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Product Structure Metrics as an Indicator of Demand-Supply Chain Efficiency: Case Study in the Cellular Network Industry

TIMO KASKI

Helsinki University of Technology
Department of Industrial Engineering and Management
P.O.Box 9500
FIN-02015 HUT
Finland

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ABSTRACT

Product structure affects demand-supply chain performance, this is almost self-evident. But how to develop better product structures? Which design alternative is the best among several options? Markets define the number of product variants needed. Therefore, limiting product variations is not a feasible solution. This research made an effort to develop a method to guide product structure development and to quantify comparison of alternative design implementations. The study aimed at reducing both the operating costs and the asset costs without limiting the customer offering.

This thesis consists of four main parts. First, problem area is reviewed and research methods defined. Second, principles in designing demand-supply chain efficient product structures are discovered, and then operationalized into the product structure metrics to measure how well the design principles are met in a given product. Third, the metrics' usefulness is verified through applying them to eleven products from the cellular network industry. Fourth, the product structure metrics are validated by simulation models measuring operating cost and inventory value, and by following real products in their day-to-day business operations.

Based on the research results, the design metrics are suggested as a useful tool to predict new product structures' implications for demand-supply chain cost efficiency. The number of physical modules, dependency index and commonality index guide new product development to reduce operative and asset costs in the demand-supply chain over the life cycle of a new product. The new metrics combine several product-related factors that drive demand-supply chain efficiency, resulting in a new kind of quantification of product structure goodness in terms of demand-supply chain efficiency.

FOREWORD

This doctoral dissertation is based on a research project that was carried out while I was working for a telecom company and doing my post-graduate studies in the doctoral program of the Executive School of Industrial Management (ExIMa) at the Helsinki University of Technology (HUT). Both background organizations flavored the research project. My industrial position provided good practical insights, whereas studies at HUT paved the way to academic thinking through countless interesting and inspiring discussions.

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Helsinki, 26th of April 2002

Timo Kaski

Supervisor

Professor Eero Eloranta
Department of Industrial Engineering and Management
Helsinki University of Technology
Espoo, Finland

Advisors

Professor Eero Eloranta
Department of Industrial Engineering and Management
Helsinki University of Technology
Espoo, Finland

Dr. Jussi Heikkilä
Department of Industrial Engineering and Management
Helsinki University of Technology
Espoo, Finland

Reviewers

Professor Björn Andersen
NTNU-SINTEF
Norwegian University of Science and Technology
Trondheim, Norway

Dr. Jukka Nihtilä
Nokia, New Ventures Organization
Helsinki, Finland

Opponents

Professor John Johansen
Aalborg University
Aalborg, Denmark

Professor Björn Andersen
NTNU-SINTEF
Norwegian University of Science and Technology
Trondheim, Norway

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PART I

The purpose of part I is to describe the research problem, its background and existing research findings around it. Based on the research problem and the questions, appropriate literature is reviewed and research methods are selected.

1 INTRODUCTION

1.1 Background

Globalizing competition has increased pressures on demand-supply chain performance, measured in terms of customer satisfaction and efficiency (Bowersox 1986, Fischer 1997, Christopher 1998, Yoffie & Cusumano 1999). To take and maintain a leading position in the market, companies are forced to develop and deliver a continuous and ever-expanding stream of new products to reach smaller customer segments in the global markets. Markets require wide product variety and a single company can rarely affect that requirement in a feasible time period.

Market complexity has increased rapidly during the last decades. Hence, many companies have faced increased product range complexity, which tends to decrease efficiency of the company. To avoid cross-margin reduction, different paradigms have been used. A rough illustration of the 20th century paradigms and complexity increase is shown in figure 1.

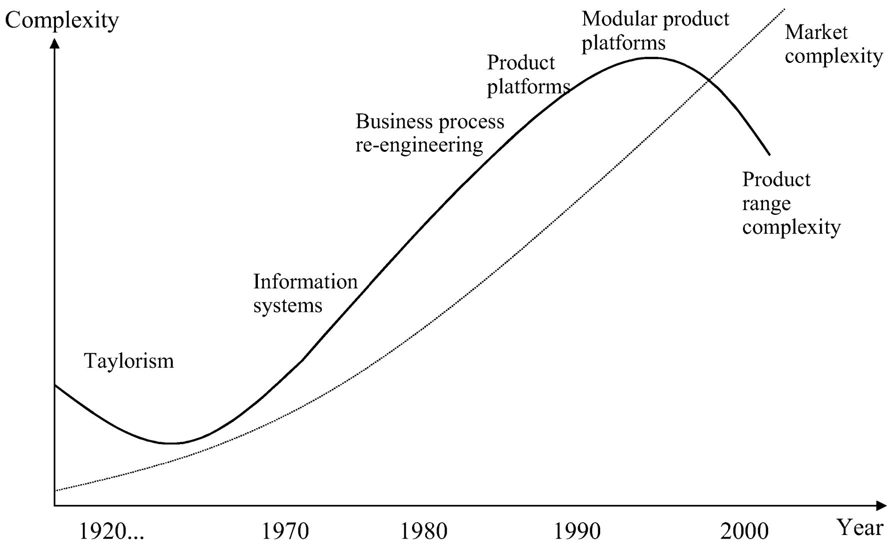

Figure 1. Market complexity and some paradigms to improve efficiency (Based on Erixon 2000).

From the 1970s to the 1980s, development focus has been on business processes and information management tools. However, developing only the business processes does not reach one of the fundamental drivers of business performance. Namely products as a heart of a company drive a big share of company's costs structure and customer service capability. That has been found generally in the early 1990s, from which modularity and product platforms have increased their emphasis in research portfolios all over the world.

One of the basic assumptions in this research was that product variations can not be limited without taking the risk of serious disadvantage in competition (also Chong et al 1998). Markets define the number of product variants needed, which tends to reduce efficiency of the demand-supply chain operations. Customers also strongly influence the lead-time and delivery accuracy with which the industry operates. Lots of efforts have been put into developing demand-supply chain performance. However, new products should be designed and structured so that they allow a high number of final product variations simultaneously with good demand-supply chain performance. This aspect should be analysed explicitly already in the concept design phase of new products.

Products require resources to be ordered, produced, and delivered to the customers. The total cost of one delivery depends not only on the direct material cost of the product but also on how much the product consumes resources in operative processes and what assets are required in inventories to guarantee service capability to the customers. To be efficient in the delivery operations, companies should find a balance with a good customer service and minimisation of total costs that are dependent on product structures.

Another factor, in addition to the product structure, affecting the phenomenon is demand variability. In an uncertain business environment, when a lot of product variations are delivered and demand is fluctuating and unpredictable, operating and inventory holding costs represent a notable portion of companies' cost structure. Demand fluctuations mean that the type and functions of the product wanted in the market change, often rapidly and heavily. Companies still must continuously keep up the demand forecast in order to reserve materials, manufacturing and distribution resources in place for the future deliveries. In a fluctuating environment, final customer orders may consist of different types of products than forecasted. Hence, a company must reorganise operations to match a new situation, which causes extra work and costs.

Companies also have physical inventories in various points of the demand-supply chain to serve customers fast. When content of the orders change, part of the goods inventories will become obsolete and new, different types of goods need to be stored. To be successful in demand-supply chain cost efficiency, new products should be designed to meet the requirements of effectiveness and efficiency. Meeting market requirements and technical challenges is not enough for profitable volume business, especially in an uncertain business environment. (Pine 1993, 2000, Andersson 1997, Ulrich 1993, 1998)

What a company can do is to live with this set-up in the most cost efficient way. *Therefore, the business problem is how to offer the required range of product variations with the delivery lead-time and reliability defined by the market as cost efficiently as possible.* Many practical situations during five years' work experience have motivated the researcher to discover better ways of managing product range proliferation and its increased cost implications on daily operations. Experience from manufacturing and logistics development, sales interface and NPD projects pointed out that efficiency of the victim area can be improved by better products, but good enough tools to evaluate products' goodness are missing.

The researcher is working in the cellular network industry, which provides practical understanding and good data access to the industry. The cellular network industry is relatively young; there is only one decade of history of volume business. The industry differs from traditional industries in several ways. First, change is rapid because technologies change to better performing ones faster than the lifetime of the product. Second, there is a variety of different mobile network standards and technical solutions in the world. Different continents, countries and even single customers have developed their own solutions quite much due to historical bases. Inside standards there are lot of technical variations, e.g. different frequency bands in radio access network that can not be affected by a single telecom equipment supplier in the short term. E.g. use of frequency bands in a cellular network is controlled by authorities and licensing procedures. Equipment manufacturers must adapt with the technical solutions that are used in the target markets.

That kind of variation in products often requires different technical solutions and is therefore seen as a large number of different physical entities in the demand-supply chain processes, which complicates management of the demand-supply chain operations and increases total costs.

From telecom operator point of view, the cellular network industry is challenging. Because of tough competition, operators have to minimize total costs, which mainly consists of capital costs (investments for network equipments as base stations) and network operating costs. The operators tend to prefer the vendors that have the products with the highest flexibility towards alternative market scenarios. The type of technologies and products actually needed depends on data and voice traffic in the network, which in turn depends on services consumers prefer to use. To protect investments on network equipment as long as possible, products should enable smooth evolution path to new technologies in the long run, and flexibility to serve different traffic types and capacity needs (to change network and product configurations) in the short run. That kind of anticipation is typical feature of cellular network industry.

A typical cellular network (e.g. GSM) consists of hundreds of base stations, tens of base station controllers, and a few switches. All the base stations have to be installed before starting operation of the network and the respective money flow. Therefore, network building project management is an essential skill to be able to set-up a network and run profitable business. The better is on-time-delivery capability and the shorter is the customer order lead-time, the easier it is to set-up a network successfully. Extra challenges come from changing network plans, because permissions acceptance can not be forecasted well. One telecom equipment site may require up to 20 different permissions. If some permission fails, a new place has to be found which may affect on the equipment configurations. This means that delivery lead-time must be agreed to few days which is short enough for network planning and project management to adapt to a new plan without delay in the network operations starting date (Heikkilä 2000). A typical cellular network implementation process is illustrated in figure 2.

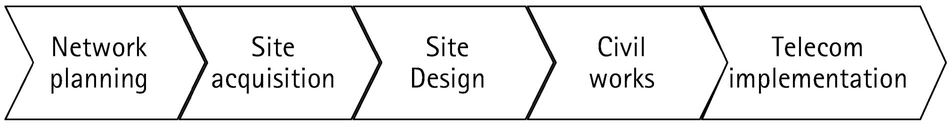

Figure 2. Phases of the cellular network implementation process.

New product development (NPD) and its connection to manufacturing processes is a well researched area. Existing literature includes some pieces that handle the problem area discussed. Sharman (1984) emphasizes that increased product variety increases inventory costs. Products designed to dedicated purposes strongly affect inventory costs. Dowlatshahi (1996) states that usually 70-90% of product life cycle costs are defined in the conceptual design phase, i.e. in very early phases of NDP, which means that product structure decisions in the early design phase dominate also operative costs of delivering the product during its life cycle. The mass customization paradigm is suggested as a solution to simultaneously reduce the complexity of a product structure and a delivery process, and to create more product variety (Feitzinger & Lee 1997, Pine 1993, Andersson 1997, Lambel & Mintzberg 1996). A design for logistics concept is presented by Foo et al. (1990), Lee (1995, 1996) and Dowlatshahi (1996) to develop better products for logistical processes.

Meyer (1997) presents a product platform strategy as a solution to manage business processes better. He defines a platform as a set of subsystems and interfaces that form a common structure from which a stream of derivative products can be efficiently developed and produced. Sophisticated product platforms, which take into account manufacturing and marketing process capabilities, create a basis for modular products. Modular products are easier to manage in operational processes because they share common capabilities and resources (Baldwin & Clark 1997, Ulrich 1993, Ulrich 1998, Sanchez 1999 (or 1996), 2000).

These earlier studies generally handle the problem discussed here but they do not meet it well enough. It still needs to be better understood how to take into consideration all the demand-supply chain cost implications, not only the manufacturing part, in new product development. Quantifiable metrics to evaluate alternative technical solutions already in the concept design phase are little discussed in the existing literature. That kind of concrete tool could indicate early enough what the demand-supply chain efficiency implications of a proposed new product would be. Its intended utility covers efficiency improvement through evaluation and comparison of design alternatives prior to decision making. The current body of knowledge should be extended in that area.

1.2 Research Problem

The basic argument in this work is that product variations can not be limited by a single company without losing market share to the competitors (also Chong et al 1998). Companies have to serve smaller and smaller customer segments in globally competed markets forcing companies to increase product variety and complexity accordingly (Pine & Gilmore 2000, Pine 1996). Simultaneously, delivery performance should be good by default. Delivery time and accuracy are commonly defined by markets in many industries. To meet ever-increasing pressures on delivery complexity, a lot of effort has been put into developing demand-supply chain processes. Anyway, just developing those processes is not enough to respond to the mentioned challenges. New product structures should be designed to meet ever-increasing requirements in a complex business environment (Pine 1993, 2000, Andersson 1997, Ulrich 1993, 1998). It should be possible to measure a product structure's goodness in terms of demand-supply chain efficiency.

To study this area, the following research problem is defined: *Is it possible to measure a product structure's goodness in terms of demand-supply chain efficiency already in the new product development phase?* If those kinds of metrics are already presented in the existing literature, it will be possible to guide new product development to better meet ever-increasing requirements of cost efficiency and customer service capability in the demand-supply chain operations. If they do not exist, it will provide room for new research in the area.

1.3 Research Questions

According to preunderstanding of the problem area, it seems that a new solution needs to be developed to measure a product structure's demand-supply chain efficiency. Therefore, to further address the research problem the following research questions are presented:

Q1: How can the demand-supply chain efficiency of product structures be measured?

Q2: What is the effect of changing a product structure on demand-supply chain efficiency?

The first question specifies metrics to quantify goodness of the product structure in terms of demand-supply chain efficiency. In this research it means that operating and inventory costs during the product's life cycle are minimized. The second question captures the relationship between the specified product structure metrics and demand-supply chain efficiency measured by operating cost and inventory value. These questions are potentially valuable because it seems that currently it is not possible to identify well enough what the cost implications of the new product's design phase decisions will be. There are two aspects that make it challenging. First, implications will become visible in various ways in different process phases. Second, they are future implications and therefore not accountable at the time of evaluation of product structure alternatives in the NPD phase.

1.4 Structure of the Thesis

The thesis is divided into four parts. A brief description of the four parts and related chapters is as follows:

PART I – The business background for the study is illustrated, and the theoretical framework for this study is defined. Based on presented research questions, a research method is selected and explained.

Chapter 1 presents an introduction to the problem area discussed in this research and definition of the research problem and questions. It preliminarily defines concepts and terminology used in the study.

Chapter 2 represents relevant literature pieces around the research problem. Multiple approaches to the new product development and related tools are reviewed. Dependent variables of the research are derived in this chapter.

Chapter 3 analyses existing artefacts and selects research methods used in this thesis. A couple of words are written about the research tradition in the area of Industrial Engineering and Management. Then research questions are defined to guide method selection. Research phases of this work are described.

PART II – Handles creation of DSC efficient product design principles and their operationalisation.

Chapter 4 includes criteria setting for new solution and discovery of demand-supply chain efficient product design principles based on literature reviewed.

Chapter 5 includes creation of the new construct through operationalization of demand-supply chain efficient product design principles.

PART III – Verification of the metrics by applying them to eleven different products. This part demonstrates potential utility of the metrics.

Chapter 6 consists of definition of eleven product structure cases and calculation of corresponding product structure metric values.

PART IV – Construct validation through simulations and empirical data.

In Chapter 7, the operating cost simulation model and the inventory value simulation model are developed for metrics validation. Eleven cases are used to rationally validate the product structure metrics.

Chapter 8 describes three real products to validate product structure metrics fully empirically. Efficiency of manufacturing, distribution, and order handling processes are studied in relation to the product structure metric values of the case products.

In Chapter 9, results of rational and empirical validation are presented. The relationships between the product structure metrics and the dependent variables are analysed.

Chapter 10 includes a review of the research questions and methods. The quality of the research designs is evaluated, and the contribution of the study is analysed. Finally, future research directions are presented.

1.5 Concepts and Terminology

Terminology in the NPD area is quite diversified. Different biases of the writers and contexts in which they have been studied seem to affect the terminology. To help reading this work, preliminary definitions for some NPD concepts and technical terms related to this study are presented. They are handled further later in this text.

