizes of design teams. The tradeoff could be explained as a balance of the design complexity between and within the subunits. According to Fixson, this seems to be the most resource efficient approach. In terms of development time, similar effects have been found. Consequently, both costs and time reach a minimum if the product is decomposed into a medium number of subunits, and increases when fewer but larger subunits, or more but smaller subunits, are chosen (Fixson, 2004).

Also the characteristics of the interfaces between the subunits affect the efficiency of the design process. Weaker interface connections enable the design teams to work independently on different subunits. This can reduce the number of iterations between the teams, and thereby increase the overall design process efficiency i.e. cost and time. The fact that weaker interface dependencies allow design tasks to run parallel will also shorten the development time. Other positive effects are increased design flexibility and reduced risk of having to repeat experiments (Fixson, 2004).

As the design cost is a one time cost, its contribution to the unit costs is very dependable on the production volume. This issue is also relevant when considering the amount of sharing (commonality) of parts, modules and components between products and families (Fixson, 2004).

3.3.5 Production costs

The primary focus in this phase is on determining the optimal design of the product to produce and assemble the parts in a productive way. The logistic support to handle the material flow is also of interest (Asiedu & Gu, 1998).

Looking closer at the manufacturing and assembly costs, they are highly influenced be the size and number of subunits. The basic idea of design for manufacturing (DFM) and design for assembly (DFA) is a good approach of this analysis. Both of them suggest the designer to focus on a product design that consumes the least amount of resources during manufacturing and assembly, but they do it with different underlying principle. DFM aims at simplifying manufacturing processes to reduce investments and process variability, which leads to higher productivity and lower costs. In general, to achieve simple processes, simple subunits are needed. This means that the designer should try to keep the size of the subunits below a certain complexity level that makes them difficult to manufacture. Consequently, a larger number of subunits are needed to keep the size i.e. the complexity down. In contrast, DFA aims to keep the number of subunits as low as possible, which keeps the assembly costs down, as they are direct correlated to the number of subunits to be assembled. This results in two cost curves increasing in opposite direction, see Figure 19 (Fixson, 2004).

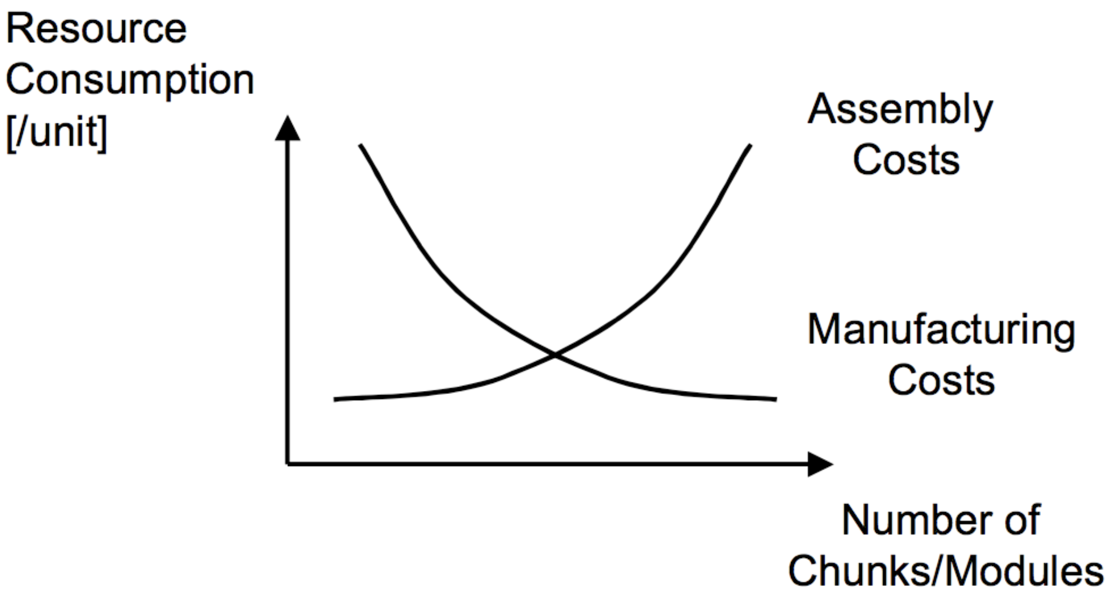

Figure 19: Manufacturing and assembly costs (Fixson, 2004)

Sharing components within a product family will also affect the manufacturing and assembly costs. When the commonality increases, the volume of some subunits will increase. If the volume of some subunits increases, the fixed costs for these subunits' production processes are distributed among a larger number of units, which decreases the fixed cost per unit. Also when commonality increases, some subunits might not be of use anymore, which leads to that the total number of different subunits decreases. If the total number of different subunits decreases, the number of production processes might also decrease, which saves fixed costs. Consequently, the manufacturing and assembly costs decrease when commonality increases. However, the magnitude of these savings need to be compared to the extra costs occurring for "over-designing" a subunit due to higher sharing. For instance, products whose costs are dominated by material costs i.e. variable costs, will not gain much through commonality (Thonemann & Brandeau, 2000).

Also the characteristics of the interfaces between the subunits might affect the efficiency of the production processes. Preferable the interface characteristics between the subunits should minimize complexity and uncertainty within the production process as well as minimize the total number of different processes. This will lower the production costs (Fixson, 2004).

To the logistic costs do storage, transportation, inventory and work-in-process (WIP) related costs belong. Storage and transportation need to be considered both inside and outside the plant. The product design affects the inventory and WIP costs through commonality level and location of customer order decoupling point (CODP). Postponement of CODP and late customization usually results in lower storage and WIP costs. Sharing components automatically leads to a decrease of number of different components needed, which will reduce the safety stock levels (Collier, 1982).

3.3.6 Use costs

During the product use, three types of costs occur, namely operation costs, maintenance costs and external cost incurred by the operation of the product.

The cost of input needed to operate the product belongs to the operation costs. Such inputs can be fuel, electricity, water, pressurized air, etc. Depending on how the products are designed, cost is influenced. For example, sharing components across individuals in a product family might allow a reduction of personnel training costs. Aircraft producers are trying to install similar, even identical, cockpits into different airplanes to reduce the retraining of the crew. Another example is if a product is frequently used in multiple modes, e.g. change of machine tool, a product design enabling quick changes and reconfigurations will improve the productivity and thereby reduce the operating costs (Fixson, 2004).

Considering the maintenance costs, there are two major questions in concern:

- what is the probability that maintenance and its costs will occur during the product's phase of use?
- what will be the anticipated cost for the maintenance?

By grouping parts with similar expected lifetimes together, it is likely to reduce the repair and replacement costs. Additionally, a product design that allows easy and fast access for maintenance and repair, due to the interface, will most likely lower the maintenance costs. An increase of sharing components across individuals in a family will reduce the safety stocks of spare parts without changing the availability. At last, the operation of a product might cause external costs due to e.g. damage to public health or environment through emissions (Dahmus & Otto, 2001).

3.3.7 Retirement and disposal costs

In the last phase of the product's life cycle, costs might occur due to disassembly and disposal. In general, it is difficult to predict the impacts caused by product usage and disposal and take them into consideration in the early design phase, since the factors are usually hard to quantify (Asiedu & Gu, 1998). Fixon agrees and adds that it is particularly hard to estimate the disassembly costs, which complicates the choice of the most economic disassembly sequence (Fixson, 2004).

In the end of the product's life, there are a few options available regarding what to do with the product, see Figure 20 (Asiedu & Gu, 1998).

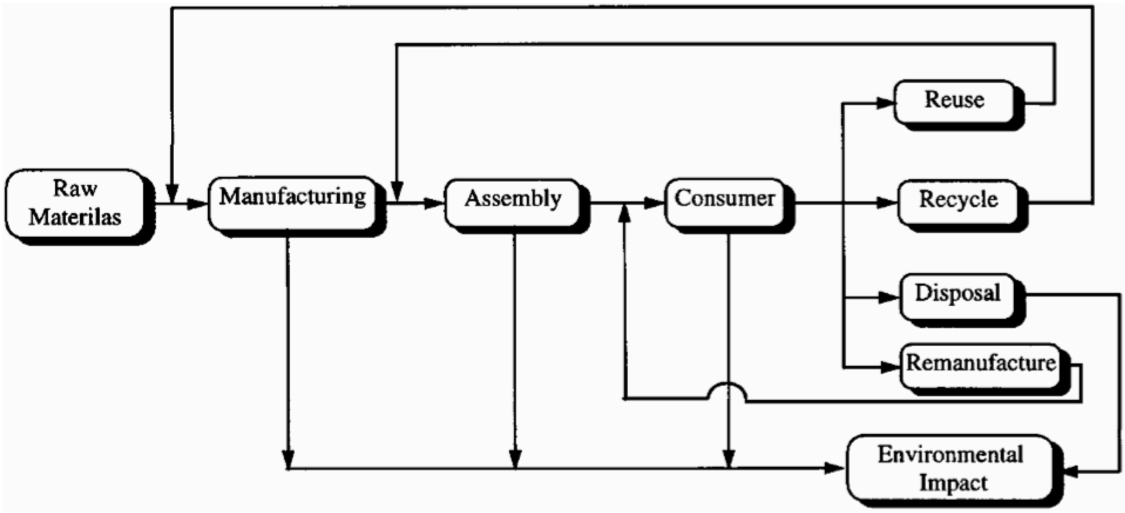

Figure 20: Retirement process (Asiedu & Gu, 1998)

When recycling, the product is broken down to raw material as the new part to be manufactured might not be similar to the old one. By reuse the product is torn apart but not to raw material. The worn parts are either recycled or disposed and the reusable parts are reused in a "new" product. To just regain the function and performance of products that usually are unserviceable, they can be remanufactured through refurbishing and restoration processes. The last option is disposal of the product, which basically leads to waste giving no value back (Yan & Gu, 1995).