Base station	A key element of a cellular network. Receives and transmits radio signals between the user terminal (mobile phone) and the core network.
Cellular network	Network of base stations, base station controllers, mobile switches and other relevant equipment that form connections through the air interface between two users/consumers.
Commonality	The same entities used for different product families, not entities used for different configurations of one product.
Modularity	Division of a complex system into independent functional entities. Enables increased variety and reduced complexity by freely combining entities with standard interfaces.
Module	A functional part of a product that has specified interfaces to other modules of a product.
Product	An entity that offers functions for a user. It may consist of hardware, software, services, and documents.
Product family	Variety of products that share certain assets. Entity used normally for management and follow-up purposes.
Product structure	Defines how a product is formed from the building blocks (modules) that are hardware, software, services, and documents.
Product architecture	Defines the scheme by which the modules interact with each other to provide functions.
Radio access network	A consumer edge part of a cellular network consisting of base station sites.
Variable module	A module type of a product that has variation in a functional and a physical domain.

2 LITERATURE REVIEW

2.1 New Product Development

New product development (NPD) theories have a target to structure a design process in a way that a product would be well functioning and selling.

Design theories have a long history. The earliest approaches were mostly introduced by university professors that had worked with design and realized that engineering design would have to be based on physics, mathematics, and information technology, which required a more systematic practices. Those early thoughts of theories and concepts are coloured by the inventors' connections to special areas in which they had been active. First steps in design theories and concepts naturally focused on a product itself as a pure technological entity because decades ago single products have been locally developed mostly for single purposes. (Erixon 1997)

Pahl & Beitz (1988) mention that the main objective of the designer is to solve technical problems based on scientific knowledge, and to optimize these solutions within given constraints and limitations. A product must satisfy customer requirements and its profitability under the constraints and limitations. "Design is the intellectual attempt to meet certain demands in the best possible way". (Pahl & Beitz 1988)

An important milestone was the proposal to structure design in a stepwise process. The main activities in the model are: Clarification of the task, Conceptual design, Embodiment design, and detailed design. The conceptual phase uses a black-box representation of the technical artefacts as products, machines, assemblies and components in order to support the abstraction of the actual problem beforehand. This can be seen as an input output system which defines the functions of the system. A set of sub-functions in a main function is called a function structure. After dividing functions until the lowest level in the function structure, it is then possible to substitute the functions with something more concrete, i.e. some technical solution that provides the function wanted. (Pahl & Beitz 1988)

Almost the same kind of theory is the Theory of Technical Systems (TTS) presented by Hubka and Eder (1988). This is also based on the process approach and it has been widely used in practice (Ringstad 1996). The basic principle behind TTS is that all technical artefacts should be considered as systems connected to the environment with the help of inputs and outputs. The main objective of this model is to aid the design engineer in the synthesis phase of the problem solving process, i.e. when a desired function has to be solved, the designer can select the best solution principle from the list to further work on. The TTS introduces "organ structures" which have an important role in the design process. "Organs" are the link between the function and the component. It means that an organ realizes a function and can be defined as a "function carrier". (Hubka and Eder 1988, Pahl & Beitz 1988)

Suh (1990) introduces one significant development step in the axiomatic design principle. It states: "The basic goal of the axiomatic approach is to establish a scientific foundation for the design field, so as to provide a fundamental basis for the creation of products, processes, systems, software, and organizations". The design process is a dialogue between what we want to achieve and how we achieve it. According to Suh, a design process has four stages: Definition of the problem, Generation of solutions (synthesis), Evaluation and selection of alternative solutions (analysis), and Implementation. This process can be defined as a regulating circuit illustrated in figure 3.

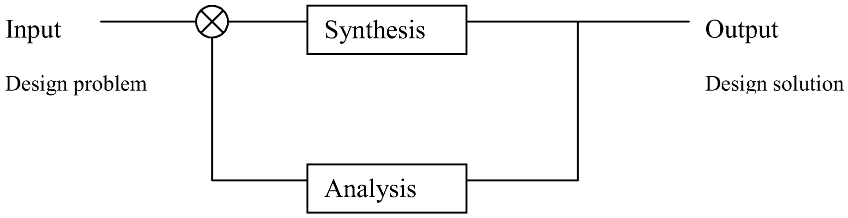

Figure 3. The design process as a regulating circuit. According to (Suh 1990).

The evaluation analysis is based on two fundamental axioms that have a basis in many practical examples, the *independence axiom* and the *information axiom.* (Suh 1990, 1998)

**The independence axiom*: "Maintain the independence of functional requirements"

**The information axiom*: "Minimize the information content"

These axioms are used to map functional requirements (FRs) to the physical domain as design parameters (DPs). To explain the independence axiom, the design of shower taps in bathrooms can be used as an example. One alternative of design is to use one cold water tap and one warm water tap for the temperature control and flow. With this solution it is impossible to control temperature and flow independently (coupled design). Another alternative is to use one flow tap and one thermostat tap, which gives the possibility to control temperature and flow independently (uncoupled design). In this example the first design solution does not satisfy the independence axiom but the second does. The number of FRs and DPs is equal. The information axiom, in turns, offers a tool to compare the relative merit of equally acceptable designs that satisfy functional independence. It guides the selection of design parameters so that minimum amount of information is required to be transferred between the physical components. (Suh 1990, 1998)

According to Suh, the design consists of four discrete domains: Customer domain, Functional domain, Physical domain, and Process domain. These domains must be mapped in the design process to develop a good product. Unfortunately, these domains often drive design in the different direction. The key is to identify tradeoffs embodied behind those domains. As an example, a customer domain has quite divergent drivers from the process domain, especially from the demand-supply chain processes point of view. The customer domain requirements are satisfied better if more different products can be offered to meet individual customers' needs. However, the demand-supply chain processes will suffer from that. One standard product would be better for DSC efficiency.

During the last decades, along with the globalization of businesses, there has been an explosion of variants in many industries. This phenomenon has received attention from several researchers and practitioners. The variant explosion is driven by the requirements to fulfil the needs of a growing number of different customer segments in the very competitive global markets and, on the other hand, companies want to introduce new products faster and faster (Uzumeri & Sanderson 1995). This development also happens in the telecom industry. Despite attempts to standardize technologies, several different standards and customer-specific features and technical solutions are used in the industry.

Therefore, new product development's scope can not any more be a pure technological product. It is not enough that a product functions and has good performance. In addition, it has to fulfil multiple divergent requirements from markets and internal cost efficiency viewpoints. The design scope should be expanded from a core product to a "whole" product. Research community and industry developers have been active in recent years to develop new methods and concepts to better manage increased complexity related to new product development.

Clark and Fujimoto have made a lot of research in automotive industry in early 1990's. They emphasize couple of issues that are very relevant to current complex NPD environments:

- Product integrity
- Integration in the development process

Product integrity means a product concept that coherently covers internal requirements and map those with the customers' perceptions. When the product concept covers functions, technical solutions, design methods, used organizational structure, working methods etc., and link these together, internal integrity occurs in the product concept. To add essential external integrity, the product concept should continuously involve customers' experiences of the product to match all these aspects together and develop well selling competitive products. (Clark and Fujimoto 1990, 1991)

Implementation of the ideas requires lot of emphasis in the NPD process to enhance overlapping activities and cross-functional communication. Otherwise process lead-time could suffer from integrity intensions. On the other hand, clear understanding and vision of the customers' preferences and experiences is needed, as well as strong product concept leadership to run organization in a way that enables integrity over the NPD process. (Clark and Fujimoto 1990, 1991)

2.2 Modularity

Modularity has become a successful and common means to manage complexity. But what does it mean for a system to be complex? F.A. Hayek (1967) holds that the complexity is a function of the minimum number of elements of which an instance of a pattern must consist in order to exhibit all characteristic attributes of the class of pattern in question. Later on, Herbert Simon simplified that definition by defining complexity as one made up of large number of parts that interact with each other in a nonsimple way. The whole is more than the sum of parts. (Simon 1962)

Global competition and new technologies have increased complexity in NPD and other business processes over industries (Langois 1999). Hence, many firms are pursuing modular product development strategies. Modularity is used to manage increased frequency of new product introductions and product range proliferation. Because of its potential importance, modularity is a quite well researched phenomenon even if most studies handle the issue on a general level only. According to Sanchez and Mahoney (1996), modularity is a scheme by which interfaces shared among components in a given product architecture are specified and standardized. Ericsson and Erixon (2000) continue the same line by defining modularity as a decomposition of a system according to company-specific reasons that are called module drivers.

One common definition of modularity is by Ulrich and Tung (1991). They define modularity as a similarity between functional and physical structure. They say that modularity comes from the division of a product into independent modules, which allows companies to standardize modules and components and create wider product variety to meet customers' needs more precisely. Two features can describe product modularity: 1. Similarity between the physical and functional architecture of the design, and 2. Minimization of the degree of interaction between physical modules. Ulrich and Eppinger (1995) define modularity as a minimum interaction need between physical modules.

Recently Baldwin and Clark (2000) defined modularity very broadly: as a means to manage complexity. They say that complexity can be reduced by modularity because modules of a system do not have to know how other modules function, i.e. to hide complexity of a system from individual modules. They only need to know standardized simplified interfaces between the modules.

Andreasen et al. (1996), in turn, define modularization as a creation of physical sub-systems with convenient interfaces that are used for:

- Reduction of variance at process level. Process units have such interfaces that they can be combined in different ways to reduce process costs.
- Reduction of variance at effect level: Added functions are created as "building blocks" with interfaces that allow independent and flexible assembly.
- Reduction of variance at organ level: Central functional organisms may be designed as units with interfaces to the functional building blocks so that different configurations may be optionally created by combination without added design and manufacturing costs.
- Reduction of variance of parts level: Component modularization and parameterization for ensuring productive activities.

In this study, the definition by Ulrich and Tung is used because it includes both functional and physical aspects that are important when analysing product variety from a DSC point of view.

Modularity aims to increase efficiency and to reduce complexity. The objective is to develop a product design that can serve as the basis for a number of product variants. In the other words, to achieve "more with less". All the products can be thought to be more or less modular because modularity is a relative property and can occur in terms of multiple aspects. (Baldwing & Clark 2000, Ulrich & Eppinger 1995, Ulrich & Tung 1991, Duray et al 2000, Erixon 2000, Andreasen & Olesen 1990, Reinders 1993, Sanchez 1999)

To clarify the relative nature of modularity and to offer a framework for development, Ulrich and Tung present the following classification of modularity types:

- **Component sharing modularity.** Common components used in the design of a product. Products are uniquely designed around a base unit of common components. Example: Elevators.

- **Component swapping modularity.** Ability to switch options on a standard product. Modules are selected from a list of options to be added to a base product. Example: Personal computers.

- **Cut-fit-modularity.** Alters the dimensions of a module before combining it with other modules. Used where products have unique dimensions such as length, width, or height. Example: Eyeglasses.

- **Mix modularity.** Also similar to component swapping, but is distinguished by the fact that when combined, the modules lose their unique identity. Example: House paint.

- **Bus modularity.** Ability to add a module to an existing series, when one or more modules are added to an existing base. Example: Track lighting.

- **Sectional modularity.** Similar to component swapping, but focuses on arranging standard modules in a unique pattern. Example: Lego.

Duray et al. (2000) adopted Ulrich and Tung's typology into the framework of the design/production cycle. That reference allows modularity types to be assigned in terms of design/production cycle and customer involvement. Mapping of module types is depicted in figure 4.

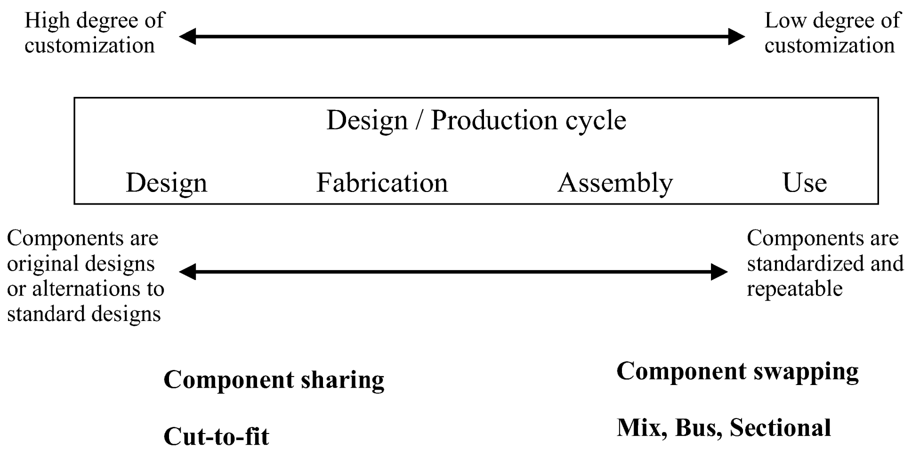

Figure 4. Customer involvement and modularity in the design/production cycle. (Duray et al 2000)

During the design and fabrication phases, specific customer requirements can be taken into account. Modules can be altered according to customer requirements. For example, cut-to-fit and component sharing modularity require that modules are newly designed or changed. With cut-to-fit modularity, one physical dimension of a module is altered according to customer requirements during fabrication phase. Component sharing is also placed there because the commonly shared part has to be designed beforehand, and the rest of the product specific parts are designed or fabricated according to customer specifications. During later phases of the production cycle, predefined modules are combined according to customer specifications. It is not possible to alter modules any more. Component swapping, mix, bus and sectional modularity represent that kind of modularity. (Duray et al 2000)

Eppinger (1994) has been developing the modularity idea from an NPD process point of view. He has developed a construct called the design structure matrix (DSM) which emphasizes better product development performance through reduced iterations during development. The effective instrument behind the DSM is an analysis of component interactions within the product architecture. Decomposed elements of a system are placed into the matrix in which interaction analyses enable elements to be clustered so that interactions are minimized. One drawback of this method is that the clustering phase requires certain procedures to be followed, which may make it challenging in the case of large systems. Specialized algorithms should be used. This way a product architecture with as independent modules as possible can be built up.

Eppinger's research has also pointed out that the product architecture has an interrelation with the organizational structure of a firm. Hence, the DSM tool should also be used to organize development projects. Obviously, such a tool is a good discussion aid to talk about different angles for architecture clustering. The DSM tool offers one structured way to define a modular structure instead of mutual formulation even if it does not consider strategic viewpoints of a firm and does not consider implications for DSC efficiency. (Eppinger 1993, 1994)

Modularity provides benefits to several business areas. According to Ulrich (1995), much of a manufacturing company's ability to create variety resides not with the manufacturing processes but with the modular architecture of the product. Erixon (2000) lists some of the benefits of a modular product design:

- Higher flexibility in product management in terms of market or technology changes through separation of changing parts.
- Reduction of product development lead-time through parallel development activities.
- Parallel development of the product and production system.
- Reduction of product delivery time.
- Less capital tied up in the delivery chain.

- Improved quality because modules can be tested before final assembly, which means shorter feedback links to the testing process.

Kaski (2002) says that modularity with minimized function-module relationships in the product architectures has positive implications to operational efficiency of the company including activities as demand planning, order handling, inventory management, production planning etc. Sanchez (2000) has studied modularity implications at a strategic level. He argues that modularity can become a means to achieving the following forms of strategic flexibility:

- Ability to create greater product variety
- Ability to develop and introduce technologically upgraded products more quickly
- Greater speed to market
- Lower design, production, distribution, and service cost

Many different levels can describe the product offering in which modularity is applied. One of those is the illustration by Erixon (1994) in figure 5.

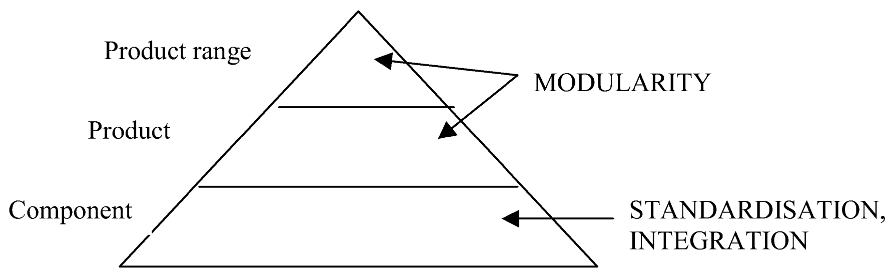

Figure 5. The different levels of a product architecture and appropriate development actions.

He divides product offerings into three levels: Product range level (assortment), product level, and component or part level. Practical studies have shown that the effect derived on the product range, product, and component levels is in the ratio of 100:10:1. Therefore, it is important to see what kind of decisions and actions are needed at what level of the product architecture. Erixon also contributed to modularity research by introducing a method to define a modular structure. Modular function deployment (MFD) is a matrix tool derived from ideas of quality function deployment (QFD). The MFD emphasizes that modularity has multiple drivers that should be company specific. There cannot be any universal way to modularize products. The method consists of five steps:

1. Define customer requirements
2. Select technical solutions
3. Generate concepts
4. Evaluate concepts
5. Improve each module

Understanding customer requirements is the basis for modularization. After that engineers should find out potential technical solutions to carry out functions and select the best ones. In step three, module drivers are selected cross-functionally and technical solutions are analysed based on the module drivers. Examples of module drivers can be: common module, carry over module over the product generations, technical evolution and variety in market requirements. The idea is to find the best possible way to integrate technical solutions into physical modules, i.e. to maximize modularity benefits for several dimensions. Potential solutions are evaluated and effects calculated with the tools each firm has available. Finally, each module is improved, e.g. to maximize manufacturability of each module. (Erixon 1998, Ericsson & Erixon 2000)

Current literature presents several guidelines and methods for modularization. Each of them emphasizes a certain aspect of the problem area. The MFD method is a holistic one compared to the other methods presented so far. One summary of modularization methods is presented in Sungren's thesis. (see Sundgren 1998)

In general, modularity has been studied mostly qualitatively only because it is more challenging to develop a modular design than integral one. Sanchez (2000) illustrates differences between integral conventional design and modular design in the NPD process (figure 6).

	DEFINITION	**DESIGN**	**DEVELOPMENT**
Conventional product creation	Attributes of optimal product are determined by market research.	Desired functionality is decomposed into components, but interfaces evolve during development	Component designs and interfaces co-evolve in a recursive process.
Modular product creation	Product architecture is conceived as a vehicle for leveraging product variations and upgraded models.	Before beginning of component development, standardization of fully specified component interfaces defines input/output reqs for component designs.	A fully defined product architecture is the primary input to and driver of component development. Concurrent and self-managing component development process.

Figure 6. Comparison of conventional versus modular product creation.

Currently, modularity has been applied successfully in some industries. Automobiles, aircrafts, consumer electronics, household appliances, personal computers, and software products are the most typical modular examples mentioned in the literature. One list of modular products is represented by Sanchez (2000).

There are fewer tools to analyze and quantify how modular the product is. In addition, it is still unclear how to quantify many indirect modularity benefits, which is an important criterion in practical decision-making. To be successful in modularization, organizational structure and communication cultures should support modularity ideas. These issues are not well known so far. In addition, no tool can replace the role of competent and experienced people who have understanding of the dimensions where modularity has implications.

2.3 Mass Customization

Today, customers are demanding that products highly match their preferences and that their orders be fulfilled ever more quickly. Products or services developed to meet the needs of an average user do not satisfy an individual customer well enough. To remain competitive, companies are forced to offer products that are closer to customers' real preferences than the products of the competitors. Hence, wider offerings potentially lead to increased sales if variance is offered in attributes that customers care about. Mass customization has been one of the successful paradigms to deliver variety.

Zipkin (2001) defines mass customization as a capability to offer individually tailored products or services on a large scale. Only a few companies have realized it in practice (e.g. Levi Strauss and Andersen windows). Andersson (1997) says that mass customization is the ability to design and manufacture customized products at mass production efficiency and speed. Pine and Victor and Boynton (1993), in turn, define mass customization as an instrument for flexibility and quick responsiveness in an ever-changing environment. A bit later, Pine and Pepper and Rogers (1995) emphasize mass customization's holistic approach by defining mass customization as a capability to efficiently provide individually customized goods and services, and one-to-one marketing that elicits information from each customer. In this study, mass customization is defined as an ability to provide customized products or services at mass production efficiency and speed, and to capture and use information from each customer to develop that system.

Some successful companies, especially in the electronics business, have dramatically increased their product variety, slashed the time they require to fulfil a customer's orders, and reduced cost. Mass customization tries to optimize product variance and the process complexity caused by it. (Pine 1996, Andersson 1997) The key to mass customizing is to create customer unique value. Often it means postponing the task of differentiating a product for a specific customer until the latest possible point in the supply chain (Freitzinger and Lee 1997). It sounds simple but it is not. Demand for variety should be known, which requires an excellent elicitation mechanism to obtain specific information from customers. To use that information effectively, process flexibility should be high in order to minimize the cost of producing different product variants. Finally, logistics operations should support capabilities of products and manufacturing process technologies. All of these elements should work well individually and together. Therefore, mass customization works better with fewer variety dimensions. Identification and selection of those variety attributes is essential. They should be the ones that create value for a customer and on which people's preferences differ sharply when they are easier to discern. As a rule of thumb, companies should mass customize as much as necessary but as little as possible. (Zipkin 2001, Freitzinger & Lee 1997, Anderson 1997, Pine 1996)

The capability to mass customize does not reside with the products or processes individually. It is integration of capabilities of product architecture modularity, one-to-one marketing with a good customer interaction process, flexibility enabling manufacturing technologies, and efficient instantaneous logistics processes (Zipkin 2001, Pine & Peppers & Roger 1995). According to Pine (1996), mass customization is a fundamental thing; it is not just differentiation of products. A company's management culture, supply chain design, and product architectures must be redesigned when transforming from continous improvement mode to mass customization. Freitzinger and Lee (1997) describe three basic building blocks of an effective mass-customization program:

- A product should be designed so that it consists of independent modules that can be assembled into different forms of the product easily and inexpensively.
- Manufacturing processes should be designed so that they, too, consist of independent modules that can be moved or rearranged easily to support different distribution network designs.
- The supply chain network - the positioning of inventory and the location, number, and architecture of manufacturing and distribution facilities – should be designed to provide two capabilities: 1) to supply the basic product to the facilities performing the customization in a cost-effective manner, and 2) to have flexibility and responsiveness to take an individual customer's orders and deliver the finished, customized goods quickly.

Andersson (1997) clarifies the ideology of mass customization by saying that wide product variety is a different thing to mass-customization. Product variety means that a company offers a lot of alternatives to a customer and hopes that customers will find someone that is near enough to their needs. Often these companies give too many alternatives when customers have to stand their hands and give up. They cannot make the selection. He continues that customers do not want any alternatives, they want just what they want. Mass customization must be able to fulfil a customer's individual need without significant extra cost.

Gilmore and Pine (1997) contributed to the development of the mass customisation paradigm by creating four approaches to mass customisation. They argue that it is appropriate to apply different type of mass customisation strategies for different businesses. Businesses are differentiated in two dimensions: 1) change in the product itself, and 2) change in representation of the product. Four types are described in figure 7.

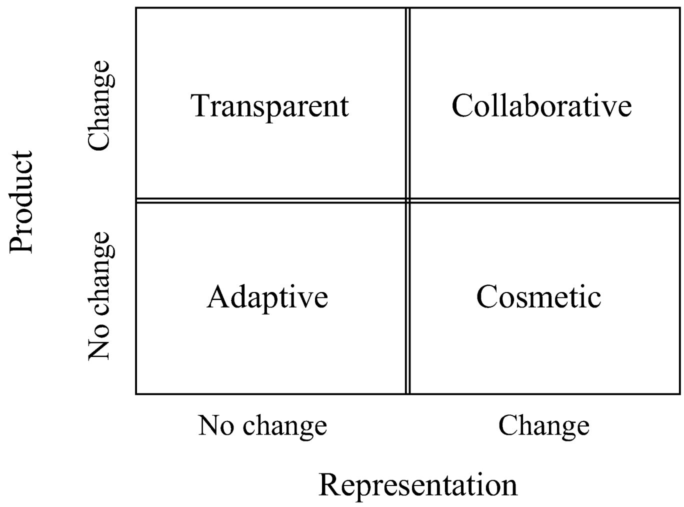

Figure 7. The four approaches to customization (Gilmore and Pine 1997).

Collaborative customizers use dialogue with individual customers to help them articulate their needs, to identify the precise offering that fulfils those needs, and to make a customized product for them. Collaborative customization is often associated with the term mass customization because it changes both the product and its representation. The approach is useful when customers cannot articulate their preferences easily.

Adaptive customizers offer one standard, but customizable, product that is designed so that users can alter it themselves. They change neither the product nor its representation but provide the customers with the ability to change both aspects themselves. This type is appropriate for businesses whose customers want the product to function and look differently in different situations, and for whom altering is easily possible.

Cosmetic customizers present a standard product differently to different customers. This approach is appropriate when customers want the same kind of functions and differ only in how they want a product presented. Often changes in colour or packaging can make a valuable difference for certain customers. Even labelling (e.g. a customer's name placed on the product) can offer a real value.

Transparent customizers provide individual customers with unique goods or services without letting them know explicitly that those products and services have been customized for them. That kind of action is possible when customers' specific needs are predictable and relatively stable. Customer behaviour is observed without direct interaction. An example of that is Chemstation of Dayton, in Ohio, United States. Based on customers' needs analysis, a product, industrial soap, is customized in relation to mixture and order size. Chemstation constantly monitors customer usage and learns more about customers' needs. They can deliver the right formulation and the right amount of soap before the customer has to ask for it. The customer gets the soap that works and is always available when needed.

Whatever the mass customisation strategy is, the role of the product architecture is crucial. In mass customisation, development of modular product architectures is aimed at maximizing reusability of standard building blocks in functional, technical, physical, and process domains – and postponing the point of easy product variation in the demand-supply chain. It is not necessary to limit variants offered to the customers. Instead, methods must be aimed at better ways of designing and managing product variance. (Pine 1996)

To manage increased pressures on the product architectures, a company's product development needs to be turned to create more or less modular products or services. That is a prerequisite for a successful mass-customization program. Such a design separates the composition of end products into subassemblies, some of which are common to all product options, others of which are not. According to Feitzinger and Lee (1997), the main benefits from modular design for mass customization are:

- A company can maximize the number of standard components it uses in all forms of the product, and can postpone and increase the differentiation of the products.
- A company can make the modules of the product separately.
- A company can more easily diagnose production problems and isolate possible quality problems.

Organizing product development is a key topic of Andersson's experience. First, product development should be seen as an investment for the future. Second, when developing a new product architecture, a process architecture also needs to be redesigned simultaneously. In this way, it is ensured that product design modules will match with process capabilities, and flexible product differentiation is possible. As a third issue, design teams must be cross-functional. Different product ideas are reviewed towards constraints and capabilities of different process modules. So it is possible to see what the effects are on process phases in terms of cost and customer service capability. This kind of cross-functional design team must have the power to make decisions whether they have an effect on product or process designs. In addition, there should be a formal way to organize all needed competencies into a new product definition from different organizational departments. (Andersson 1997, Sanchez 2000)

After all, there should be company-level management principles and processes when making decisions about new products. Product decisions must be based on total understanding of required development effort for a new product, or process technologies versus potential new revenue, or cost savings in operations. Traditional optimization of direct costs and design effort of one product is not enough any more.

Today mass customisation has faced criticism. First, holistic transformation to a successful mass customization system requires a lot of resources and a deep understanding of a firm's competencies and potential markets achieved through transformation. The challenge is that customers' preferences are often difficult to obtain, or new markets for new variants may be too small. Second, in new businesses that are in early market phase of their life cycle, mass customization is not appropriate strategy because management focus should be on developing markets and new products. E.g. new technology enables new kinds of businesses, and new kinds of products and services for the customers. That kind of thinking requires that the demand, the market, should be created first. If both markets and products are novel, mass customization may be even impossible to implement. Widely used business life cycle phases are presented by Geoffrey Moore (Moore 2000).

2.4 Modular Platform Architecture

Product architecture has increased its role in many performance improvement activities. Most activities in the firm handle products in the one way or another. Therefore, several aspects of the firm's competitiveness are interrelated to the product architecture. This emphasis is clearly visible in figure 1, which illustrates typical industry paradigms during the 1990s. Sanchez (1996) says that a *product architecture* is a scheme that defines the functional components and how they interact with each other. Ulrich and Eppinger (1995) emphasize that a product architecture means interface specifications to transform information or energy between the components. Sanchez's definition is used in this study because it includes elements important from an operational performance point of view.

The demand for frequent product launches has made it impossible to develop a brand new product each time (Ericsson and Erixon 2000). Simultaneously, product complexity has increased because products have to acquire more functions. On the other hand, the rate of change in many markets has increased rapidly. As a result, product development managers should have unrealistic abilities to make accurate long-term forecasts for new requirements.

Hence, *modular product architectures* have been developed and applied to offer more flexibility in new product development. According to Ulrich and Eppinger (1995) modular product architecture includes alternative components with standardized interfaces. Standardized interfaces enable isolated development of different components of the product architecture, which make it possible to introduce new products more frequently. Baldwing & Clark (2000) add configuring rules for alternative components to the definition of modular product architectures. Therefore, modular product architectures have a more holistic view of the potential product variety, which can be derived from the first launched product of the architecture. Eloranta (2001) has contributed to the development of modular process architectures. He says that modular architecture structurally facilitates variety and opportunity for change, which is relevant for product architectures as well. Meyer and Utterback (1993) also emphasize the importance of broader and consistent long-term scope in developing modular architectures.

Modularity in the architecture enables better reuse of architecture modules, which can reduce the time-to-market and development cost of new products. Modular architectures can offer significant benefits especially when the market is turbulent and/or technology is changing rapidly. Reusing the same modules means less module-level variety in demand-supply chain operations, which increases demand-supply chain performance through more accurate planning and more simple operations. (Robertson & Ulrich 1998, Ulrich & Eppinger 1995, Baldwin & Clark 1997, 2000)

On the other hand, pressures on the time-to-market and high cost of developing new technologies have lead to development of the *product platform* concept. Meyer & Lehnerd (1997) define a product platform as a set of subsystems and interfaces that form a common structure from which a stream of derivative products can be efficiently developed and produced. Ulrich and Eppinger (1995) argue that standardised interfaces between system elements define a product platform. Meyer & Lopez (1995) define a platform as the physical implementation of a technical design that serves as the base architecture for a series of derivative products. Muffatto (1997) in turn defines a platform as a relatively large set of a product's components that are physically connected as a stable sub-assembly and is common to different final models. According to Robertson and Ulrich (1998), a platform is a collection of assets that are shared by a set of products. Robertson's definition is used for platform in this study because it implicitly describes the broad reuse of many types of assets.

Combining modular architectures and platforms into modular platform architecture, NPD efficiency and flexibility can be improved. Eloranta (2001) introduces this idea in business process development context, but it could be applied to NPD as well. A *modular platform architecture* is a modular architecture that incorporates a platform as a part of it. It simultaneously facilitates variety and change while gaining reuse of platform modules.

A modular platform architecture is created by freezing common elements in the modular architecture to a subset of modules representing a platform. Different product development projects can use this group of modules as a platform for their new products. Product-specific features and modules are added to the platform modules. The emphasis is on a continuous stream of new products with lower risk of failure and better timing capability. Modular platform architecture makes it possible to focus development efforts on the strategically important areas at the time, and the platform things can be carried over product generations and product families. The result should be explicitly represented in order to be able to share it. One characteristic of a good product platform architecture is that it can not be easily copied outside the company because it includes a wide range of context related knowledge. (Meyer 1997, Robertson & Ulrich 1998, Baldwing & Clark 1997, Ericsson & Erixon 2000)

Robertson & Ulrich (1998) argue that through successful platform planning, companies can reduce R&D cost and time. Sanchez (1999) presents that a company can achieve 50-80% reduction of time-to-market and development resources in modular architecture approach compared with a traditional sequential approach. The final target, to maximize business profits, is the same as in mass customization, but the approach is more product and technology oriented. (Meyer 1997, Robertson & Ulrich 1998, Verganti 1999, Baldwing & Clark 1997)

Flexibility and reusability of a platform architecture can be improved through increased modularity, e.g. having two or more modular layers in the platform architecture. The bigger the platform part of the product architecture, the better it is from a development cost point of view, but often worse from a product differentiation point of view (Sundgren 1998). Therefore, high use of platforms in visible components may hurt brand image, which forces companies to deal with critical trade-off. (Robertson & Ulrich 1998, Baldwin & Clark 1997, 2000)

Sundgren (1998) presents important findings in his research of product platforms. Shifting to platform development requires special attention on how to balance end-product integrity and parts standardization, how to manage a large number of interdependencies in the platform development, how to manage a large number of parts-whole architecture relationships. Boundaries between the product-unique elements and platform elements are crucial. Therefore, a product platform should be translated explicitly down to a level of interfaces and subsystems.