3.3.8 Cost models

The development of a cost model aims to find the designer a tool with certain decision variables that generates an accurate estimation of the product life cycle costs (Fixson, 2004). There are a number of different cost models to help the designer to estimate the economic consequences of a design decision. Asiedu says that life cycle cost analysis in the early design phase should be done on a rather simply level using basic accounting techniques and a simple constructed model. Later on in the detail design phase the analysis can be more sophisticated, as the uncertainties are lower (Asiedu & Gu, 1998).

It is crucial that not just the product is decomposed in parts, but the costs too. Such a cost decomposition is known as a cost breakdown structure (CBS), as earlier mentioned. Out of this structure, cost functions can then be allocated to the various categories. The major benefit with a cost structure is that the total cost can easily be analyzed and calculated (Asiedu & Gu, 1998).

Normally, there are three different types of cost models: parametric, analogous and analytical models.

3.3.8.1 Parametric models

Cost estimation with a parametric model is based on predicting products' or components' costs by establishing scaling factors for the cost drivers of the various activities. Regression analysis is a common method to establish the scaling factors out of historical data (Fixson, 2004). According to Asiedu, the parameters (i.e. scaling factors) usually taken into consideration are for manufacturing complexity, design familiarity, weight and performance. A very simply model, on the other hand, could just consider the relation between the cost of buildings and floor area. Due to the models simplicity, it is used in many industries. On the other hand, the systematic collection and revision of parameter changes to keep the model updated can take a lot of effort. Another drawback of parametric estimation is that it is not very good for estimating costs for products using new technologies. Last to mention, it is a top-down estimation technique (Asiedu & Gu, 1998).

3.3.8.2 Analogous models

When cost estimating through analogy, a similar product or component is identified and the differences between existing and new product/component determines the difference in cost. The effectiveness and accuracy of this model depends heavily on the ability to identify correct differences between existing and new product/component to be compared. Therefore, the main disadvantage of estimating by analogy is the level of knowledge required. A complete knowledge of the products and processes is needed to identify and understand the similarities and differences. Positively, cost estimation by analogy tends to be very good for new products (Asiedu & Gu, 1998).

3.3.8.3 Analytical models

The analytical cost modeling can be divided into abstract modeling and detailed process based cost modeling. The abstract model is based on a mathematical approach, where emphasis lay on structural tradeoffs and the relationship between design decisions and costs are affected by the shape of the product. In the detailed process based cost model, normally referred to as detailed model, labour time and cost rates along with quantities and prices are needed to estimate the direct costs of a product or process. An allocation rate is then used to estimate the indirect/overhead cost. This is a bottom-up estimation technique used to build up estimates from an operative level. Consequently, this is the most time consuming and costly approach, which requires a very detailed knowledge of the product and processes. According to Weirda, the main difficulties with this method are (Weirda, 1988):

- Determining or collecting the basic standard times
- Determining the hourly rates and keeping them up to date
- Management of a large amount of information
- A large number of simple but time consuming calculations
- The skill and experience required to use the basic information properly

However, the most accurate cost estimations can be done using this model. It is also very flexible as it uses basic information. In opposition to the other models, no existing product(s) is needed to resemble the new product in some way.

3.4 Product variety optimization

Looking at design strategies, product families and platforms is a well known strategic approach among many companies today. Product families and platforms support the basic features of mass customization as the strategy generates certain cost advantages in life cycle process i.e. product design, manufacturing and inventory. A lot of research has been done to develop models and tools to guide the product designer in the difficult process of finding a product family design that provides variety to the customer while maintaining near mass production efficiency. Some approaches focus on ways to increase external product variety for the customer while maintaining low costs, as other focus on keeping the internal variety down without losing the variety appeal to the customer. However, the underlying idea of most of these approaches is to increase commonality across the products in the family, meanly to reduce the total life cycle cost and time to market. It is important though to be aware of how cost, revenue and performance are affected when changing the commonality. For instance, an increase of commonality can cause cannibalization between the products, which has a decreasing affect on the revenue and the performance. On the other hand, the cost savings will most likely go up (Fixson, 2004).

Considering the balance of cost and quality, many products contain two types of components. The first type has a strong influence on product quality and the second type has a weak influence on the product quality. For the components having a weak influence on the product quality, the cost is the only decision variable needed to be taken into consideration (Fixson, 2004).

3.4.1 Costs in product variety optimization

In the traditional cost structure, the decomposition into direct/indirect costs and fixed/variable costs is a usual approach. Product variety optimization, on the other hand, focus on the cost effects when changing the volume and number of product individuals and modules (Fujita, 2006). Fujita suggest the following grouping:

- Costs depended on production volume
- Costs depended on the number of different products and modules.

Costs depended on production volume mainly concerns material costs, manufacturing costs and assembly costs. Significant for these costs is that they are proportional to the volume produced. Due to learning effects the manufacturing and assembly costs tend to sink as the volume of produced units increases.

Costs depended on the number of different products and modules concerns mainly design and facility costs. These costs are usually counted as a fixed cost when considering a single product. When commonality increases the number of different modules to be designed and manufactured reduces, which normally leads to cost reductions. Furthermore, supply chain costs also tend to decrease as the number of different modules is reduced. On the other hand, commonalization of modules for different products increases the costs due to over-specification.

Besides from costs, the profit is an important issue when building a cost estimation model. The change in profit, on the other hand, is harder to estimate than the cost. It requires that the utility can be estimated and that an understanding of how the utility affects the customers’ willingness to pay a certain price exists (Fujita, Product variety optimization, 2006).

3.4.2 Tradeoffs

Looking back at the cost structure for product variety optimization, it is clear that higher commonality leads to both benefits and penalties (Fujita, Product variety optimization, 2006). This scenario is illustrated in Figure 21.

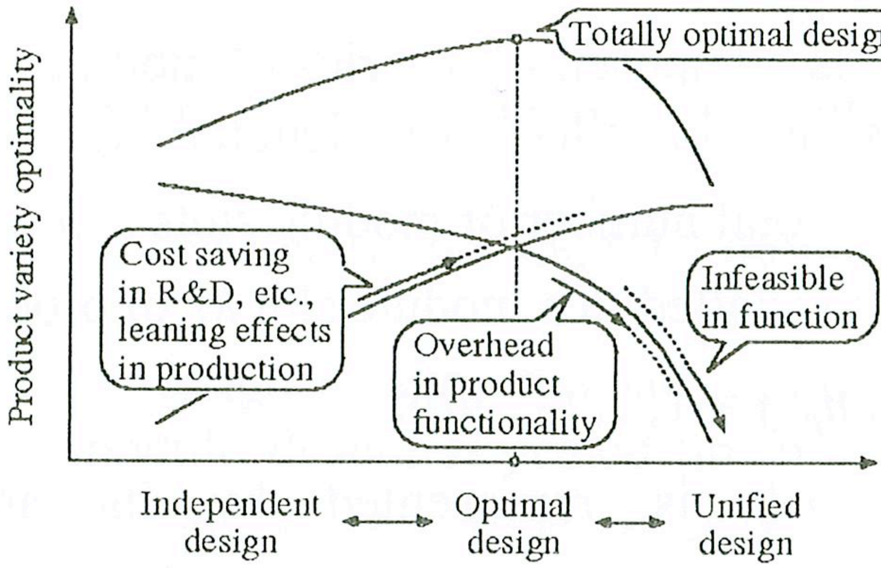

Figure 21: Product variety optimality (Fujita, Product variety optimization, 2006)

The horizontal axis in Figure 21 shows the commonality level. The left end of the axis corresponds to the situation where every product in the family is independently designed and produced. The right end of the axis corresponds to the situation where all products in the family are identical i.e. one product covers all segments. The vertical axis shows the product variety optimality. As commonality increases, starting from the left end going to the right, the costs depended on the number of different products and modules decreases, and consequently optimality increases. A part of the costs depended on the production volume i.e. cost influenced by learning affects, also decreases. However, not in the same ratio as the costs influenced by overhead in functionality (over-specification) increases. This means that the total cost depended on production volume increases, and consequently optimality decreases. Furthermore, the performance of each individual (feasibility in function) decreases as commonality increases. All these cost and performance changes form a tradeoff situation between the benefits and penalties, where an optimal solution is to be found within the design region (Fujita, Product variety optimization, 2006).

4 Analysis

The analysis is focused to connect the theoretical perspectives from the Theoretical Review with the empirical facts of the ABB IRB 6640 family.

4.1 Robot family and platform analysis

As described in the theoretical review: *“a product family is a set of similar products in terms of features/functions that are based on a common platform”*. The robots in the IRB 6640 family do all function the same way, they use the same technology, and share some of the components, for example, all robot individuals have the same gear in joint one, the same gear in joint two, and the same gear in joint three. Also, the robot individuals with the same reach share basically the same hardware.

It is clear that the IRB 6640 family supports the basic theoretical ideas behind product family thinking. If referring back to the definition of a product family stated above, it needs to be built on a common platform. In some way, the 6640 family is build on platform thinking as the individuals share some components, but the type of platform used is unclear.

4.1.1 Modular platform

When redesigning a robot family, a common approach is to change the reach and payload of the robot individuals to see how the performance requirements (for example rated torque) influence the choice of motors and gears in the joints. Also new arm(s) are needed if the reach is changed. Taking this into consideration, a modular platform would be suitable, as the new robots are created through configuration of existing parts. Described in the theoretical review, a configurational product family design approach should aim to *develop a modular product platform, from which product family members are derived by adding, substituting and removing one or more modules*. This, in fact, supports the choice of a modular platform. In specific, the modular platform should consist of different gears, motors, lower arms, upper arms, etc, with restrictions of how the components can be assembled together.

4.1.2 Analogous cost model

When changing the configuration/interface of the components, the costs of the robot are influenced. The more the interface is changed, the more are the costs influenced. For example, if the gear is changed for a joint, the gear and robot interface might need to be changed. The change in costs is correlated to how much the interface(s) needs to be changed. Cost for investments at the supplier, testing time, change of assembly manuals, etc. do in general get bigger as the more the interface is changed. It is therefore suitable to choose an analogous model to estimate these changes in cost, as the difference between existing and new component/interface determines the difference in cost. Additionally, the robot family design is done in the early design phase, where the uncertainties are high and lack of detailed information is a fact. It is therefore important that the analogous model is kept simple focusing on the large costs.

4.1.3 Internal product configuration system

The backside of using an analogous model is the knowledge and information required to understand how the products, components and processes are similar and different. To manage that, ABB needs to take help of an internal product configuration system, which facilitates this information. The internal product configuration system should not only contain the necessary information needed for the analogous model, but also the specifications of the production-/logistic processes.

Considering the theoretical framework for product family design and development, the internal configuration system should focus on supporting the connections between the physical, process and logistic domains, according to Figure 22.

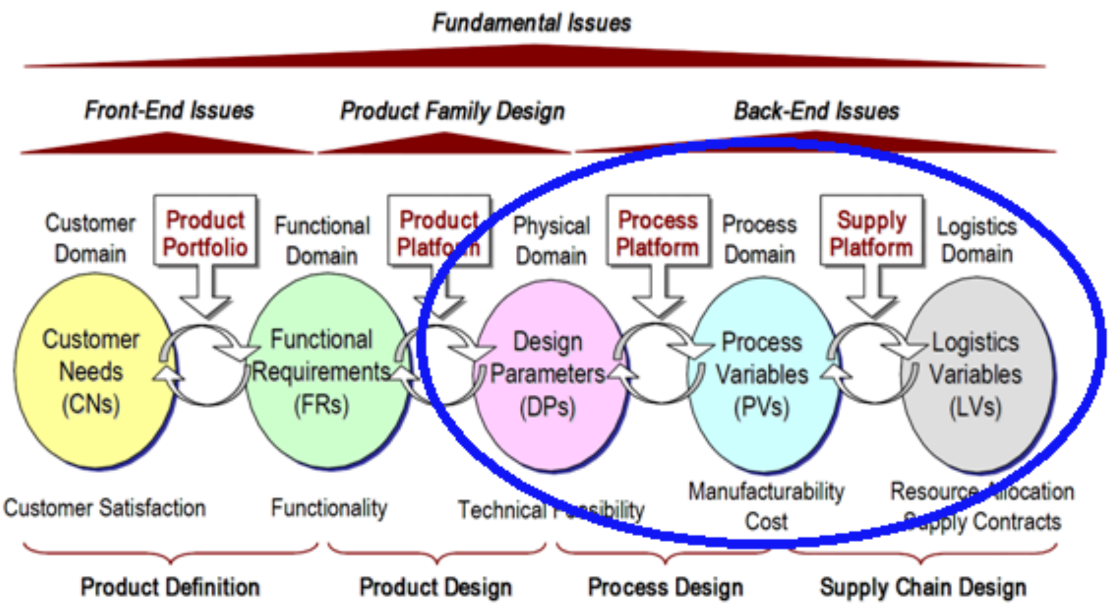

Figure 22: Focus of internal configuration system

As the configuration system is meant to be used internally, facilitating the groups involved in the design process with information from the assembly and logistic processes, it is not necessary to include the external connection to the customer. However, when this system is implemented and running, ABB has the possibility to add the customer focus into the system by connecting these domains. But at this stage it is not necessary, as the study focuses on the cost perspective, making the market perspective irrelevant. The internal configuration system's area to function is described in Figure 23.

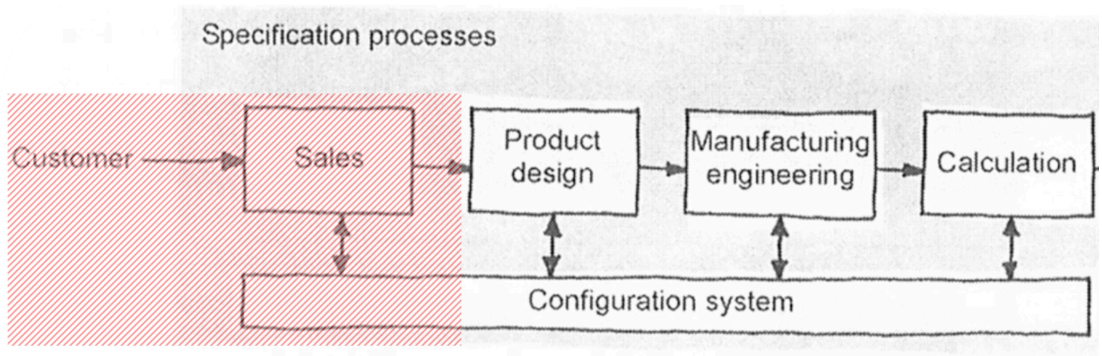

Figure 23: The internal configuration system's area to function

It is important that the different groups involved in the design process together develop the specification processes working out the specifications, so that the processes are stable over time and functions well in practice. The type of specification process to be developed is "Modify to order", which suits robot family design well as it supports products based on modules.

As ABB are using the assembly to order (ATO) production strategy, they have the right prerequisite for increase their customization level in the future. By extending the configuration system with the customer domain and developing specification processes for order processing, the customers can get robots that are assembled to their specific order and therefore meet their requirements better. On the other hand, the robot design process is very complicated and built on many manual design steps. Therefore is a configuration system where the customer can "assemble" their own robot far from realistic with today's design methods. To make it possible, the design process must be automated, which would speed up the individual design process for a customized order. Another solution is that every possible design configuration is predetermined and the performance and cost of every possible configuration is precalculated.

4.2 Robot life cycle cost analysis

4.2.1 IRB 6640 family

Reflecting on an IRB 6640's characteristics such as length of life cycle and total life cycle cost, it is obvious that the robot belong to the "Mid scale" according to Table 5.

Table 5: IRB 6640's position regarding life time and total cost

Large scale	Mid scale	Small scale
• Multiple, multi-year, on-going development cycles • Decade length operational life • Customer product cost/unit ≈ $\$10^6$ - $\$10^9$ • Annual unit production volumes ≈ 1 - 100 • Multiple complex subsystems • Large integration effort • High infrastructure development and maintenance • Mid-life upgrades to selected subsystem • Continuing sales value • Examples: aircraft, production plants, power plants.	• 1-5 year development cycles • 1-5 year operational life • Customer product cost/unit ≈ $\$10^3$ - $\$10^5$ • Annual unit production volumes ≈ $\$10^3$ - $\$10^5$ • Critical subsystems • Medium scale integration effort • Low field infrastructure support costs • Replacement by new product models (obsolescence) • Examples: computers, cars electronic instruments.	• Less than 1 year development cycles • Less than 2 year operational life • Customer product cost/unit ≈ \$10 - \$100 • Annual unit production volumes ≈ $\$10^6$ - $\$10^7$ • Simple subsystems • Incremental design changes • Little or no field support costs • Disposal after failure • Examples: consumer electronics, small appliances.

The robots operational life time is between seven and eight years, which could be understood as a little bit too long for mid scale, but in comparison to large scale where the operational life time is normally several decades, there is no doubt. The further development of existing robots is done continuously, but as the operational life time is seven to eight years, it is likely to assume the development time is somewhat shorter, maybe five to six years.

As the robot is a mid scale product, its life cycle cost has a similar distribution as a medium sized product, sold in medium volume, according to Figure 24.

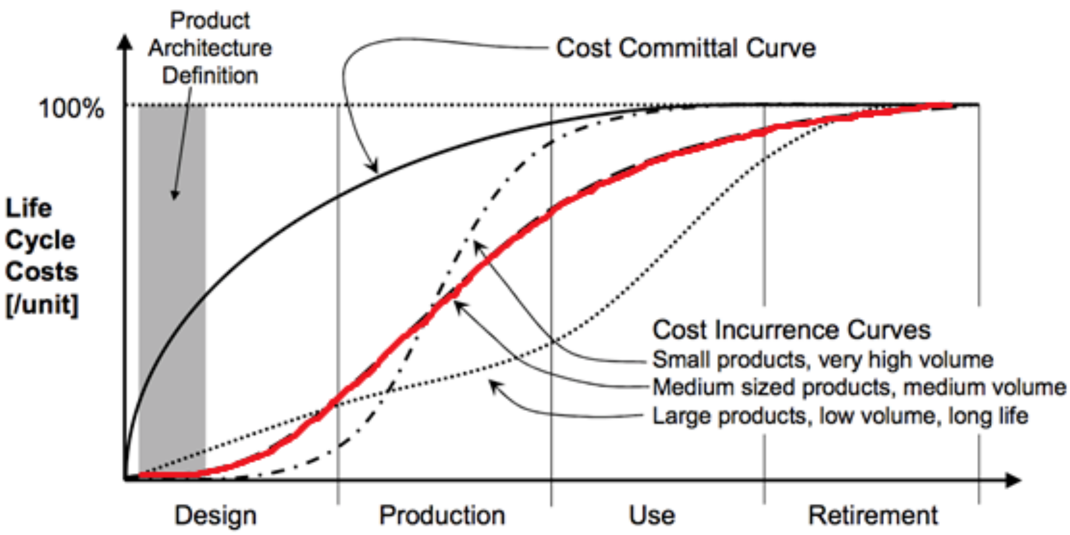

Figure 24: A robot's life cycle cost distribution

When taking a closer look at Figure 24, the cost distribution for a robot is concentrated to the production phase. However, the design and use phase is not to be neglected in the life cycle cost analysis, as they together stands for about 40% of the total cost.