In addition, architecture design, feature definition and interface specification become more challenging due to the amount of anticipation required. Managing interfaces between product-unique parts and platform elements requires wide understanding of requirements in horizontal and vertical dimensions. Therefore, compared to traditional single product development, these activities require more cross-organisational efforts. This development sets new requirements for the preliminary design evaluation phase of the NPD. So far there is a lack of tools and methods to quantify benefits of potential architecture solutions. Explicit tools would be a good aid in this work.

In the current literature, modular product platforms are seen as benefical also from a demand-supply chain performance point of view. Reuse of physical modules of the modular product platform between product families reduces material assets through a smaller number of different components and modules. Hence, inventory costs can be reduced a lot. On the other hand, customer service is improved through better responsiveness towards demand fluctuations, because more different products can be configured from the same materials. In addition, overall management of deliveries and the manufacturing process becomes easier, which means lower indirect costs in most operations. (Meyer & Lehnerd 1997, Sanchez & Mahoney 1996, Robertson & Ulrich 1998)

According to Fine (1998), fast clockspeed industries are trying to speed up their new product development in order to enter a marketplace with a new product faster than their competitors. Telecom equipment manufacturers can be considered as a fast clockspeed industry. In the last decade, telecom equipment manufacturers were reasonably well able to manage their new product development for the second-generation radio access network products. It was quite tolerable to allow one new product development project to last about three years, because the industry could focus on expanding telecom networks, which were using rather mature technology.

Now the telecom industry is forced to step out from its comfort zone, for alternative technologies are now battling against each other about who is going to take a lead in future generations of telecom networks. The longer the new product development time, the more likely it is that product requirements are subject to changes, especially when the industry is experiencing a vast revolution. In turn, the more changes in a focus of new product development project, the more a new product is delayed in a market and the more market share is lost to rivals.

2.5 Design For "X"

Modularity is a good basis for applying Design for excellence (DFX) or concurrent engineering (CE) paradigms. There is an ever-growing number of different "Design for …." tools which focus on some special areas. They have been defined in order to emphasize special requirements in some business cases. The X in DFX stands for either a certain life phase of the product life cycle (e.g. manufacturing, installation) or some universal virtue (ability) like cost, time, flexibility, environmental effects etc. Based on this division, DFX disciplines are divided into life phase oriented aspects of DFX and ability oriented aspects of DFX. The objectives of DFX disciplines, regardless their various aspects, are to estimate the effects of the proposed design alternatives with respect to a certain life phase system. (Olesen 1992)

Olesen says that there is a basic relationship between the development of a product, aspects of a life phase system (e.g. assembly, installation) that is independent of such development, and the achievement of targets for the activity of manufacturing as a whole. The decisions on the new product development process, e.g. on product architecture, determine the type, content, and sequence of the activities in the "victim area", e.g. in the assembly and installation phase.

Design for manufacturing (DFM) and Design for assembly (DFA) are maybe the most utilized disciplines of DFX. Several researchers have said that it is impossible to define a well functioning general method for, e.g., DFM. Every product development project is an intellectual attempt to solve its own challenges; a fully generic method won't fix all the problems. That is why there are not very detailed definitions for any DFX discipline. Hence, guidelines and checklists are more dominant in that area. Maybe the most frequently cited guidelines are the DFM guidelines developed by (Stoll 1986):

- Minimize the total number of parts in a product
- Develop a modular design
- Use standard components
- Design parts to be multi-functional
- Design parts for multiple use
- Avoid separate fasteners
- Minimize assembly directions
- Maximize compliance

These principles are empirically derived and they were noticed to be applicable to many different situations. These principles also comply with the Axiomatic Design Principle by Suh (1990).

Several authors have stressed the importance of product design when talking about improvements in the logistics processes. Especially product variance as described in the earlier chapter is mentioned in many studies. (Janson 1993, Martin & Ishii 1996, Lee 1995, Lee & Tung 1997)

Sharman points out the trade-off between designing a product family where each individual product is composed of parts uniquely suited for its requirements, and, on the other hand, the high inventories and complicated management of deliveries that will follow this kind of product assortment. (Sharman 1984)

Hau Lee has written several articles about delayed product differentiation. He emphasizes that companies can minimize negative performance implications of product variance by postponing the point of product differentiation. Lee's research expands the scope of analysis from the pure manufacturing process to the whole supply chain, a network of facilities that performs the functions in the order fulfilment cycle. He uses term "design for supply chain management (DFSCM)" to describe the concept of design products and processes that would support supply chain performance. He argues that the performance improvement potential of integrated product and process designs are great for a global manufacturing firm. (Lee 1996, 1999, Lee and Billington 1992, Lee and Sasser 1995, Freizinger and Lee 1997, Lee and Tung 1997)

The basic concepts in the DFSCM are delayed product differentiation and increased part commonality. The first one refers to delaying the point in time when a product assumes its identity. Typical benefits are:

- More accurate forecasting
- Lower inventories
- Better customer service through flexibility

Part commonality, in turns, can result in cost savings in part number administration, inventory reduction, and supplier management. It is even more powerful when it is used as a means to achieve delayed product differentiation. Lee has found that regardless of the benefits of these concepts, implementation is difficult. Reasons could be required broader scope in product design and development, and missing mechanisms to evaluate implications of alternative design options.

Quantification of benefits is a key step to implement such concepts. (Lee 1996, 1999, Lee and Billington 1992, Lee and Sasser 1995, Freizinger and Lee 1997, Lee and Tung 1999)

Three examples are described that have applied delayed product differentiation. One was a computer disk drive manufacturer which delayed the PCB insertion phase in the manufacturing in order to make the most of the manufacturing process and inventories generic. Another example was a deskjet printer manufacturer that separated localization activities from manufacturing facilities to the international distribution centers. The third example is a color printer manufacturer that uses some common parts between color and mono printers to enable commonality. They found that the value of commonality is high for product mix flexibility but it naturally depends on the demand variability. The more variable and unpredictable is the demand, the more commonality is required in order to keep up customer service capability at the same cost level. All the example cases succeeded in reducing their inventory costs significantly. (Lee 1996, 1999, Lee and Billington 1992)

Several divergent requirements from different domains should be concerned when defining a new product. To simplify requirements, according to Feitzinger and Lee (1997), it can be said that different interest groups demand the following features from the product design:

- Marketing wants to offer as many product options as possible to attract more customers.
- R&D wants to offer the product with the greatest possible functionality at the lowest possible cost.
- Manufacturing and distribution want to make one product at a stable volume.

According to Ulrich and Eppinger (1995), the most important stakeholder in product development is the end customer who buys the product. That is why the main effort in the product development process should be to satisfy the needs of the end user.

Foo et al. (1990) discussed that an ideal product for manufacturing and logistics should be designed with the following considerations:

- A minimum number of possible parts, including maximized number of standardized parts.
- A modular and reusable physical product architecture.
- A limited number of different end products.
- A modular bill-of-materials (BOM) architecture.
- Interchangeability

There seems to be one common element that appears in the all studies of researchers, namely variance of physical items. Minimization of different parts is mentioned as being important through all levels of the product architecture hierarchy.

Janson made one interesting step in variance management in 1993 when he introduced a "variance management" iterative procedure. It consist of five phases: standardization - division in common and variant specific parts – combination of parts – multifunctionality and integration - size variation, as illustrated in figure 8.

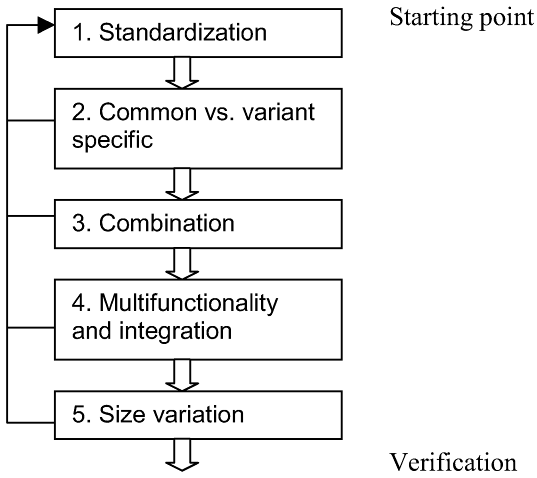

Figure 8. The variant management procedure according to (Janson 1993).

Dowlatshahi also adds that this kind of design guideline should be transformed into quantitative rules and constraints in the product development process. There must also be a formal way to put these constraints into action in practice. (Dowlatshahi 1996)

Martin & Ishii (1996) represent a method called Design For Variety, DFV. The main idea in that method is to provide a rough tool for engineers to estimate cost effects on the manufacturing system caused by product variance. There are three indices, Commonality index, Differentiation index and Set-up Cost index, which combines some important cost drivers, associated with the introduction of variety in a product, from a manufacturing system. Commonality index measures the share of standard parts in a product, whereas differentiation index and set-up cost index measure complexity incorporated into the process. This helps engineers to meet a product design that takes into account manufacturing costs and lead-times that are affected by the product structure.

2.6 Product Complexity Metrics

The current literature includes quite a wide range of metrics that aim at reduced complexity of a product in order to improve performance of a company in one way or another. Viewpoints vary e.g. from NPD, manufacturing, logistics and quality. Pure design principles in new product development are not enough because it is difficult to see which design alternatives would best meet those principles. To make evaluation of alternative concepts easier, some principles have been operationalized into metrics. Metrics try to quantify the goodness of a potential new product in relation to some commonly known virtue, i.e. cost, lead-time, flexibility, or quality. Table 1 represents the most relevant of them. (Pugh 1991, Ericsson and Erixon 2000, Martin and Ishii 1998, Mikkola 2001)

Table 1. Examples of product complexity metrics.

METRIC	**EFFECT**
Number of modules in product	Manufacturing lead-time
Assortment complexity	Product cost
Multiple use	Variant flexibility
Interface complexity	Development lead-time
Commonality index	Product cost
Differentiation point index	Product cost
Set-up cost index	Product cost
VEP (variety effectiveness process) parts index	Product cost
Modularisation function	Modularity benefits

Ericsson & Erixon (2000) define a metric "number of modules in a product" to estimate manufacturing lead-time. It is assumed that each module is concurrently assembled with the others and delivered to the main assembly line, where complete modules are assembled with each other. Hence, the value for a lead-time can be calculated through process work phase lead-times and the number of parts and modules needed for an average product. The lead-time is:

$$L = \frac{Np * Ta}{Nm} + Tt + \frac{Nm - 1}{Ti}$$

Where

L = lead-time

Np = number of parts in a complete product

Nm = number of modules in one average product variant

Ta = average assembly time for one part (10 seconds is best practice)

Tt = average time for functional testing of modules

Ti = average final assembly time for interfaces between modules

According to Erixsson's calculations, it will be possible to shorten lead-time by dividing each module into submodules until the certain optimal stage. The shortest lead-time occurs when the number of modules is between $0.5 * \sqrt{Np}$ and $\sqrt{Np}$. This kind of behaviour requires an assembly system that accommodate modularization, i.e. enables concurrent module assembly and testing.

Pugh (1991) has specified an assortment complexity metric at component level to measure the complexity of a product. Ericsson & Erixon (2000) modified it to the assortment level as:

$$Ac = 3 * \sqrt{Nm * Nmt * Nc}$$

where

Ac = assortment complexity

Nm = number of modules in one average product variant

Nmt = total number of module variants needed to build up the product range

Nc = number of contact surfaces between modules in one product

Complexity here means the number of module variants and interfaces. Therefore, complexity of the modular product assortment is increased with the number of modules in each product variant, the total number of module variants needed to build all product variants, and the number of contact surfaces in the interfaces. It is argued that this metric would have correlation especially to indirect manufacturing costs, as set-ups, tools, and fixtures, but there is no data presented to show relationships. The challenge of quantifying contact surfaces reduces the usefulness of the metric.

Ericsson & Erixon (2000) also specify multiple use metric to illustrate variant flexibility. It is a simple measure of relation between the number of product variants and the total number of modules needed:

$$Ev = \frac{Nv}{Nmt}$$

Where

Ev = total number of modules needed

Nv = number of product variants required by customers

Nmt = total number of modules required to build up all the product variants

The higher is the value, the more flexible is the product because similarity between the product variants is higher. It has advantages in many operations such as set-ups, tooling, production planning etc. For example, the well-known Nippondenso panel meter can be assembled into 288 variants out of 16 total modules and has an Ev of 18.

The same researchers have modified Boothroyd and Dewhurst's design for assembly index in order to specify interface complexity. The interface complexity measures the possibility for parallel product development, which is based on the argument that the lead-time in development will decrease when there is a possibility to work in parallel. Low interface complexity means that the information content in the interfaces is low (e.g. energy, material flow, signals, fixation principles) when components under development are more independent. The interface complexity is calculated as follows:

$$Ic = \frac{\sum Ti}{At}$$

Where

Ic = interface complexity

Nm = number of modules in one product variant

Ti = assembly time for one interface

At = ideal assembly operation time (assumed to be 3 seconds)

The equation means that the probability of successful parallel development with minimal information flows between design projects increases when the value of the interface complexity is low.

Martin & Ishii (1998), in relation to their DFV concept, have specified three indices to describe indirect costs associated with the product variety. The commonality index measures the number of unique parts and is defined as follows:

$$CI = \frac{1-U}{\sum_{1}^{v} Pj}$$

Where

CI = commonality index

U = number of unique parts for the product family

Pj = number of parts in one model

V = final number of product variants offered

A higher index value is better since it indicates that the wanted product variants can be achieved by fewer unique parts. It covers one product level only. The challenge can be how to define the number of product variants offered, it is not specified further in any way.

The differentiation point index measures where differentiation of the product occurs within the process flow. It is claimed that by differentiating later in the process, the complexity of the assembly operation can be reduced and work-in-progress decreased. It is calculated as follows:

$$DI = \frac{\sum_{1}^{n} Di * Vi * Ai}{N * Di * Vn * \sum_{1}^{n} Ai}$$

where

DI = differentiation index

Di = estimated throughput time from process i to sale

Vi = number of different products exiting process i

Ai = value added at process i

n = number of processes

D1 = estimated throughput time from process 1 to sale

V = final number of product variants offered

The lower the index value, the better the product, because value is being added later in the process flow. The set-up index is an indirect measure of how set-up or changeover costs contribute to the overall costs of the product. The purpose is to act as an indicator of how important set-ups are for the product, not to describe true cost for the company. It is calculated as follows:

$$SI = \frac{\sum_{1}^{n}(Vi * Ci)}{\sum_{1}^{V} Cj}$$

Where

SI = set-up index

Vi = number of different products exiting process i

Ci = cost of set-up at process i

Cj = total cost (material, labor, overhead) of product j

The fewer different products and the lower the cost of set-up, the less is the share of set-up costs from total costs.

Martin & Ishii's indices capture the main cost drivers of product variety in a manufacturing context. They define seven victim areas which are covered by these indices. They are represented in table 2.

Table 2. Rough expected relation between indices and indirect costs of providing variety (based on Martin & Ishii (1998)). CI=commonality index, DI=differentiation index and SI=set-up index.

INDIRECT COSTS	**CI**	**DI**	**SI**
Logistics	X	X	
Materials	X		
Labor		X	X
Quality	X	X	X
Inventory holding	X	X	
Capital equipment	X		X
Inventory obsolescence	X	X	

Martin & Ishii (1998) argue that these indices will correlate to the indirect cost listed in the table. There is a strong belief but evidence for this belief is missing or linkage is loose. Although they have some speculative features and the scope is limited to manufacturing only, they are useful to estimate overall intuitive cost implications of product variety.

G.D.Galsworth (1995) has introduced Variety Effectiveness Process (VEP) to reduce total cost and maximize customer selection. To enable quantification of effects and comparison of alternative product designs, he specified the VEP parts index as a universal measure of complexity. It approximates product costs as a function of the number of part types and their occurrences by product. It is calculated using a table as follows:

PART TYPE	**MODEL X**	**MODEL Y**	**PART TYPE OCCURRENCES**
Housing	X	X	1
Cap clip A	X		2
Cap clip B		X	
Ball bearing	X	X	1
Ink A	X		2
Ink B		X	
Pen tip	X	X	1
Ink retainer	X	X	1
Pen guide	X	X	1
Plug A	X		2
Plug B		X	

The VEP parts index is a sum of all the part numbers in the associated BOMs multiplied by the sum of the times each part number occurs across those models. Model X includes 8 part numbers and model Y also 8 part numbers, a total of 16 part numbers occuring as a part type 11 times (see example table). This gives the VEP parts index as 16 x 11 = 176. The value is a relative measure of variety within the product group. It reflects total quantity of parts to be handled and therefore describes indirect costs associated with the product variety. The main viewpoint is once again the manufacturing process and quantification of real cost implications is missing.