4.2.2 The gear commonality

When changing the gear configuration in IRB 6640 family, the level of sharing gears is affected. Consequently, the volume per gear and number of different gears are changed, which are pointed out as central factors in the theory. A third factor will be added in this case study, considering the fact that when the commonality of gears within the family is changed, it might require new gear(s). The relationship is described in Figure 25. The new gear could lead to new suppliers, new spare parts, extra testing, change of assembly process, etc.

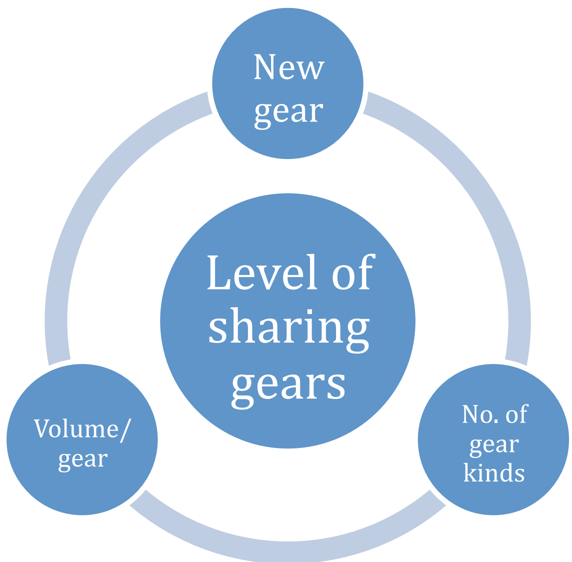

Figure 25: Level of sharing gears

To be more exact, the cost analysis is done in regard to that the following happens when the commonality of gears is changed within a product family:

- Volume per gear increases when commonality increases
- Number of different gears decreases when commonality increases
- A new gear might be needed when commonality increases/decreases

4.2.3 Product design and development costs

The fact that ABB is designing the robots and their biggest resource is personnel, it is likely to assume that their biggest cost is salaries. If all five robots in the family share the same gears for joints one, two and three, instead of having individual ones, the number of different gears decreases. It can thereby be assumed that less time and money is needed for design and specification due to similarities between the robots. However, it is quiet hard to estimate how much the amount of design hours will be affected when changing the commonality.

When a gear is changed in a robot, it needs to be tested before set in production. The amount of testing needed is hard to estimate in the early design phase, but it can be assumed that the cost is correlated to what robot joint is changed and how much the interface/configuration of the robot and gear are changed. Generally, joint one, two and three are more expensive to change than joint four, five and six (Pind, 2010).

4.2.4 Production costs

Looking at the manufacturing and assembly costs, even if ABB are only doing the assembly in-house, the manufacturing costs for the suppliers will affect ABB's costs through the price of the purchased parts.

If volume per gear increases, the manufacturing and assembly costs will decrease due to the learning effect. Also, if a higher volume is ordered from the supplier, the volume discount might increase which will decrease the manufacturing cost i.e. the price per gear. As the gears are very expensive this could have a high effect on the total cost.

If the number of different gears decreases, the cost of external transportation, material handling, safety stock, and assembly will decrease. The external transportation cost goes down as the supplier has fewer or no gear left to deliver. If the supplier stops to deliver a certain gear, but still has other parts that they sell and deliver to ABB, the transportation cost might not go down so much as they usually deliver all their parts at the same time. However, if the supplier does not have any other parts to deliver, the transportation cost is reduced to zero. The cost for material handling goes down because activities such as income control, transportation to incoming storage, and transportation from incoming storage to assembly line can be cut. As the total number of gears in safety stock decreases, the capital tied up decreases and thereby also the cost. The assembly cost might also go down because less number of articles means less instruction and training of operators. Possibly a postponement of the customer order decoupling point can be done if, for instance, the robots are identical from stand up to joint 3, which enables this part of the robot to be preassembled.

If a new gear is needed, the costs of procurement, new equipment and new working manuals will increase. If an existing supplier is used, the cost for procurement will not go up so much, but if a new supplier needs to be found the cost will be higher. The cost for new equipment, either for the supplier's site or for ABB's own assembly process, is correlated with how familiar the new gear is the supplier's production process and how much the assembly process must be changed to support the new gear. Most likely, in the same degree will the work manuals for the operators have to be changed.

As the robot architecture is not changed in our study, the aspects where manufacturing costs decreases when commonality decreases, due to simpler modules and thereby simpler processes, is not applicable.

4.2.5 Use costs

Typical usage costs affected are electricity for operation, training for service and repair, and safety stock of spare parts.

If the number of different gears decreases, the cost of electricity for operation, training for service and repair, and safety stock of spare parts are affected. The electricity usage is probably closely connected to the performance of the robot, where of course the weight is an important factor. A higher commonality among gears penalizes the performance of each individual robot, which simply means that the robot is not optimal for its task. Therefore, it is likely to assume that the energy efficiency is negatively affected and more electricity is used in operation. This costs, on the other hand, is not a company cost but a users cost, which will only affect ABB's profit indirectly as the customer requires a lower price if the operation cost is higher. The training of service staff will probably be easier and quicker if the robots are sharing gears, because more gears probably means more to learn for handling the service and repair. Also the costs for safety stock of spare parts will go down as the number of gears decreases, which means that the capital tied up decreases.

If a new gear is needed, its interface might be different to the prior one's and the existing spare parts might not be compatible with the new joint configuration/interface on the robot. Consequently, the spare parts must be changed, which leads to administrative, logistic and possibly disposal costs.

4.2.6 Retirement and disposal costs

Considering the gears in specific, they are fragile and usually the part in the robot, which constraints the overall robot life time. It is therefore unlikely that the gears are reused, which on the other hand does not mean that the other parts in the robot are not reused. Even if the gears are disposed, the complexity in the process of reuse or remanufacturing might be affected by the number of different gears in the family. However, this affect is very hard to predict in the early design phase.

When grouping the cost into the categories "company cost", "users cost" and "society cost" according to Table 4, all costs mentioned above belongs to "company cost" except for electricity for operation which belongs to "users cost".

4.2.7 Quality and time

Important complementary objectives to cost, when doing a design change, are quality and time. The relationship between cost, quality and time can be described as in Figure 26.

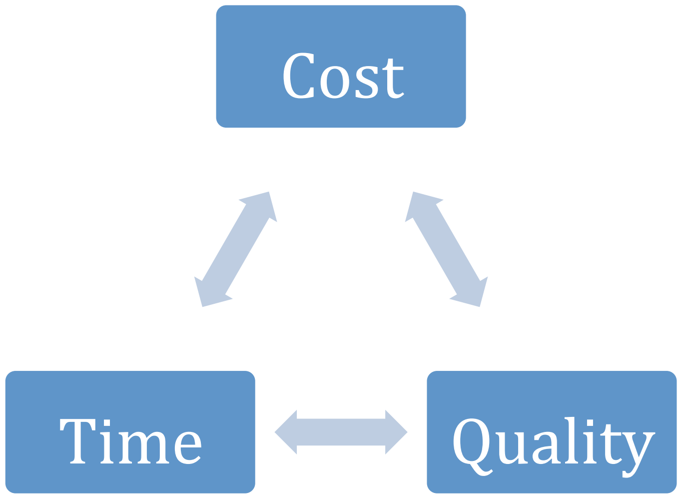

Figure 26: Relationship between cost, quality and time

Cost, quality and time usually work against each other, meaning that when for example the quality is the most important objective and needs to be maximized, the cost and time will be negatively affected.

When the volume per gear increases, the quality and time will be affected. The quality is closely connected to the batch size manufactured, and the batch size is determined by the volume to be produced. When manufacturing a gear, it takes a while before the machine is tuned in and the quality level is stable. Consequently, gears from a smaller batch size will have worse quality than gears from a larger batch size. Therefore, the quality increases with the volume to be produced. On the other hand, a higher volume can lead to capacity problems in the manufacturing processes, causing queues and delays that have a negative influence on time.

When the number of different gears decreases, the time will be affected. The number of deliveries for suppliers are closely related to the number of different gears (and the number of suppliers). If the number of different gears goes down, the number of deliveries will also go down. For instance, if the average rate for delivery on time is 98% and a robot has different gears on all six joints, the probability that the assembly of the robot can start on time is 88% (=(0,98^6)*100%). However if the robot has the same gear on all six joints, the probability that the assembly of the robot can start on time is 98%. Therefore will a decreased number of different gears affect the time positively.

When a new gear is needed, the quality and time will be affected. The past shows that if a gear lacks so much in quality that measurements need to be set in during the warranty time, the costs usually become huge. The risk for an insufficient quality level is also higher if the gear is bought from a new supplier, instead of from an existing supplier where ABB already have experienced their quality level. A new gear does also require a certain time for testing, where delays can occur. A new supplier might also be needed, which means a higher risk in delivery, as ABB might not have any experience of the suppliers potential to manufacture and deliver on time.

4.2.8 Cost estimation model

As discussed above, the following factors are affected by a change of commonality in the family:

- Volume per gear
- Number of different gears
- A new gear might be needed

Consequently, these factors affect the objectives cost, quality and time. This relationship, discussed in the prior sections, is illustrated in Appendix 1.

One part of this study is to build a cost model in Excel, where it is analyzed how the actual costs for the IRB 6640 family are affected when changing the commonality. Due to lack of information could not all costs be considered. The focus lies within:

- Initial costs: Development and testing, change of spare parts and system before SOP, logistics at suppliers, and investments at suppliers. All these costs are considered as *"fix" costs* and occur before Start Of Production, SOP.
- Maintenance costs: Spare parts & system after SOP, and suppliers maintenance after SOP. Considered as a *"fix" cost*.
- Gear cost: Gear prices. Volume discount and over dimensioning influences the gear prices. Further explanation later in this chapter. Considered as a *variable costs*.

The costs mentioned above are the same ones as in the figures 29, 30, 33 and 34. The connection between these costs and the cost types in Appendix 1 can be seen in Appendix 2. Simply, the costs types that are considered in the cost model for calculations are written in the color of red. The other cost types written in black are not considered in the cost model.

The objective of the study is to see how the costs listed above are affected when changing the gear configuration, more exactly the commonality of the gears, within the IRB 6640 family. The costs are analyzed out of a family perspective and not from an individual robot perspective. The commonality will be measured with two different indices: Commonality Index (CI), see Equation 1 and Component Part Commonality Index ($CI^{(C)}$ or CIC), see Equation 2. Also, only the gears in joint one, two and three of the five robots are considered. The current gear configuration in the family is shown in Table 6.

Table 6: Current gear configuration for IRB 6640 family

Current configuration			
Robot	**Joint 1**	**Joint 2**	**Joint 3**
1	same gears	same gears	same gears
2			
3			
4			
5			

To change the commonality level within the family, the level of common gears between and within the robots is changed. Six different configurations are studied, where the level of common gears increases from configuration one to six. The six different configurations are showed in Table 7.

Table 7: Gear configuration one to six

Configuration 1			
Robot	**Joint 1**	**Joint 2**	**Joint 3**
1	gear a	gear b	gear c
2	gear d	gear e	gear f
3	gear g	gear h	gear i
4	gear j	gear k	gear l
5	gear m	gear n	gear o

Configuration 2			
Robot	**Joint 1**	**Joint 2**	**Joint 3**
1	same gears	same gears	same gears
2			
3	gear g	gear h	gear i
4	gear j	gear k	gear l
5	gear m	gear n	gear o

Configuration 3			
Robot	**Joint 1**	**Joint 2**	**Joint 3**
1	same gears	same gears	same gears
2			
3	same gears	same gears	same gears
4			
5	gear m	gear n	gear o

Configuration 4			
Robot	**Joint 1**	**Joint 2**	**Joint 3**
1	same gears	same gears	same gears
2			
3	same gears	same gears	same gears
4			
5			

Configuration 5			
Robot	**Joint 1**	**Joint 2**	**Joint 3**
1	same gears	same gears	
2			
3			
4			
5			

Configuration 6			
Robot	**Joint 1**	**Joint 2**	**Joint 3**
1	same gears		
2			
3			
4			
5			

Normally, CIC is a number ranging from one to α, but as a normalized value ranging from zero to one is needed, the equation below is used to recalculate the value. The regular CIC, shown in Equation 2, is called $CIC_{reg.}$ and the CIC used further on is described in Equation 4.

$$CIC = \frac{CIC_{reg.} - 1}{\alpha - 1}$$

Equation 4

Table 8 below shows the relationship between number of different gears, commonality index (CI), see Equation 1, and component part commonality index (CIC), see Equation 4, for the different gear configurations.

Table 8: Gear configuration and commonality level

Configuration	No. of different gears	CI	CIC
1	15	0	0
2	12	0,21	0,03
3	9	0,43	0,06
4	6	0,64	0,11
current	3	0,86	0,29
5	2	0,93	0,44
6	1	1	1

It is obvious that the commonality indices increase as the number of different gears decreases. Highest commonality, which is one, is reached when only one gear is used in the whole family.

Figure 27 also shows the relationship between the configurations, number of different gears, CI and CIC. CI decreases linear and CIC decreases exponentially when the number of different gears increases. The different behavior of CI and CIC also shows that they are not linear to each other.

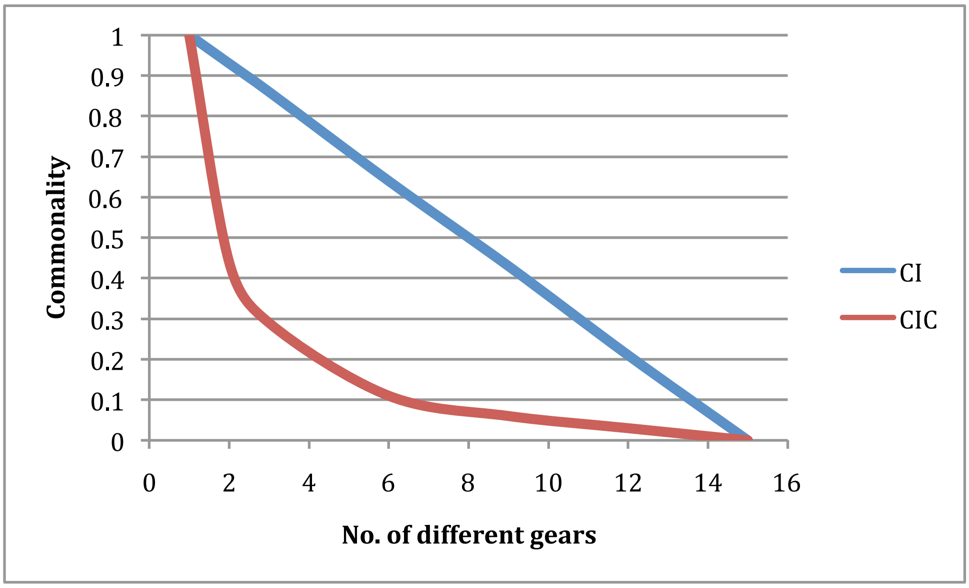

Figure 27: Relationship between number of different gears, CI and CIC

The study is based on two different scenarios, which share a lot of similarities. In both scenarios, the calculations are based on that the price, profit margin, sales volume per year, volume discount level for gears and robot life cycle time are same for the different robots in the family. What differs the scenarios from each other is that scenario two takes into consideration that a higher commonality leads to over dimensioning of some gears, and thereby higher gear costs. For example, joint two has a higher torque than joint one and three. If a robot has the same gears in joint one, two and three, the gear must be dimensioned to handle the higher torque in joint two, making it over dimensioned for joint one and three. There is a correlation between the size of the gear and the cost. The higher torques the gear can handle, the more it costs. Consequently, the average cost per gear will be higher if all three joints share the same gear in comparison to if they all have individual dimensioned gears. Scenario one, on the other hand, takes no consideration to over dimensioning.

The costs considered in the model are the costs earlier mentioned in this chapter (4.2.8. Cost estimation model). The calculations of the costs have been done in steps, one for each configuration in Table 8. Then the costs have been plotted to the corresponding CI and CIC values, also coming from Table 8. The result is to be seen underneath in "4.2.8.1 Scenario 1" and "4.2.8.2 Scenario 2".

4.2.8.1 Scenario 1

In the first scenario is no consideration taken to over dimensioning of gears. The only factor affecting the gear price is the discount occurring when buying bigger volumes from the suppliers. Figure 28 shows the relationship between CI and change of total cost of the family, which is on a life cycle basis. The change of total cost is measured in "money" and equals zero when CI is 0,86 as that is the current configuration. The actual cost value is not interesting in this case as only the curves increasing or decreasing behavior is the focus of the analysis. The CI values used come from Table 8. When taking a closer look at how the total cost change when increasing CI in Figure 28, a linear behavior can be seen (see "change of total cost"). But the fact that the current state means no gear changes and therefore no change of costs, is the reason to why there is a "dip" of the fix costs at CI equals 0,86. The change of total cost can be approximated as a linear decreasing function, see the black line in Figure 28. This line could be interpreted as how the total cost would change if the design of the family was done from scratch.

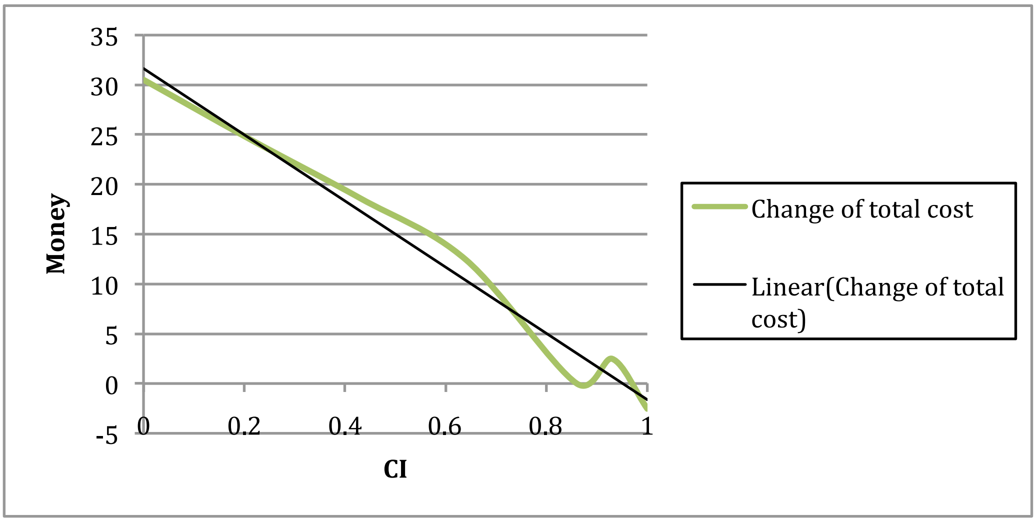

Figure 28: Scenario 1 – CI and change of total cost

In Figure 28 is the change of all costs together (total cost) considered. In Figure 29, on the other hand, are the different costs specified. It is obvious that all fix costs, which are all costs except for the gear price, decrease linear when CI increases. The gear price, which is a variable cost, does react a little bit different. It looks like it decreases exponentially. Also here appears a “dip” at CI equals 0,86 with the same reason as before.