Mikkola (2001) contributed to modularity research by quantifying the degree of modularity of a product architecture. The major viewpoint is product complexity in NPD. She presents a modularity function equation to describe the degree of product modularity. The logic behind the metric is that the fewer the interface constraints between the modules and the fewer the modules in the architecture, the more modular is the product. From an NPD point of view, the more modular the product, the more effective is the development process because design iterations do not have so much impact on other modules. In general, modularity leads to many implications as reviewed in the modularity chapter. The modularity function is calculated as follows:

$$M(u) = e^{-u^2/2Ns\delta}$$

Where

M(u) = modularization function

u = number of NTF components

N = total number of components

s = substitutability factor

δ = interface constraint factor

It is assumed that the degree of modularization in a given product architecture is constrained by the composition of its components, interfaces shared among the components, and degree of substitutability. The substitutability factor (s) is calculated so that if a module can be used for 10 product families and it has to share 2 interfaces, the substitutability factor is 5. The interface constraint factor (δ) is approximated as a ratio of the total number of interfaces per the number of modules or sub-systems in a given product architecture. According to the defined modularity function, a higher level of modularity can be achieved through (Mikkola 2001):

- Physical reduction of the number of interfaces through the integration of components
- Standardization of interfaces
- Multi-functionality of the sub-modules (substitutability)

Quantification of modularity requires quantification of issues that are not straightforward and their importance can vary depending on the context in which they are applied. Therefore, a lot of assumptions are needed to get a numerical estimation of the degree of modularity of the given product architecture. The result is just an estimation of the degree of modularity, there are no correlations studied to potential modularity benefits. This measure may have a relationship with demand-supply chain performance even if the viewpoint has mainly been new product development performance.

The presented complexity metrics offer a quantifiable alternative to manage new products' effect on a company's performance from different angles. They take a step forward in the direction that many researchers have emphasized as future research (e.g. Dowlatshahi 1996). The problem is still that they are too theoretical in nature and empirical evidence of the relationships with real performance is missing. In addition, intended utility areas are quite broad, demand-supply chain performance has not been the focus area.

2.7 Demand-Supply Chain Management

Logistics as a discipline has been developing a lot during the last fifty years. From a historical basis, logistics has developed from local individual activities (individual order-delivery processes) towards a modern logistics chain or integrated logistics thinking. Several researchers contributed to this development; maybe Howard took one of the most significant steps in 1956 when he introduced total cost analysis in a logistics context (Bowersox et al. 1986). After that, Jay Forrester in 1961 paved the way to chain thinking by investigating chain-wide effects by dynamic simulations with fluctuations in demand and inventories (Bowersox et al. 1986).

The European Logistics Association (ELA) defines logistics as "*the organization, planning, control and executing of the goods flow from development and purchasing, through production and distribution, to the final customer in order to satisfy the requirements of the market at minimum costs and minimum capital use"* (Lehtonen 1999).

Bowersox (1984) gives the following definition for logistics: *Logistical management includes the design and administration of systems to control the flow of material, work-in-progress, and finished inventory to support business unit strategy.*

According to La Londe (1994), Bowersox's integrated logistics concept was an important step in logistics history. In this concept, different functional views within a company were integrated into the logistics chain, eg. The purchasing angle was called materials management as part of a logistics chain.

Many researchers prefer the term supply chain management instead of logistics management, which describes a networking phenomenon in many industries. The major part of physical components of final products is often manufactured by subcontractors that can also have subcontractors. Hence, the focus has to be moved from single companies to the whole chain because customers care only about product availability at the point of sales, not how an individual firm organizes its operations. Christopher's terminology corresponds to Bowersox's integrated logistics.

Christopher's (1998) definition of supply chain management is: "*the management of upstream and downstream relationships with suppliers and customers to deliver superior customer value at less cost to the supply chain as a whole.*" Upstream chain refers to the activities between the supplier and the company and downstream chain refers to the order-delivery process activities between the company and customers.

The idea in supply chain management is to gain competitive advantage for a company. It has to satisfy the market demand by the correct supply. A physical function is to convert raw materials into parts, components, and eventually finished goods, and deliver all of them from one point in the supply chain to the next. O'Laughilin and Copacino (1994) in turn say that low-cost customer service, value-added services, flexibility, and regeneration are the ways to use logistics to gain competitive advantage. The market success of a company increasingly depends on logistical factors of delivery capability and delivery reliability. Supply chain performance consists of several drivers, typically speed, reliability and cost. Bowersox (1986) mentions that supply chain performance includes cost, service, and quality.

Delivery capability means the ability to keep the commitment to a desired supply date. It is an aggregate of several layers: product architecture, process structures, information technology (IT) systems, and organizational structure. They together build up logistics capability. None of them alone guarantees superior capability but any of them can spoil it. In this sense total capability is a multiplication of the factors, not a sum. Figure 9 describes main factors of delivery capability (based on Wahlers and Mittendorf (1997)).

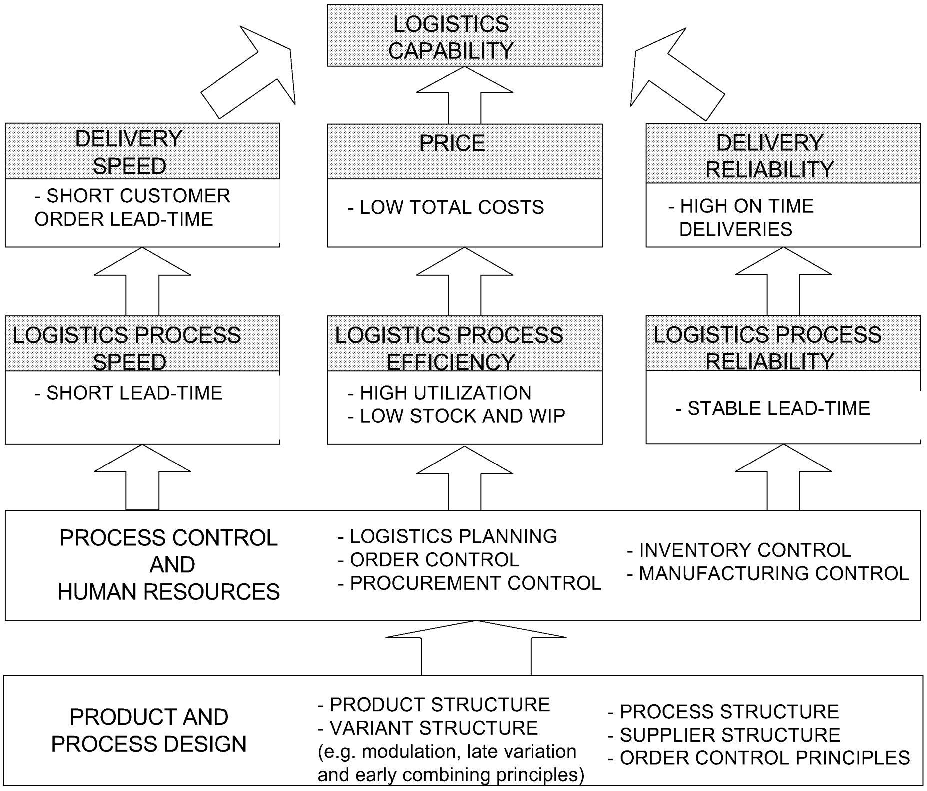

Figure 9. Forming of logistics capability (based on Wahlers T. & Mittendorf M. (1997)).

To achieve higher delivery capability requires higher logistical process ability, thus meeting market requirements. High delivery reliability demands high process reliability, which is distinguished through a low and stable lead time and a high schedule performance. The prerequisite for a marketable price is low logistics and manufacturing process costs, which can be reached mainly through simple process structures to reduce indirect costs, raise utilization rate, and lower inventories. (Wahlers and Mittendorf 1997)

Customer service is the first thing because it directly enables the business targets of the firm by ensuring product availability. Supply chain operations have to be able to deliver a product to the right place at the right time at minimum costs (Hoover et.al 2001). Typically delivery lead-time and delivery accuracy are used as a performance measure for customer service or delivery reliability. (Bowersox 1986, Wahlers & Mittendorf 1997)

Quality is one element of performance, for customers can not have a value added from the product if it does not work as it should or a product has not been received when it should have been. Supply chain operations have to ensure that products are manufactured properly from the correct components and shipped without damage. Hence, traceability is one of the tasks in the supply chain to guarantee quality steering. (Bowersox 1986, Christopher 1998, Wahlers & Mittendorf 1997, Hoover et al. 2001)

Cost is a very important performance factor in the supply chain because supply chain operations in a global company may represent a big share of the total costs of the company. Therefore, they have a considerable impact on the company's profitability. Differences between the companies' cross-margins, based on supply chain efficiency, vary by several percentages of sales. Hau Lee (1995, 1999), Sharman (1984), Dowlatshahi (1990) and many others have studied cost elements in the supply chain. The following types of costs are listed:

- Inventory
- Purchasing
- Order handling
- Production planning
- Manufacturing set-up
- Picking & packing
- Transportation

- Receiving
- After sales activities

According to most researchers, inventory costs are the biggest single factor. They consist of cost of materials buffered, obsolescence costs, facility costs and handling costs. Days of Supply (DOS) is often used as measure of inventory efficiency. It describes how long goods are buffered in the inventory on average. Hoover et al. (2001) present an estimate that ten days in the DOS measure corresponds to one percentage of total sales of the company. This means that when reducing DOS from 50 days to 40 days, profit percent can be improved e.g. from 8% to 9% of total sales.

In addition to this list, there are many invisible costs that are difficult to estimate. According to Fisher's (1997) definition, the major costs of that kind are lost sales opportunities and dissatisfied customers. Fischer calls these market mediation costs which arise when supplied products do not meet the market demand. Other indirect costs are personnel training, quality mistakes, use of information systems, etc. The share of different cost elements varies a lot depending on the industry nature, type of products, and structure of the supply chain. Often the total costs of the supply chain operations are underestimated. (Hoover et al 2001, Bowersox 1986, Lee & Sasser 1995, Christopher 1998)

Fisher (1997) argues that the supply chain strongly depends on the type of products to be delivered. He classifies products into functional ones and innovative ones because they have different drivers in the supply chain management. Functional products should have more traditional supply chain operating with quite stable demand. The idea is to maximize performance of the chain and minimize costs. But if products are innovative, it is impossible to respond quickly enough to unpredictable demand. Lot of stock-outs, forced markdowns, and obsolete inventory can occur. Market mediation costs dominate the cost structure of the supply chain. Therefore, the supply chain should be built to be a market responsive process in which the primary focus is on speed, flexibility, and quality. In that case, the role of product structures is important - modular architectures should be used to allow late product differentiation. (Fisher 1997)

Other researchers have also found that the nature of market demand is a significant factor in supply chain development. While Fisher said that the supply chain structure depends on the type of product, Heikkilä (2000) says that it also depends on single customers. It is not enough to understand the demand of the one product, for different customers may have different preferences about how they use the product and how new demand comes up. Therefore, companies should be able to analyse potential varieties in their customer base and build up capability to offer different configurations of the supply chain. Because demand is the starting point, Heikkilä prefers the term demand chain instead of supply chain.

Hoover et al. (2001) continued that trend in their new book. They use the term demand-supply chain in which they separate demand chain to refer to information flow from the customer to the supplier, and supply chain to refer to material flow from the supplier to the customer. The purpose of the demand-supply chain management is not only to improve efficiency but also to increase value for the customer. To describe that phenomenon they propose a concept of value offering point (VOP). The VOP links supply to demand. It is the point in the customer's demand chain where the supplier fulfils demand.

The order penetration point (OPP) is the point where the customer order specific product configuration is defined. It links demand to the supply. Before that point, all activities are based on forecast, and after the OPP based on real customer orders. Figure 10 illustrates the demand-supply chain with the traditional locations of the OPP and VOP. (Hoover et al 2001, Lehtonen 1999)

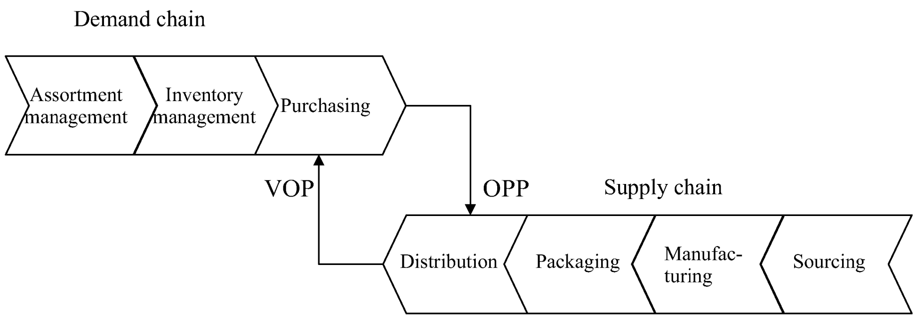

Figure 10. The demand-supply chain (Hoover et al. 2001).

The demand chain carries the demand information from the market and drives the supply chain that carries the material flow from the component vendors to the market. Efficiency of the demand-supply chain improves when the OPP can be moved upstream, closer the manufacturing phase. On the other hand, moving the value offering point downstream can generate new value added to the customer. A value threshold is a supplier value offering that produces a quantum improvement in the operations and performance of the customer. It requires that thinking is expanded beyond the customer order, to the starting point of the real demand. Potential sources for value innovations are:

1. Reshaping the customer relationship.
2. Taking a new perspective on costs.
3. Extending delivery to fulfillment.

The conventional relationship is a buyer/seller relationship between purchasing and distribution departments. An example of adding value to the customer is that the VOP is moved from the purchasing phase of the demand chain to the assortment planning phase, which is possible through collaborating on the assortment determination. The supplier's retailing activity looks together with the customer at consumer categories, which the supplier's products serve. For instance, a retailer can save by more accurately balancing demand and supply. A supplier can save by better capacity utilization and fewer inventories. That kind of change is more obvious in accordance with the development of new information technologies. (Holmström et al 1999, Hoover et al 2001).

2.8 Dependent Variables

According to Bowersox (1996), demand-supply chain performance consists of speed, reliability, and cost. Also Lee & Billington (1992), Holmström (1995), Levy (1997), Hoover et al. (2001) and many others have studied performance of demand-supply chains. Because the basic assumption in this study is that delivery lead-time and reliability are strongly affected by the markets, the focus is only on the cost part of the demand-supply chain.

The current literature on demand-supply chain management has quite much focused on the asset cost part of the total demand-supply chain costs. Sharman (1984) and Lee & Sasser (1995) say that product structure has implications for inventory costs. This finding is already almost self-evident, for the same results has been pointed out by several other researchers as well.

To measure this implication, **"Inventory value",** dependent variable V1, is defined. Inventory costs are especially important in high technology industries where product life cycles are short and new technologies constantly replace the previous technology generations. This measure covers the main physical modules of the product and it is measured in the regional distribution center (DC) buffer from which customer deliveries are typically shipped. This buffer from the demand-supply chain was selected because it usually is the biggest one having the biggest implications on cost efficiency and business profitability. Another important buffer could be the component and raw material buffer, but it is not possible to allocate directly to certain products because many products use the same components. Hence, the DC buffer is enough to illustrate the phenomenon under the study.

Unfortunately, another important cost part is often neglected or scope of the analysis has been too narrow. This part is the process cost to carry out product delivery operations over the demand-supply chain. To deliver a product to the customer at the right time and to the right place as cost efficiently as possible, the following processes are usually needed:

- forecasting
- sales configuring & quoting & pricing
- order handling
- purchasing
- manufacturing & production planning
- distribution
- invoicing

Performing the demand-supply chain, configuring, ordering, manufacturing and delivering products to the customers, requires resources as employees in direct and support functions, machines, information systems, and various facilities. Traditionally usage of these resources for demand-supply chain operations is kept to a small cost part in the demand-supply chain management literature. Studies have been focusing only on the manufacturing part of the demand-supply chain. Anyhow, this operating cost plays a crucial role when dealing with more complex products and globally operated demand-supply chains. Especially product variant explosion has increased companies resource usage in these operations.

Many product development researchers have found the product's implications on operative business processes. For example, Ulrich (1993, 1998) emphasizes that unmodular product structure requires more effort in different delivery process activities. Also Ericsson and Erixon (2000) argue that complex products make operative processes more complex, which increases costs. Therefore, it can be said that better products potentially cause less negative implications for operative costs and inventory assets over the demand-supply chain.

On the other hand, many management accounting researchers have written about the increase in indirect costs in the industries. Cooper and Kaplan (1991), Cryzewski (1991), Campbell (1995) and many others have pointed out that the share of this kind of indirect cost is continuously increasing in the industries. The development of indirect cost share is illustrated in figure 11 below.