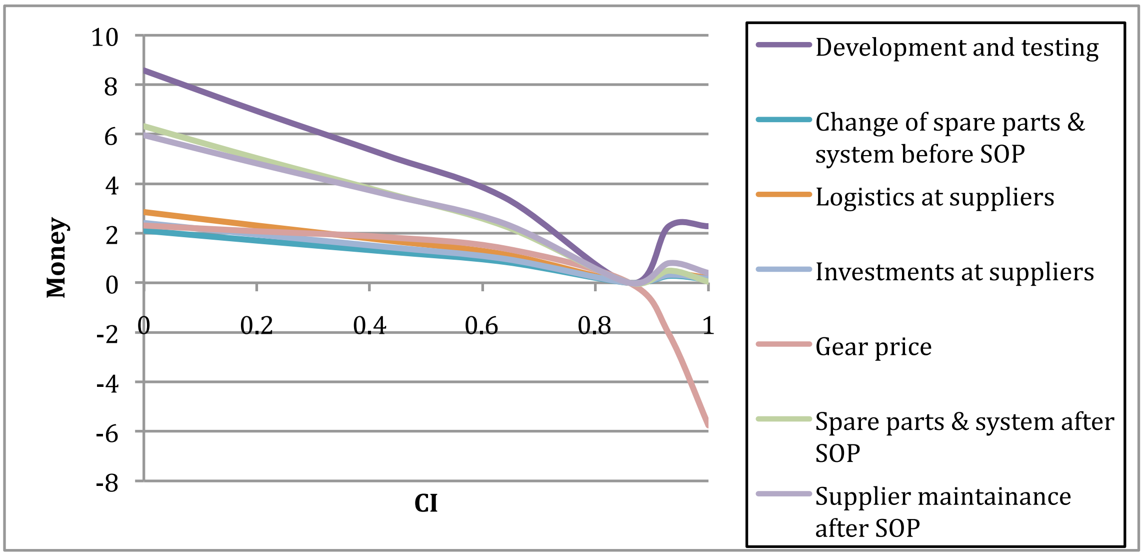

Figure 29: Scenario 1 – CI and change of different costs

In Figure 30 are the different costs plotted towards CIC, which is an index that takes the gear price into consideration in its calculation (see Equation 2). An interesting notice is that the gear price decreases linear as CIC increases, approximated with the black colored line “Linear(Gear price)”. All other costs, on the other hand, are not linear to CIC. By “the other costs” it is meant all costs but the gear price, prior referred to as fix costs. Also here appears a “dip” where the current configuration takes place, which is at a CIC value of 0,29 according to Table 8.

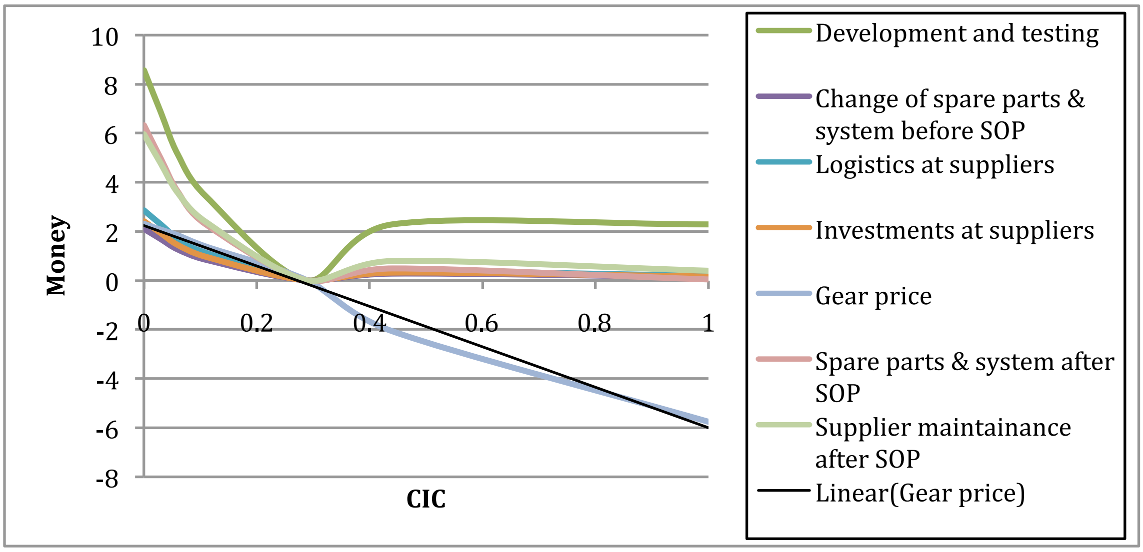

Figure 30: Scenario 1 – CIC and change of different costs

4.2.8.2 Scenario 2

In the second scenario, consideration is taken to the over dimensioning of gears. The average total gear cost could be seen as the average cost for all gears. When the number of different gears in the family varies will this cost be affected. For example, if the number of different gears in whole family changes from three, which is the current configuration, to only one gear, over dimensioning will occur in some joints leading to unnecessary over sized gears and therefore extra costs. These extra costs will affect the average cost of all gears in the family negatively. According to Figure 31, the average total gear cost increases with 10% when going from three to one gear. As mentioned, three gears refers to the current configuration, which means that the change is 0%. If, on the other hand, the number of different gears would increase to more than three, the average total gear cost will go down as the gears will be better dimensioned for the joints than in the current configuration. The biggest change occurs when going from 3 to 6 or 9 different gears. This is obvious, as choosing between 12 or 15 different gears will probably not lead to much better dimensioning. How much the average total gear cost is changed, see Figure 31, is based on the author's own assumptions and analysis. For ABB is the gear cost and gear price the same thing, as they buy the gears from suppliers. Therefore is the term gear price used instead of gear cost, even though the price can be seen as a cost as it has to be payed.

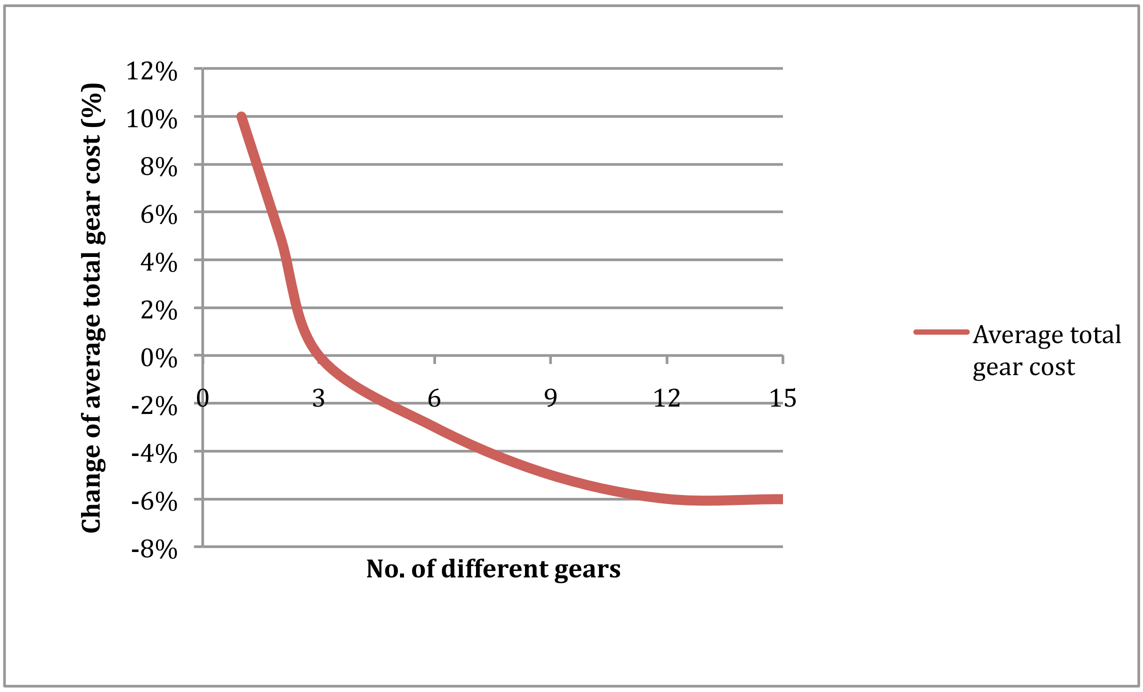

Figure 31: Change of average total gear cost

When the cost aspect of over dimensioned gears are considered, the total cost changes according to Figure 32. In comparison to Figure 28, the total cost does not decrease linearly when CI increases. In fact, the total cost tends to go at a quite high commonality i.e CI equals 0,9. This is due to the over dimensioning, affecting the gear costs more negatively than the volume affect them positively when CI increases. The "dip" of the total cost going down to zero at CI = 0,86 is obvious, as that is our current state with zero costs due to no changes of the family. If this ”dip” is neglected, it looks like the optimum could lie somewhere in between 0,7<CI<0,9.

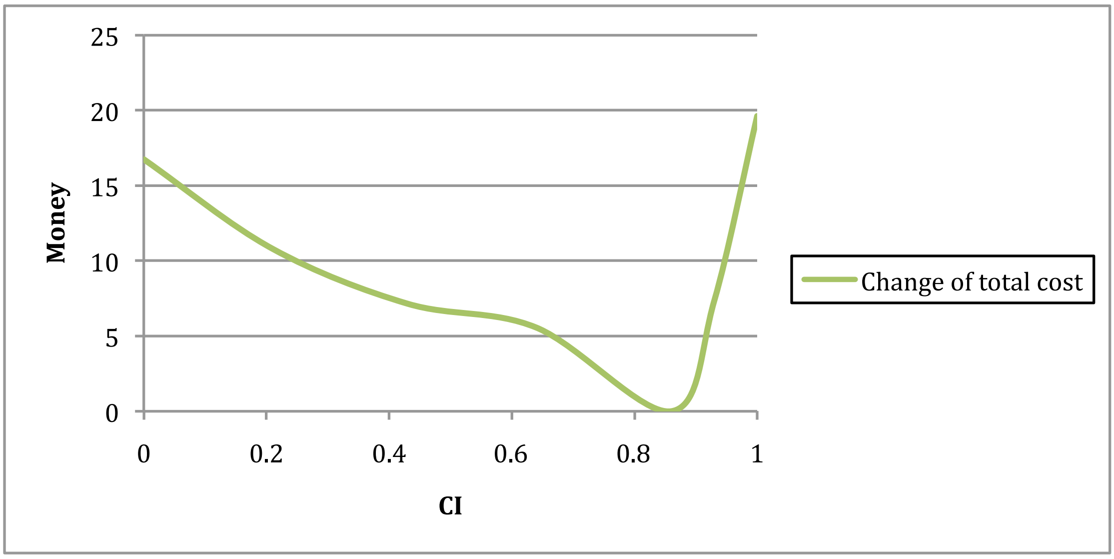

Figure 32: Scenario 2 – CI and change of total cost

Figure 33 shows how the gear price goes up exponentially as CI increases. In scenario one, the gear price went down when CI increases due to the volume discount. This confirms the already mentioned theory of how over dimensioning have a greater impact on the gear prices than the volume discount. The fix costs are not changed from scenario one.

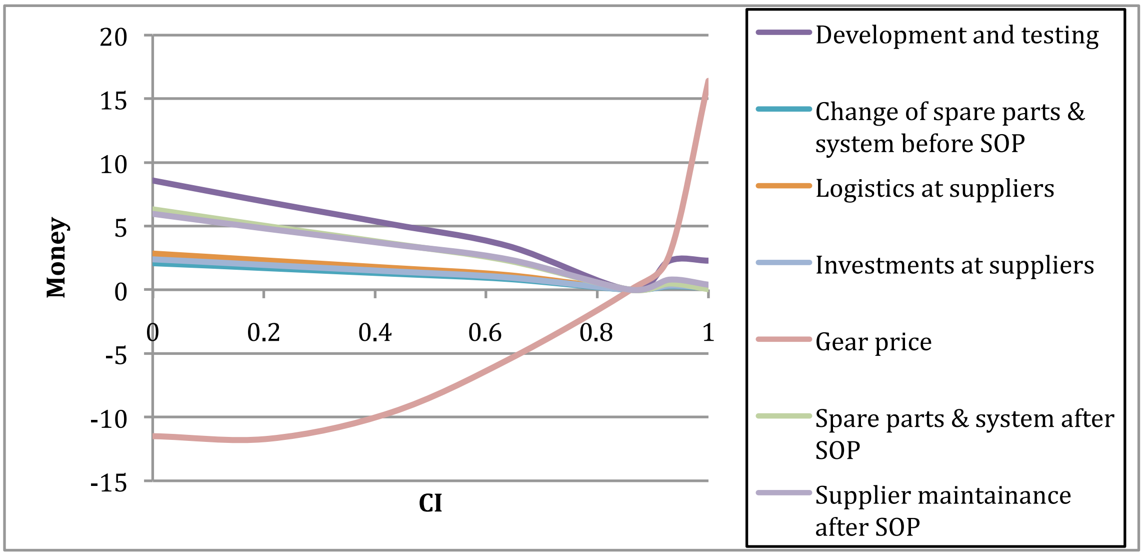

Figure 33: Scenario 2 – CI and change of different costs

Figure 34 shows that the gear price is still linear to CIC, even if the curve is increasing instead of decreasing in comparison to Figure 30. The gear price has been approximated with the linear line “Linear(Gear price)”.

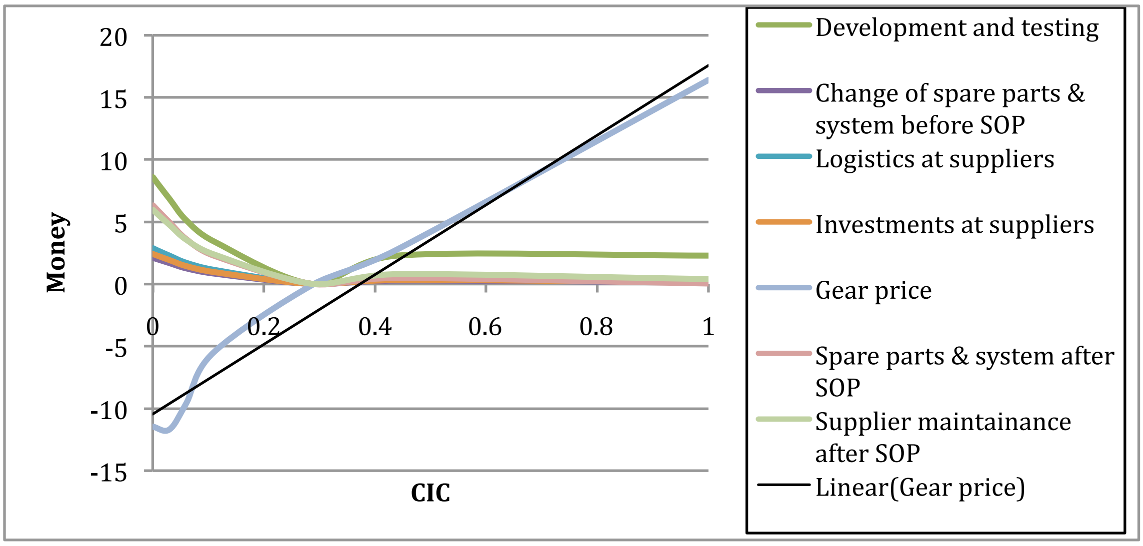

Figure 34: Scenario 2 – CIC and change of different costs

As a conclusion, to describe how the total cost within the family changes for different gear configurations, commonality index can be used. But to describe the costs linearly, two commonality indices are needed, namely CI and CIC. In the specific case of gears must the issue of over dimensioning be considered as it affects the choice of an optimal configuration. The analysis shows that the optimal gear configuration is between 0,7<CI<0,9, which corresponds to gear configuration 4, current configuration, and configuration 5, according to Table 8.

5 Conclusion

Considering the result from the cost estimation model, a comparison of scenario one and two shows that it is not obvious that a higher commonality always means lower costs. Scenario one does actually represent a general case where the common opinion on how increased commonality results in decreased costs is confirmed. But when looking at the specific case of robot gears, where the gears' prices are high in relation to the fix costs, the issue of over dimensioning must be taken into consideration. Scenario two shows that the optimal solution out of a cost perspective do no longer exists at the highest commonality possible, but at a slightly lower commonality level, i.e. 0,7<CI<0,9. With other words, the current gear configuration of the IRB 6640 family with a CI value of 0,86 is probably good out of a cost perspective.

The analysis also shows that the "fix" costs and the volume-variable gear price are not linear to each other, which complicates the situation when trying to describe the change of total costs with one commonality index. Consequently, two different commonality indices are needed: CI to describe the fix costs and CIC to describe the gear price. In the future, the cost model built in this study can be used for the IRB 6640 family. For other robot families, ABB can use commonality indices to estimate the change of costs, but in that case, they need to use both CI and CIC. When defining the objective, where for example the performance and costs are the subobjectives, the cost objective needs to be divided into two subobjectives, CI and CIC. The weighting between the commonality indices should then be done relatively to how big portion of the total cost they represent. What is important to remember though, when looking at gears, is that the issue of over dimensioning must be considered. This affect the cost of the parts, for example the gear prices, in a negative way when commonality increases. If the penalty due to over dimensioning have higher affect on the cost than the benefits of volume discount, the cost will increase instead of decrease when commonality increases.

However, worth to mention is some critic to the method used. In this study, the gears have been in focus. It is important to remember that the gears are very expensive parts of the robot. Consequently, when analyzing how the total costs of a robot family changes for different commonality levels of just the gears, it is likely to assume that the gear price is overrepresented in comparison to how much the average part price represents the total costs. For instance, the motors are two to three times cheaper than the gears but have a similar representation and amount of fix costs, which change the same way as the gears' fix costs when commonality varies. In such an analysis of only the motors, the over dimensioning of motors would not have the same impact on the total costs. Therefore, the cost effects of over dimensioning are higher when looking at only the gears instead of when considering the cost of all parts. Another consequence of just looking at the gears is that only some types of the costs are affected. Considering Appendix 1, the types of costs listed there are especially picked out for the analysis of gears and might not be representative when studying all robot parts. Many of the cost types are most likely the same, especially for the motors, but it is the authors' suggestion that ABB do look over the types again when involving other parts such as arms and stands in the analysis.

Also worth to mention is that the cost values used in the analysis come from a prior analysis at ABB. The aspects of time and quality has not either been considered in the cost model, which are very important objectives when changing the family design. Especially for gears as they are quite sensitive and usually determines the lifetime of a robot. A high gear quality is extremely important because if a gear breaks down, it will affect the life cycle costs in a negative way.

6 Future work

From here on, ABB can choose from two different approaches when proceeding with the study of cost analysis of robot families.