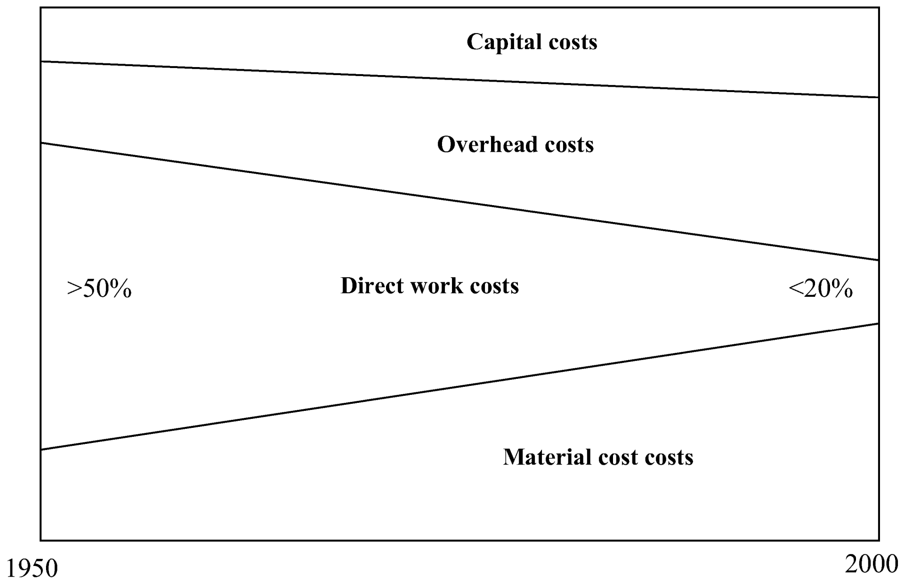

Figure 11. Development trends of cost elements from 1950s to 2000 (Kiuru 1997).

The figure shows that overhead costs have increased a lot, maybe an implication of increased complexity in industry structures and proliferation of products. Costs associated with the product itself as direct material costs and direct labor costs together are relatively lower today than they have been in the 1950s. In turn, the share of other costs is bigger.

To analyse where overhead costs come from, a company's resources can be divided into four main categories, which are represented in figure 12.

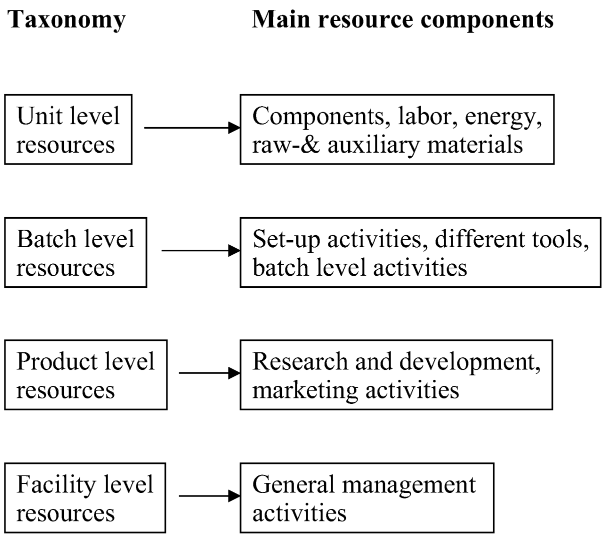

Figure 12. Resource types and respective examples of resource components. (Fogelholm 1999)

The earlier listed demand-supply chain processes consume resources from all four categories. Product structures strongly affect unit and batch level resources but also product and facility level resources. Quantification of those costs and allocation of them to the products has long been a challenge among researchers and practitioners. An important yardstick of an accounting system is how accurately it can quantify and allocate these costs to the products.

There are only a few methods to operationalize indirect costs caused in the demand-supply chain processes. Many cost management researchers argue that traditional accounting procedures do not offer accurate enough information to allocate indirect costs caused by the products (Fogelholm 1998, Kaplan & Cooper 1998). They offer only one allocation base for all the indirect costs, which does not reveal differences between the costs caused by different products. All the fixed costs are allocated to the products using a fixed percentage. Johnson & Kaplan (1989) say in their cost management book, the first main publication in the field, that today's management accounting information, driven by the procedures and cycle of the organization's financial reporting system is too late, too aggregated, and too distorted to be relevant for a manager's planning and control decisions.

To improve information accuracy, Brimson (1991) presented the idea of activity-based costing (ABC). In the ABC procedure, costs are based on process activities measuring how many resources are used to perform certain activities. Indirect costs can be allocated to products by using multiple allocation bases which improves accuracy of results (Johnson 1991, Fogelholm 1998). Activities convert resources into outputs. An activity measure is the factor by which the cost of the process varies most directly. A cost driver is a factor that creates or influences cost and defines the relationship between allocation bases and the corresponding resource consumption (Brimson 1991). The starting point for a more accurate economic model is Ashby's law, which was polished by Beer (1985) to the form: "Only variety can absorb variety", and is known as the law of Requisite Variety. It says that the economic model has to capture sufficient amount of variety to be used for steering purposes. Variety in the model means, in this context, that the number of cost drivers is sufficient to describe resource consumption caused by different products.

There are three concepts used in conventional ABC theory: Resources, activities, and cost objects (Kaplan & Cooper 1998, Brimson 1991, Campbell 1995). The relations are defined in figure 13.

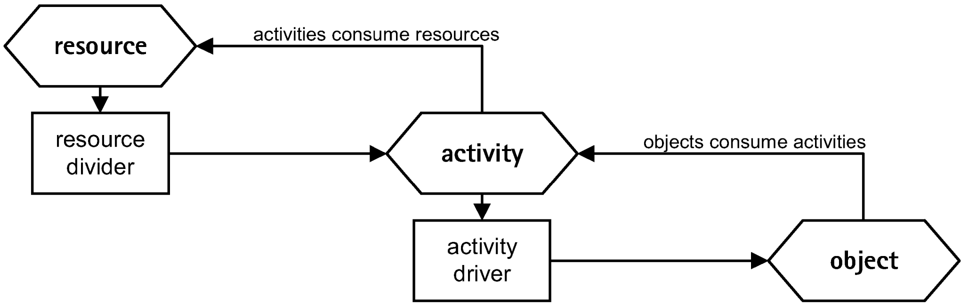

Figure 13. ABC determines the relationships between objects, resources and activities.

According to Fogelholm (1998), Cooper & Kaplan (1991) and Brimson (1991), the idea in the ABC method is that actual total costs that have already been realized are allocated to cost objects (products) using cost drivers that convert consumption of resources to the cost objects. Costs of resources are allocated to activities according to the share of used resources. Cost here represents total costs because both direct and indirect costs are allocated, fixed and variable costs are not separated, e.g. cost of the machine service function is allocated according to the percentage of machine hours used for producing the product.

Because the ABC method can offer more allocation bases and therefore produce more accurate financial information than traditional accounting method, it can be used to predict cost implications of different product structures on demand-supply chain operations. That anticipatory property is used in this study to estimate product structure's effect on operating costs. In this study, a product structure forms a cost object, a product that consumes resources according to cost drivers. Therefore, **"Operating cost",** dependent variable V2, is defined to cover costs of performing order fulfilment parts of the DSC processes. Order fulfilment processes require human work to transform product and ordering information from one place to another or from one form to another. Included processes are illustrated in figure 14.

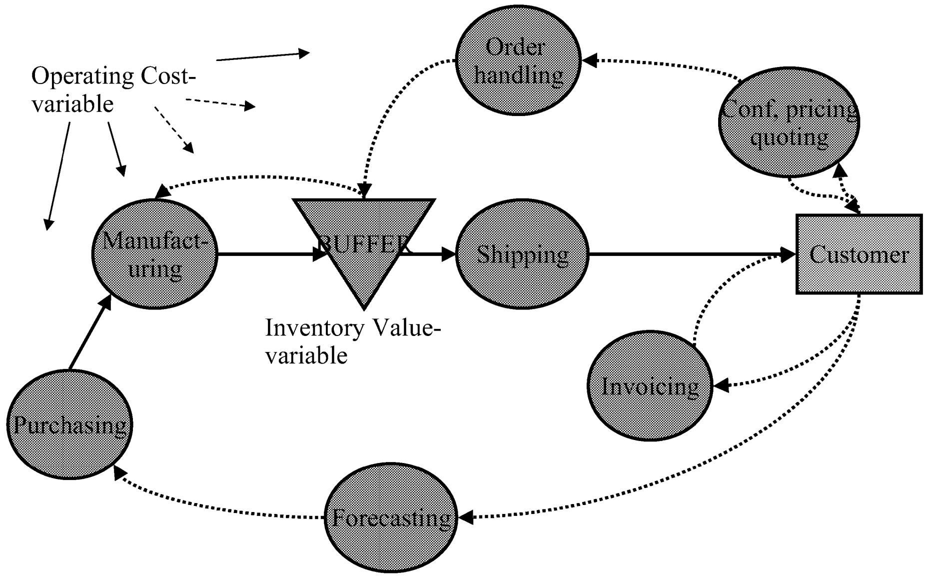

Figure 14. Scope of operating cost variables.

Configuring, pricing, quoting, order handling, manufacturing, purchasing, shipping, and invoicing processes are often driven by customer orders to fulfil certain demand. In addition, the forecasting process is also included in the scope, because it is essential to keep up capability to manufacture and deliver products. Performance of these processes is potentially affected by the product structures.

The defined limitation in the operating cost variable excludes activities done outside the company borders. They are left out because they depend on sub-assembly and component structures of the product, which are not included in the scope of the product structure analysis in this study. It is very challenging to link those levels to the module or product level on the product structure hierarchy. Besides, it would endanger the accuracy of calculating module-level implications of the product structure.

In addition to selected dependent variables, inventory value and operating cost, there are other qualitative implications on demand-supply chain efficiency that are left out. When products are not modular, overall management activities become more challenging. If the company has the wrong kinds of raw materials in the stock than real demand requires, products can not be delivered at all. It transforms to cost of poor customer service, cost of useless capacity, and cost of obsolete materials. These implications also depend on product structures, but are not considered in this study because the complexity would reduce the accuracy of the results.

2.9 Summary of the Literature Findings

Literature study of this thesis can be divided into three domains: First, new product development domain. Second, the delivery process domain. Third, a product – delivery process interface. These were included in the literature study because the thesis deals with the relationships between the products and the DSC processes. Hence, it is essential to understand general drivers involved in the both areas. After understanding that products strongly affect on operational efficiency of DSC processes some researchers started to focus especially on the interface between the product and the processes. This field naturally forms the body of the current literature related to this study. Since operational efficiency depends not only on products but especially on the process structure itself, some logistics and DSC studies are reviewed as well.

Current literature in the NPD field concentrate on managing the successful development, and on the other hand, NPD methods and processes. Studies of Pahl and Beitz (1988), Suh (1990), Clark and Fujimoto (1990, 1991), Ulrich (1995), Ulrich & Tung (1991), Sanchez (1996, 1999), Chen (1998) etc. focus on managing product development process in order to get the best performance out of the NPD. They provide a strong theoretical foundation for NPD by presenting definitions for modularity and fundamental design principles as axiomatic design principles. Drawback from this thesis point of view is that they handle the topic on general level without direct connection to the product itself and how to structure products in an efficient way. Lampel (1996), Pine (1993, 1995), Chen (1998), Anderson (1997), Baldwin (1997, 2000), Ericsson (2000), Erixon (1998), Feitzinger (1997), Thomke (1998), Duray (2000) etc. concentrate more on customer's perspective to the NPD. They provide useful concepts to match a new product with the market requirements, and to achieve a product leadership. They already stress the issue of the product architecture as an important driver of good performance in NPD. Both product platforms and modularity has been explained from product development viewpoint. Thanks to these researchers, it is well known that platforms can be used to reduce development cost and lead-time through enhanced module reuse. Most of these studies make a relevant notice that the product architecture has considerable effects on many business processes, especially to manufacturing and logistics processes, but concrete results on their effect on operational efficiency are missing.

Delivery process domain is also reviewed, because it has always kept as a dominant factor of the efficiency of operations. The existing studies confirm that the operating costs in the DSC really consist of managing information and materials. Integrated logistics concepts of Bowersox (1984) and Chistopher (1998) are reviewed to get a big picture of the domain. Hoover's and Eloranta's and Holmström's (2001) concepts of DSC as well as OPP offer tools to understand what kind of trade-offs exist in the design of such delivery processes, e.g. how service level and costs are related to each other. Anyhow, these theories do not consider the role of product in the process performance. Only Fischer (1997) includes product view in his studies, which revealed that the type of products affect on the type of the supply chain needed. This in turn, confirms that the products have relationship to DSC performance but it does not tell what is the effect of different products on the given process structure. The research questions of this study became even more interesting and relevant.

A product – delivery process interface has become a more common topic in the research during 1990's, since the importance of efficiency has increased. Many researchers have contributed on this field. Hau Lee (1993, 1995), Sharman (1984), Dowlatshahi (1990), Ericsson (2000), Mather (1986), Olesen (1992) etc. have developed design principles to optimize a product design in terms of performance of certain phase of the delivery process. The studies provide a set of guidelines to be used in the design phase. Drawback is that they deal with the trade-off between limiting the product offerings and optimizing the product costs, which is not feasible in order to maintain product leadership and high market shares in the market place. Also, guidelines are quite on general level in order to get efficient results in practice, and empirical validation of the findings is missing from most of the studies.

Lee (1993,1995) and Sharman (1984) present also empirical data but results are focused on process lead-times and product inventory costs. Other studies focus on manufacturing phase of the delivery chain, which is not the whole truth since all the phases that manage information are then left out, as well as activities after shipment from the factory. Many researchers point out that there is lack of concrete tools to evaluate goodness of a proposed product in terms of certain process efficiency.

Some researchers have quantified product structure's goodness and product structure's effects on total product cost or some other virtue. For instance, Pugh (1991), Ericsson & Erixon (2000) and Martin & Ishii (1998) have presented metrics to evaluate complexity of the product structure aiming at reducing total product cost and manufacturing cost or lead-time. These metrics have verified that it is useful to have concrete metrics to evaluate goodness of the product, even if the information would not be accurate. Regardless plenty of metrics has been presented, there are no such metrics to measure DSC efficiency.

It became clear that there is room for new research to develop concrete tools to evaluate new product's goodness and to provide empirical evidence about the product's DSC efficiency. This area is elaborated more in the solution development phase later on.

3 RESEARCH METHODOLOGY

3.1 Research Tradition in Industrial Engineering and Management

Science is generally divided into two main streams, basic science and applied science. Basic science is to describe how things are in this world, whereas applied science describes how things should be in order to achieve a certain aim (Hameri 1990). Applied science can therefore be located between the basic science and technology. According to Eyth, technology is all that realizes and concretizes a human will. In addition to truth and novelty criteria, both epistemic and practical utility are typical elements of applied science. (Hameri 1990, Järvenpää & Kosonen 1999)

Applied science aims to create utility by finding generalizable laws for phenomena. It finds instruments to perform better in this world. G.H. von Wright (1987) defines a technical norm that is the basis for many applied sciences today: "If you want A and you believe to be in a situation B, you need to do X". This statement proposes that a research programme should find solutions for X when A and B are known. This requires understanding, operationalization, data collection and analysis, and finally reasoning about the effective mechanisms. (Hameri 1990, Bunge 1967)

Industrial Engineering and Management (IEM) belongs to applied sciences. The target is to describe how an industrial enterprise should act to achieve good results. The research object is an industrial enterprise that is a multidiciplinary system. (Carlson 1984, Olkkonen 1993)

Because an industrial enterprise has a nature that is difficult to model exactly, and the business environment is changing continously, none of the traditional stereotypes of research methods ideally suit the research in IEM. IEM has connections to engineering science, social sciences, science philosophy, ecology, and legal science. Hameri (1990) has studied the methods used in IEM. He argues that much research had too nomothetic methods, close to natural science which describes how things really are. It does not offer enough utility for an industrial enterprise. Therefore, he proposes that the technical norm should be used to set-up research problems in IEM.