The first approach is to use commonality indices as a substitute to using the actual costs. As mentioned in the discussion, two different commonality indices, CI and CIC, are needed to represent the costs linearly. CI represents the “fix” costs and CIC represents the gear price. This approach does not require a lot of information regarding how the costs are influenced when the family design is changed. Basically, this means no need of an advanced system facilitating the cost relevant information. This approach does not either require a lot of time and money for implementation. On the other hand, the consideration of specifications and process restrictions at ABB is not possible without a configuration system. How quality and time are affect of a change in the family is therefore hard to estimate. Another disadvantage is the lack of accuracy using commonality indices instead of the actual costs.

Approach two is to build an internal configuration system. When redesigning the product family, the system enables ABB to consider the costs and the technical specifications and process restrictions, which affect quality and time. The cost changes should be estimated with an analogous model, where the estimation is based on comparison between the new and old robot or robot part. The platform, supporting the design, should be modular and consist of different gears, motors, lower arms, upper arms, etc, and with restrictions of how the components can be assembled together. This approach requires both time and money in designing, implementing and integrating the internal configuration system, the analogous cost estimation model and the modular platform. It also requires good communication between the different divisions working with the design and that the system is frequently updated. The main advantage of this approach is that ABB has updated information about costs and specifications and process restrictions, enabling an accurate analysis of what happens with cost, quality and time when the robot family is redesigned. The system will also facilitate restrictions of what changes that are technically possible and what changes that might be possible but very cost and time consuming.

7 References

Ölvander, J., Feng, X., & Holmgren, B. (2008). Optimal kinematics design of an industrail robot family. *ASME International Design Engineering Technical Conference & Computers* .

ABB AB, Corporate Research. (2010). *Short introduction to product families and modular design.* ABB Corporate Research and IKP Machine Design.

ABB. (2010). *www.abb.com*.

Asiedu, Y., & Gu, P. (1998). Product life cycle cost analysis: state of the art review. *International journal of Production Research, no. 4* , 883-908.

Baldwin, C., & Clark, K. (2000). Design rules: The Power of Modularity. *MIT Press, Cambridge, MA* .

Chen, Z., & Wang, L. (2007). A generic activity-dictionary-based method for product costing in mass customization. *Journal of Manufacturing Technology Management* , 680-699.

Collier, D. (1982). Aggregate Safety Stock Levels and Component Part Commonality. *Management Science* , 1297-1303.

Cutherell, D., Rosenau, M., Griffin, A., Castellion, G., & Anschuetz, N. (1996). *Product Architecture - The PDMA Handbook of New Product Development.* John Wiley & Sons.

Dahmus, J., & Otto, K. (2001). Incorporating lifecycle costs into product architecture decisions. *ASME 2001 Design Engineering Technical Conferences, DAC-21110* .

Dowlatshahi, S. (1992). Product design in a condurrent engineering envifonemnt: an optimaization approch. *Journal of Production Research, 30 (8)* , 1803-1818.

Du, X., Jiao, J., & Tseng, M. (2001). Architecture of product family: fundamentals and methodology. *Concurrent Engineering: Research and Application, 9(4)* , 309-325.

Fixson, S. (2004). Assessing Product architecture costing: Product life cycles, allocation rules, and cost models. *ASME 2004 Design Engineering Technical Conferences, 57458* .

Fujita, K. (2006). Product variety optimization. i T. Simpson, Z. Siddique, & J. Jiao, *Product platform and product family design* (ss. 188-223).

Fujita, K., & Yoshida, H. (2004). Product Variety Optimization simultaneously Designing Module Combination and Module Attributes. *Concurrent Engineering: Research and Applications, Volume 12, nr.2, June* .

Helo, P., Xu, Q., Kyllönen, S., & Jiao, R. (2010). Integrated Vehicle Configuration System - Connecting the domains of mass customization. *Computers in Industry* , 44-52.

Hill, T. (2000). *Manufacturing strategy.* New York: Palgrave.

Hvam, L., Mortensen, N. H., & Riis, J. (2008). *Product Customization.* Lyngby: Springer-Verlag Berlin Heidelberg.

Jiao, J., Simpson, T., & Siddique, Z. (2006). Product Family Design and Platform-Based Product Development: A State-of-the Art Review. *Journal of Intelligent Manufacturing* .

Kota, S., Sethuraman, K., & Miller, R. (2000). A metric for evaluating design commonality in product families. *Journal Mechanical Design, 122* , 403-410.

Krause, F. (2005). Process optimisation in the offer preparation (Prozessoptimierung in der Angebotserstellung). *wt Werkstattstechnik online, 95* , 7-10.

Li, L., Huang, G., & Newman, S. (2007). Interweaving genetic programming and genetic algorithm for structural and parametric optimization in adaptive platfrom product customization. *Robotics and Computer-Intergrated Manufacturing 23* , 650-658.

McGrath, M. (1995). Product Strategy for High-Technology Companies. *Irwin Professional Publishing, New York* .

Meyer, M., & Lehnerd, A. (1997). The Power of Product Platform - Building Value and Cost Leadship. *Free Press, New York* .

Newcomb, P., Bras, B., & Rosen, D. (1996). Implications of modularity on product design for the life cycle. *ASME Design Engineering Technical Conference* .

Olhager, J. (2000). *Produktionsekonomi.* Linköping: Studentlitteratur.

Pettersson, M. (2008). *Design Optimization in Industrial Robotics - Methods and Algorithms for Drive Train Design.* Linköping: LiU-Tryck Linköping.

Piller, F. (2004). Does mass customization pay? An economc approach to evaluate customer integration. *Production Planing and Control, 15* , 435-444.

Pind, L. (2010). ABB Robotics. (M. Björkman, Intervjuare)

Reinhart, G., Wiedemann, M., & Rimpau, C. (2009). An approch for the offer specification process for customised products. *International Journal of Computer Integrated Manufacturing* , 69-82.

Robotics, ABB. (2010). *IRB 6640/ IRB 6640ID Industrial Robot.* Västerås: ABB.

Seo, K., Park, J., Jang, D., & Wallace, D. (2002). Approximate Estimation of the Product Life Cycle Cost Using Artificial Neural Networks in Conceptual Design. *Advanced Manufacturing Technology 19:461-471* .

Siddique, Z., Rosen, D., & Wang, N. (1998). On the applicability of product variety design concepts to automotive platform commonality. *Proceedings of the ASMED Design Engineering Technical Conferences - Design Theory and Methology* .

Simpson, T. (2004). Product platform design and customization: Status and promise. *AIEDAM* , 3-20.

Simpson, T. W., Seepersad, C., & Mistree, F. (2001, 9). Balancing commonality and performance within the concurrent desing of multiple products in a product family. *Concurrent Engineering Res. Applications* , 177-190.

Thevenot, H. J., & Simpson, T. W. (2006). Commonality indices for product family design: a detailed comparison. *Journal of Engineering Design Vol 17. No.2* , 99-119.

Thonemann, U., & Brandeau, M. (2000). Optimal commonality component design. *Operations Research 48(1), pp. 1-19* .

Tseng, M., & Jiao, J. (2000). Understanding product family for mass customization by developing commonality indices. *Journal of Engineering Design* .

Weirda, L. S. (1988). Product cost-estimation by the designer. i *Engineering Costs and Production Economics, 13* (ss. 189-198).

Wortmann, J., Muntslag, D., & Timmermans, P. (1997). Customer Driven Manufacturing. *Chapman & Hall* .

Yan, X., & Gu, P. (1995). Assembly/disassembly sequence planning for life-cycle cost estimation. *Manufacturing Science and Engineering, ASME, MED-2 (2)/Mh-3 (2)* , 935-956.

Zamirowski, E., & Otto, K. (1999). Identifying product portfolio architecture modularity using function and variety heuristics. *ASME Design Engineering Technical Conferences* .

Appendix 1: The factors affect on the objectives cost, quality and time

Objective	Type	Change of obj.	Volume per gear incr.	Number of different gears decr.	New gear
R & D costs	Personnel	Decrease		Less design and specification	
	Personnel	Increases			Testing
Production costs	Manufacturing process	Decrease	Learning effect		
	Assembly process	Decrease	Learning effect	Less training of operators, CODP posepon.	
	Price	Decrease	Volume discount		
	External transportation	Decrease		Less no. of deliveries	
	Material handling	Decrease		Less income control and internal logistic	
	Safety stock	Decrease		Less capital tied up	
	Procurement	Increase			Finding a new supplier
	Manufacturing & assembly process	Increase			New equipment
	Assembly process	Increase			New working manuals
Use costs	Service	Decrease		Less training of service staff	
	Safety stock	Decrease		Less capital tied up of spare parts	
	Maintenance	Increase			Scarp old spare parts
Quality	Reliability	Increases	Larger batch size		
	Reliability	Decreases			New supplier
Time	Delay	Increases	Capacity problems		More testing, New supplier
	Delay	Decreases		Less no. of delivieries	

Appendix 2: Costs focus on in cost model

Objective	Type	Change of obj.	Volume per gear incr.	Number of different gears decr.	New gear
R & D costs	Personnel	Decrease		Less design and specification	
	Personnel	Increases			Testing
Production costs	Manufacturing process	Decrease	Learning effect		
	Assembly process	Decrease	Learning effect	Less training of operators, CODP posepon.	
	Price	Decrease	Volume discount		
	External transportation	Decrease		Less no. of deliveries	
	Material handling	Decrease		Less income control and internal logistic	
	Safety stock	Decrease		Less capital tied up	
	Procurement	Increase			Finding a new supplier
	Manufacturing & assembly process	Increase			New equipment
	Assembly process	Increase			New working manuals
Use costs	Service	Decrease		Less training of service staff	
	Safety stock	Decrease		Less capital tied up of spare parts	
	Maintenance	Increase			Scarp old spare parts
Quality	Reliability	Increases	Larger batch size		
	Reliability	Decreases			New supplier
Time	Delay	Increases	Capacity problems		More testing, New supplier
	Delay	Decreases		Less no. of delivieries	