IEM in Helsinki University of Technology (HUT) has applied empirical case study as one dominant research method. It is especially suitable when the problem area is not well known. If the problem is more exact, case research is not necessarily the best research method. Hence, there have been efforts to develop another approach suitable for problems in the area of IEM. HUT has emphasized three characteristics of an applicable research approach: relevance, contribution, and evidence (Eloranta 1998). Relevance means high priority of problems of the domain and clear practical value in the industry. Contribution means argumented increase in the body of knowledge with novel results. Evidence requires that the solution alternative is rationally and empirically verified to work as aimed. Deep understanding of the phenomenon under research enables the building of reasoning and explanation how and why utility is achieved. (Heikkilä 2000, Ranta 1999, Eloranta 1998)

A constructive research method traditionally used e.g. in business economics fulfils the three criteria set for the research in IEM. Therefore, it has become another popular research method in IEM. The idea is to, based on the literature, find a solution for a relevant problem. According to Kasanen & Lukka & Siitonen (1991), a constructive method is a solution-oriented normative method where target-oriented and innovative step-by-step development of a solution are combined, and in which empirical testing of the solution is done and utility areas are analysed.

3.2 Potential Method for the Research Problem

The research problem is formulated into the form: *Is it possible to measure a product structure's goodness in terms of demand-supply chain efficiency already in the new product development phase?* To direct the problem more precisely, the following research questions are used:

Q1: How can the demand-supply chain efficiency of product structures be measured?

Q2: What is the effect of changing a product structure on demand-supply chain efficiency?

Answering these questions enables the quantification of goodness of a product structure in order to compare design options during the NPD process. The research questions offer grounds for selecting an applicable research method. On the other hand, the research tradition in the IEM also affects method selection.

Product structure's goodness should be measured in a concrete way. This quantification could be linked to efficiency of the demand-supply chain, providing comparative power to evaluation of design alternatives. Hence, a set of product structure metrics is a potential solution to the problem because they could indicate efficiency of product design alternatives even in the early design phase.

Based on pre-understanding, a constructive research method is potentially suitable for this research because it seems that the metrics to measure DSC efficiency of a product structure do not exist in the body of knowledge and a new construct is needed to fill that hole. According to Kasanen and Lukka (1993, 1995) and Eloranta (1999), a constructive research method is especially suitable for explicit problems. It is used in technical science, mathematics, operation analysis, clinical medicine, and industrial engineering and management sciences (Kasanen & Lukka 1993, Eloranta 1999). The nature of the constructive research is illustrated in figure 15.

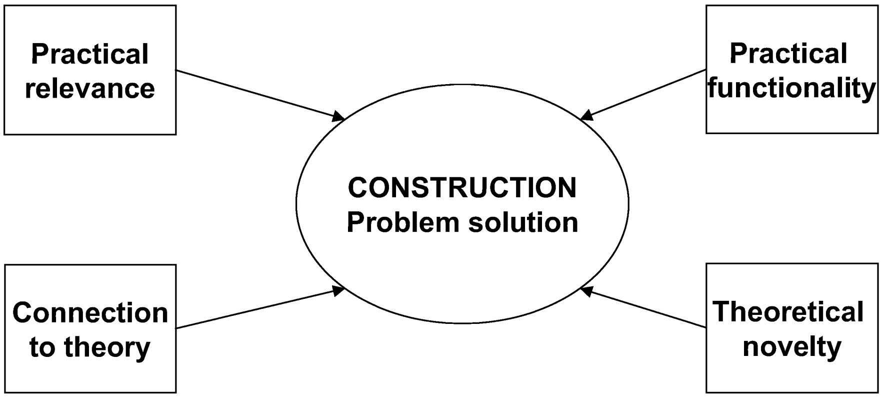

Figure 15. Elements of the constructive research (based on Eloranta 1999, Kasanen & Lukka 1993).

The research problem in the constructive research method should have both scientific and practical relevance. To solve it, a connection to practice and theory is needed (Eloranta 1999). The solution creates something that differs from anything that existed before. At the beginning, it should be identified what is the missing piece of research in the body of knowledge. On the other hand, the problem should have a great potential value in practical implementation to the industry. Often the latter one is identified first. Understanding of both dimensions enables criteria to be set for a solution and therefore gives eligibility to start finding it with the aid of literature and/or cases.

Development of a solution has heuristic features. A good result offers evidence that the solution is useful for the problem defined. It can be done through implementation of the solution. Both rational and empirical validations are usually used. In addition to practical effectiveness of the solution, it should be new to the body of knowledge. Elaboration of achieved results to the body of knowledge clarifies the scientific contribution of the research. When adding analysis of generalizability of the results, all the elements of relevance, contribution, and evidence are included in the research method.

To logically follow the idea of the constructive research, a couple of researchers have defined steps that are to be taken during the research process. Olkkonen (1993) has defined the phases as presented in figure 16.

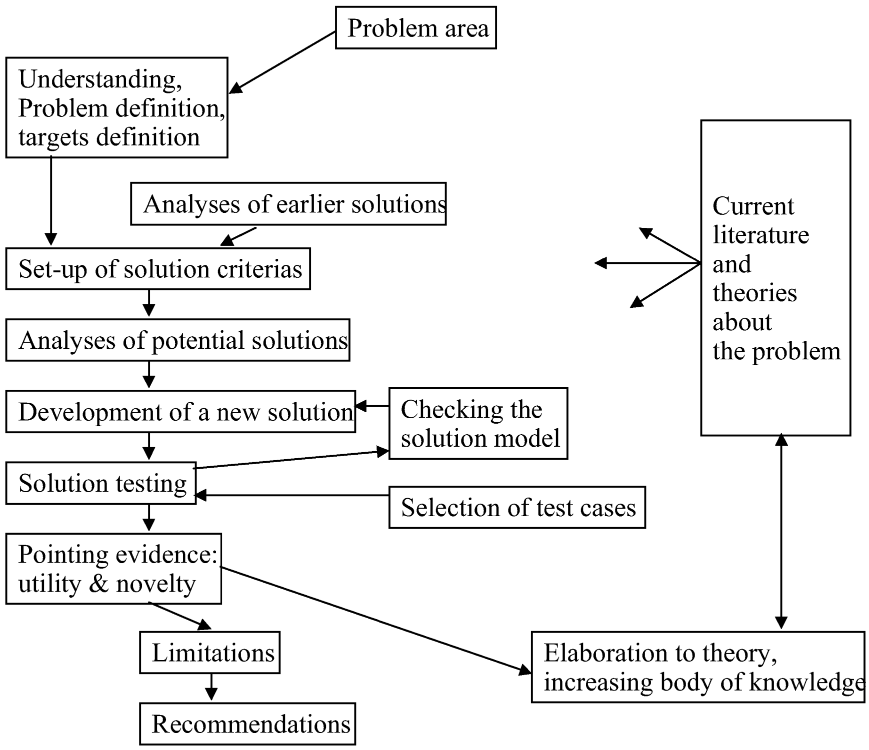

Figure 16. The phases of constructive research method (Olkkonen 1993).

The phases described in figure 16 represent quite a straightforward way to solve a problem. Development of a solution proceeds logically step-by-step using reasoning in literature and empirical understanding about the problem area. Setting criteria for a solution verifies that the problem area is understood rather than solutions found by accident. Normal novelty, utility, and generalizability analysis will follow the result of the study.

Eloranta has also contributed to the development of the constructive research process. He defines the research process in the constructive method a little bit differently. According to Eloranta (1999), the main phases are:

1. Search for a relevant and potentially novel research problem
2. Capture pre-understanding on the research object
3. Innovate construction, problem "solution"
4. Validate "solution"; workability, verification
5. Connect "solution" to the body of knowledge; identify novelty
6. Generalise "solution", i.e. elaborate novelty & domain of applicability

The search phase includes identification of a relevant problem with potential utility of the problem solution and relation and contribution to existing theories. Pre-understanding means that the problem is well elaborated in the practice and theory. The problem area is understood in practice and existing artefacts for the problem area are analysed. Synthesis of the problem area and the existing artefacts offers criteria for a new solution, which gives a solid grounding to start the innovation phase.

The functionality of a solution is then demonstrated through implementation and usefulness is validated. Connecting the solution to the body of knowledge of the problem area and existing artefacts, novelty can be identified. Finally, generalizability is analysed by defining domains in which the solution is applicable. Thus Eloranta's process emphasizes more the deep understanding of the practice and continuous conversation between theory and practice, whereas Kasanen & Lukka emphasize more the utility and market tests as a validation.

A case study method could also potentially be appropriate if there were plenty of different cases available and the research problem had not been formulated exactly.

3.3 Understanding Practice

New products should meet a lot of different requirements. Products should reach a maximum fit to market requirements in order to achieve commercial success. To create profitable business, they should also be as cost efficient to produce and deliver as possible. As commonly known, definition of a product concept and its architecture requires lot of anticipation, and implications to multiple domains should be estimated before making decisions about the implementation. Often there are several alternative design options from which the concept is to be selected. To make selection easier, design requirements should preferably be presented in an explicit form to enable evaluation and comparison of different options.

If there were concrete metrics to measure demand-supply chain efficiency of product structure alternatives, it would be possible to estimate future cost implications for the demand-supply chain in a quantitative way, and to make better selections before product design implementation. The metrics would also allow target setting for NPD projects and long-term follow-up of product structures' goodness. The need for concrete comparison of design alternatives has become more important along with the increased number of design requirements, higher development frequency, and higher importance of DSC costs.

3.4 Analysis of Existing Research Findings

The described practical need complies to design for "X" theories that aim to improve certain operational performance through developing better products. Current literature pieces approach a new product and business performance interface from multiple directions. Literature about the relationship between new products and demand-supply chain management is limited.

Modularity and product platform theories primarily aim at increasing NPD performance by offering instruments to reduce time-to-market and development cost. Benefits for other performance drivers are handled only generally and at a high level. It is only claimed by many researchers that modularity and platforms can gain performance of manufacturing, logistics, and customer service processes, but there is little evidence (Ulrich 1993, 1998, Meyer 1997, Erixon 1998, Ericsson & Erixon 1999, Baldwin & Clark 2000, Sanchez 1996, 1999). Mass customization proposes instruments to offer customer-unique products at mass manufacturing cost. It takes quite a holistic view of the problem area, the product structure's implications for business process performance, but it does not clarify the product design domain deeply enough. Mass customization researchers say that modularity and late product differentiation are enablers for easy product differentiation but they do not proceed to quantify goodness of the potential new products in relation to their concepts.

Many design for "X" concepts offer good approaches to manage the problem area. Unfortunately, they are only focused on a certain phase of the product life cycle, not covering the performance of the whole delivery process, or any other main business processes. For example, design for manufacturing and design for assembly represent quite concrete metrics to evaluate a new product's efficiency implications for the manufacturing process (Stoll 1990, Foo 1990). But when talking about demand-supply chain management, holistic solutions are missing. Dowlatshahi (1996), Sharman (1984), Foo (1990) and Martin & Ishii (1996), in their design for logistics (DFL) concept, present some guidelines for single products to perform better in logistics management. Design for supply chain management (DFSCM), launched by Hau Lee (1995), focuses on inventory management and lead-time reduction. It does not represent quantification of product structure goodness.

Even if plenty of papers have been written about the problem area, current studies handle DFL and DFSCM issues at quite a general level without either detailed guidelines or metrics. It can be understood from those studies that there is a self-evident trade-off between logistics performance and a product design, but studies do not proceed deeply enough. Unfortunately, the whole demand-supply chain and its dynamics has been ignored or product goodness has not been quantified well enough. Maybe this is due to poor product knowledge of logistics researchers. To be honest, it is also a fact that product designers do not have logistics targets as a primary interest. Dowlatshahi (1996) has emphasized that there is a gap of research results about the interface of the product design and logistics. Dowlatshahi (1996) and Foo et al. (1990) also say that there should be a quantifiable method to evaluate logistics implications of the product design.

Some researchers have tried to fill this gap by proposing product structure metrics to measure costs associated with the products. Erixon (1994) proposes assortment complexity metrics to measure overall complexity of a single product. The quantification has not been linked to any real performance measures. Martin and Ishii (1996) present Design For Variety metrics to measure product cost. The commonality index measures parts of uniqueness of a single product, which approximates direct labor costs related to its manufacturing. The differentiation point index and set-up index combine manufacturing process properties in their quantification and can not therefore be used for pure product structure evaluation and comparison purposes. Galsworth (1994) proposes a VEP parts index to measure product architecture's variety effectiveness. It offers an approximation of the goodness of a product by estimating the number of product variants and the respective total manufacturing costs.

In both cases, the scope included with the product cost is quite narrow, covering manufacturing processes, and linking metrics through empirical data to real cost efficiency are missing. On the other hand, none of the metrics include the aspect of the functional domain in their operationalizations. That is an important aspect when operating in an uncertain business environment. One problem in current quantifications is that they include variant reduction as one variable, which may be a risky operation when a company is competing for market share.

It can be said that the current literature is lacking wide enough and concrete views to improve cost efficiency affected by product structures. Existing studies have focused on either single phases of the value chain or they are too much manufacturing biased instead of market driven. The metrics to measure demand-supply chain efficiency of a product structure are missing.

Existing artefacts in the body of knowledge can not provide an answer to the research questions even if there is a clear practical need for the metrics described. Hence, there is room for new research to develop product structure metrics to better indicate demand-supply chain efficiency of a product structure. Because the problem is explicit and there is a connection to the theory and practice, the constructive research is selected as a main method in this study.

3.5 Research Process in this Thesis

Eloranta's (1999) research process is mainly followed in this thesis because it better describes the co-operation between existing artefacts and deep understanding of the problem area in practice. The process used in this study is described in figure 17:

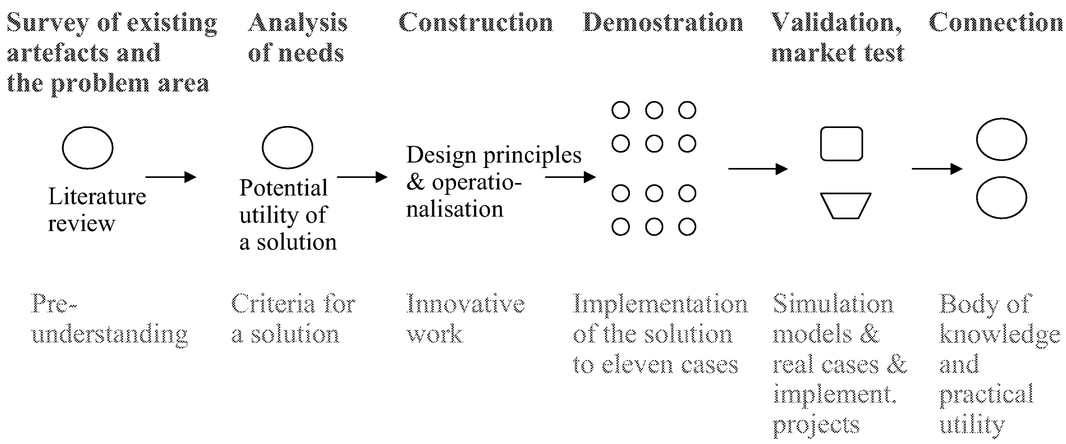

Figure 17. The constructive research process to be followed in this study.

The research starts from exploring artefacts from the existing body of knowledge for the demand-supply chain efficient product design. It requires review of product development and its interface to the firm's operative processes. The purpose is to gain understanding of the applicability of the current solutions. An analysis of needs in the second phase enables criteria to be set for a new, more applicable solution. Hence, practical relevance and connection to theory have been identified before development of a new solution.

The next phase, construction of the new solution, includes discovery of product design principles and their operationalization, which enables the analysis of how well design principles are met in a given product structure. This phase utilizes empirical experiences of the researcher and also includes innovative features, which is one property of the constructive research approach. It answers the question Q1, how to measure demand-supply chain efficiency of product structures. Basing design principles in the literature, and using empirical experience as a basis for operationalization, guarantees the required scientific and practical relevance of the problem solution.

An idea in demonstration is to verify that the solution works in practice and therefore has potential utility. Eleven different products are used as cases, which shows that different products lead to unique metric values offering comparative power to analyse DSC efficiency.

In addition to empirical validation and market tests, real world simulation models are also applied. The purpose of the validation phases is to find evidence for the product structure metrics' usefulness by establishing a link between the product structure metrics and DSC efficiency, which provides an answer to the research question Q2, what is the effect of changing a product structure on demand-supply chain efficiency. One simulation model is created to find out the relationship between the product structure metrics and the dependent variable V1, inventory value. Another model is created to find out the relationship between the metrics and the dependent variable V2, operating cost. Simulation models are built from real processes and products of the case company, so representing an empirical business environment.

In order to get better evidence about utility of the product structure metrics, they are also validated through real different products in their own business processes. Because of many challenges, not all the activities in the simulation models are validated empirically, but the meaningful subset is selected. Three products of the case company were analysed in terms of product structure metrics, and they were then followed in terms of manufacturing labor cost and the number of changed orders in the order handling process.

As is traditional in constructive research, market tests are used to validate the usefulness of the new solution. A couple of new product development projects from the case company that use the product structure metrics developed are presented. Finally, a connection to the existing body of knowledge is elaborated. This polishes the contribution of the research to the theory base. On the other hand, practical utility is analysed towards intended utility of the new solution.

Eloranta (1999) argues that a market test is not enough to evaluate quality of the research results. It is not necessarily an airtight indicator of construct usefulness. It is possible that there will always be some people who will use a new construct even if it does not offer the intended utility. It does not guarantee the quality of the research designs as such. Therefore, evaluation criteria from case study research are additionally applied to the constructive research process in this thesis. Robert Yin (1989) has presented commonly used criteria for judging the quality of research design. The following four tests are applied to this work: construct validity, internal validity, external validity, and reliability. These tests are discussed in the discussion chapter of the thesis.

PART II

The purpose of part II is to create a concept of the demand-supply chain efficient product structure as a potential solution for the research problem. Product design principles are discovered and operationalized into the product structure metrics. Finally, the metrics are evaluated against the solution criteria.

4 CREATION OF DESIGN PRINCIPLES

Since the current literature did not offer a solution to the research problem, there is eligibility to start development of a new solution. Based on the current literature and observed needs in practice, new product structure metrics to measure demand-supply chain efficiency should meet the following criteria:

1. to take into account demand-supply chain efficiency implications of new products in a quantitative way.
2. to allow a market-defined number of product variations.
3. to enable evaluation and comparison of alternative product structure implementations before making decisions.
4. to set product structure improvement targets for new products.

Those kinds of metrics make it possible to evaluate goodness of a product structure in terms of demand-supply chain efficiency without limiting customer offerings. The idea is to influence the physical implementation of a product structure, not to reduce functional options. Metrics help to take demand-supply chain performance drivers into consideration among several other design requirements early enough in NPD. Concrete metrics offer an opportunity to set targets for NPD projects to guide daily design work.

To develop a set of product structure metrics to meet defined criteria, product design principles to improve DSC efficiency are first discovered. In the second phase, design principles are operationalized into product structure metrics.

4.1 Metrics to Indicate Variability of Physical Product Modules

Pahl & Beitz (1988) presented the idea of the modular structure of the product architecture in their research of new product development. They say that functions of the product should be defined in a hierarchical way when, i.e., the upper-level function is composed of sub-functions on the next lower level of the modular hierarchy. By substituting the functions with technical solutions, the modular physical structure is achieved. On the other hand, logistics researcher Sharman (1984) found that products composed of unique parts relate to high inventories and complicated management of deliveries. Also, Foo et al. (1990) say in their design for logistics guidelines that products should be composed of the minimum number of possible parts.

The same kind of solution is suggested in mass customization by Pine et al. (1993). It is claimed that final products should be composed of modules that are as generic and multifunctional as possible. Janson (1993) proposed in his variant management framework that the share of standard modules can be increased by designing physical modules to carry out several functions.

Therefore, the design principle ***"Minimize the number of different physical modules"*** can be formulated from the existing literature (Pahl & Beitz 1988, Foo 1990, Sharman 1984, Pine 1993, Janson 1993). For example, according to Sharman (1984), Dowlatshahi (1990) and Foo (1990) a reduced number of physical modules forming the product will reduce inventory levels. Dowlatshahi (1990) also states that an increased number of products leads to more frequent delivery problems.

The basic idea is that the number of end-product variations, configurations, is defined by the market. The end-product is composed of several functional modules. The way a product is structured into modules is considered. Some ideas of applying the first principle are presented in figure 18.

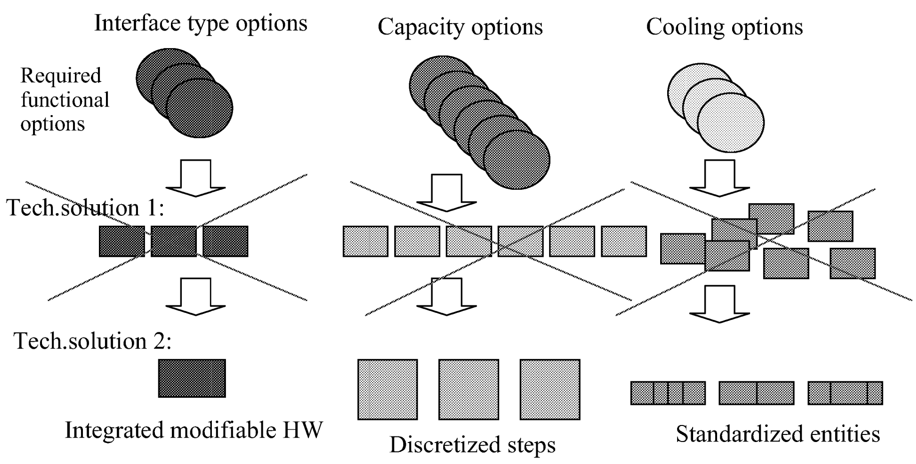

Figure 18. An idea of the design principle "minimize the number of different physical modules" applied to telecom network element products.

The first design principle is applied in three different ways in figure 18. First, functional options are technically implemented into one physical entity, which is in line with, e.g., Janson's idea in his variant management framework. As another example, to offer capacity options (capability to serve different amounts of subscribers) in the product, it is a question of how to implement options technically and how to productize the offering for the market. Using feasible discrete steps by extending the operating area of alternative modules can reduce the number of physical module variants realized. It is important to see trade-offs between potential direct cost increase and potential cost savings in DSC operations during the product life cycle.

Potential actions to improve the product in terms of the "number of different physical modules" are:

- Expand operating range of one physical unit/component to cover another option too, which may require additional components and small increase in direct costs.

- Integrate several options into one multifunctional entity. This might be useful especially in small bits and pieces.

- Optimize the number of upgrading steps from the basic solution.

- Separate hardware and software in the product architecture, and create variable/ optional functionalities by software. This is very much a strategic approach.

Dowlatshahi (1990) and Janson (1993) say that parts needed to customize the product should be separated from standard parts. This requires a reasonable understanding of the customer domain to be able to define what things may vary in the market and what things should vary in the physical product accordingly.

According to mass customization philosophy, variation of a product should be done as late as possible in the supply chain (Andersson 1997, Pine 1996, Freitzinger and Lee 1997). If goods are stored they are only in the generic form. Product variation is done by combining generic modules and/or software configuration to make wanted product functions for the customer order. This way all kinds of configurations can be offered with short lead-time and low cost if the cost of variation is low enough and number of locations where variation is done is feasible. Figure 19 illustrates the idea of late variation.

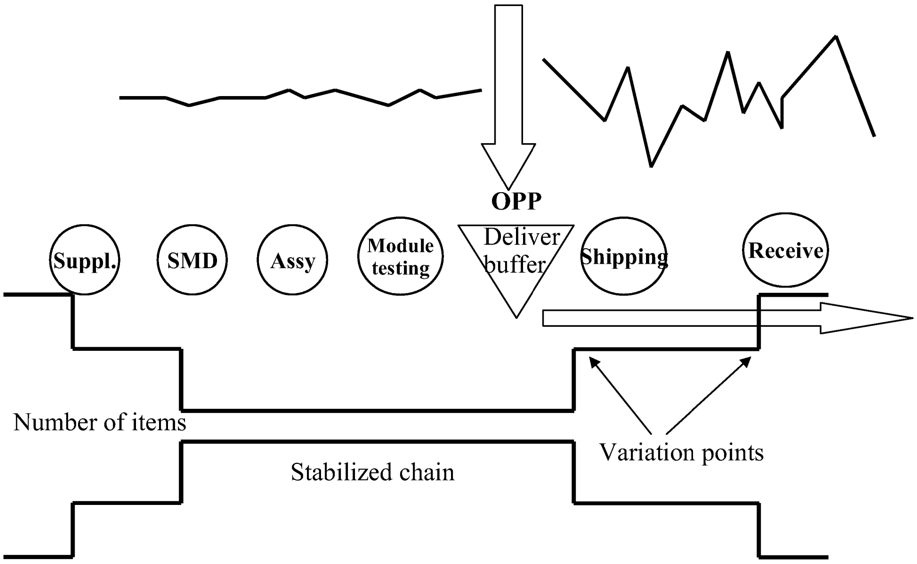

Figure 19. An idea of late variation.

Behind the variation point, module assembly, and testing phases of the demand-supply chain, the demand information is much more stable because of less variety. The funnel or "hourglass" describes the number of different item variants in the chain. The idea is to make the "hourglass" as narrow as possible behind the variation point, and to postpone the point of variety expansion until closer to the customers.

When the idea of late variation is combined with the minimum number of physical products, together they guide the solution in which benefits similar to producing standard products, and benefits of wide product range, are achieved together. Anyway, the idea of late variation is left out of the scope of product design principles in this study because the number of variations should not be maximized but optimized according to market requirements. On the other hand, capability for late variation is a process capability issue as much as a product design issue.

4.2 Metrics to Indicate Relationships Between Functions and Modules

Modularity researchers have stressed the importance of independence of the building blocks of the product. This means that a module (building block) can be changed without affecting other modules of the product (Ulrich & Tung 1991). That is achieved through definition of standard interfaces, which allows independent and flexible assembly of the product (Andreasen et al 1996). On the other hand, on the product design methodology side, researchers have found the role of independence in the functional domain. Suh (1990) states in his independence axiom that independence of functional requirements should be maintained in a product design.

According to these principles, a product structure should consist of independent physical modules with independent functions. To achieve an easily configurable structure, one functional parameter should relate to one physical entity only. Then one function is carried out by one physical module corresponding to a one-to-one relationship as illustrated in figure 20.

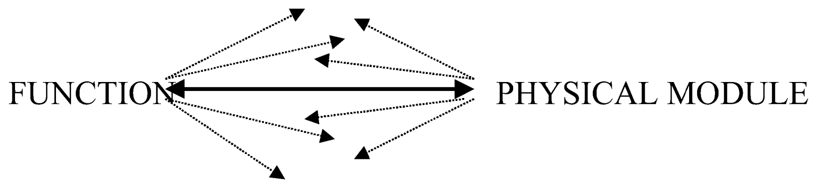

Figure 20. Funtion-module relationships.

A one-to-one function-module relationship is not always feasible or even possible in practice. Often a function is composed of several physical modules. If the functions that are wanted to be interchangeable as late as possible are composed from several physical dependent modules, then it has considerable implications on the demand-supply chain. The less different physical modules are related to one function, the less turbulence changing customer demand causes for the demand-supply chain processes. Many activities should be reorganized, and extra inventories are needed to guarantee service capability.

It can be said that functions should be independent from physical modules, but if not possible then one function should refer to one physical module only. This can be formulated as the second design principle: "***One-to-one function-module dependence***" (Ulrich & Tung 1991, Suh 1990). Standard interfaces between functional modules allow the combination of different functional modules without horizontal dependencies in the structure. Figure 21 illustrates one-to-one function-module dependence.

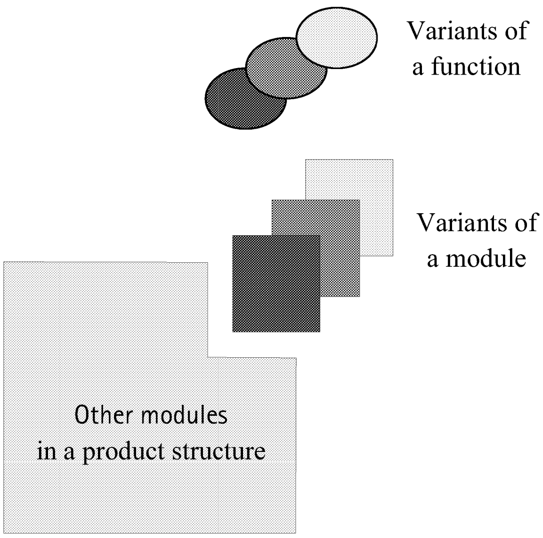

Figure 21. Illustration of one-to-one function-module dependence.

According to the one-to-one dependency principle, a change in one function reflects only on one module. This simple idea is potentially meaningful in the dynamic markets where customer demand is heavily unpredictable. If this is applied well in the product structure, it is possible to isolate physical material flow in the demand-supply chain processes from continuously changing product configuration information. Also, end-product variations do not need to be reduced because there can be as many functional variants of functionalities as required. It is important that not every functional option requires a separate physical module and that not every functional option refers to more than one physical module type.

When improving the product structure the following aspects should be considered:

- Consolidate the components affected by the same functional parameter into the same physical entity if possible. The most frequently changing ones are the most important.
- Develop software variability capabilities so that it is not needed to change the hardware components in relation to every functional change.

4.3 Metrics to Indicate Commonality of Modules

So far, design principles have handled only issues related to one product or one product family. Erixon (1994) says that the ratio of effects of actions focused on product range – product – module level is 100:10:1. In that light, development actions carried out at single product level are not enough to improve the profitability of the whole company. The most potential benefits came from product range level actions that have company-level implications. Variability of the whole product range of the company should be kept up in feasible and manageable limits, and platforms should be used to share key elements of the products (Erixon 1994, Ulrich 1998).

When using common building blocks, the process domain also benefits a lot. Foo et al. (1990) points out in his studies that the benefits for logistics processes of reusing building blocks are clear. Commonly used modules, components, and raw materials will reduce total material and process variety in a company, leading to lower inventories and less rework in daily operations. (Sanchez 1999, 2000, Meyer 1997, Ulrich 1995)

Hence, commonly-used modules need to be included in DSC efficient design principles. The third principle "***Maximized module commonality***" is proposed. Figure 22 describes the idea of common modules.

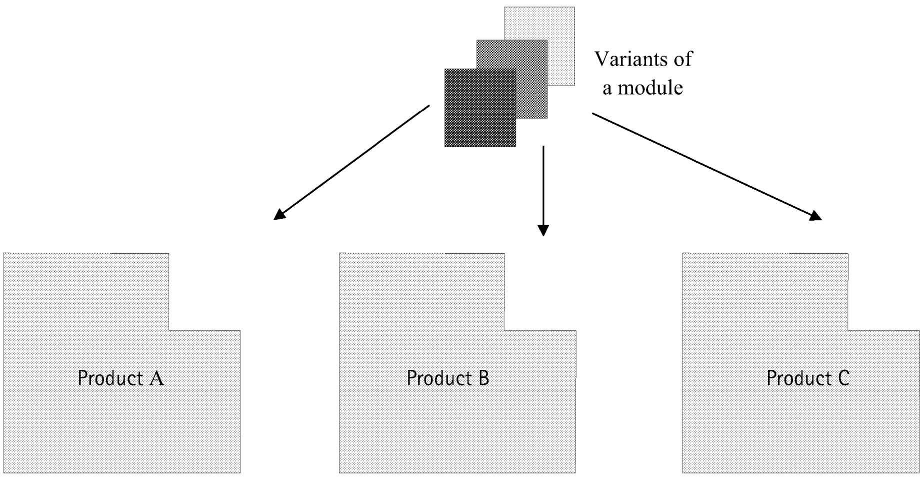

Figure 22. An idea of common modules.

The use of common modules in several products improves product mix flexibility at the product range level. Changes in customer demand will not reflect so strongly on physical modules regardless what products were sold. Also, more volumes can be centralised to the modules and manufacturing lines so that direct costs can be reduced through increased purchasing power and cost of manufacturing can be reduced through increased capacity and the learning effect of the personnel. The bigger share of common modules, the more flexibility and efficiency improvement is potentially created.

Increasing module commonality in the company is quite much a strategic and organizational issues as well as technical issue. It often requires creation of platform strategies and co-operating in requirement specification work, as well as in product management work. These will enable to expand usage of same modules across product lines/families.

Below the module level of a product structure, there can be lower-level entities where the design principles could be applied. In addition, there could be other design principles focusing on lower levels in the product structure. For instance, combining small bits and pieces at the lowest level of the structure into bigger assemblies early in the supply chain could potentially improve DSC efficiency. This idea is left out of the scope of this study because it affects mainly upstream processes. Eppinger's idea about minimized module interactions is a crucial element in developing modular products. It may have more impact on the product development process than DSC performance.

5 OPERATIONALIZATION OF THE DESIGN PRINCIPLES

To answer to the research question Q1, how to measure DSC efficiency of product structures, the discovered design principles are operationalized.

5.1 Assumptions and limitations

There are two points worth mentioning that strongly affect metrics specifications. First, a product usually has a hierarchical structure. To develop useful metrics, the level of abstraction should be fixed. Configurable products discussed in this study can be represented in a simplified three-level hierarchical structure as in figure 23.

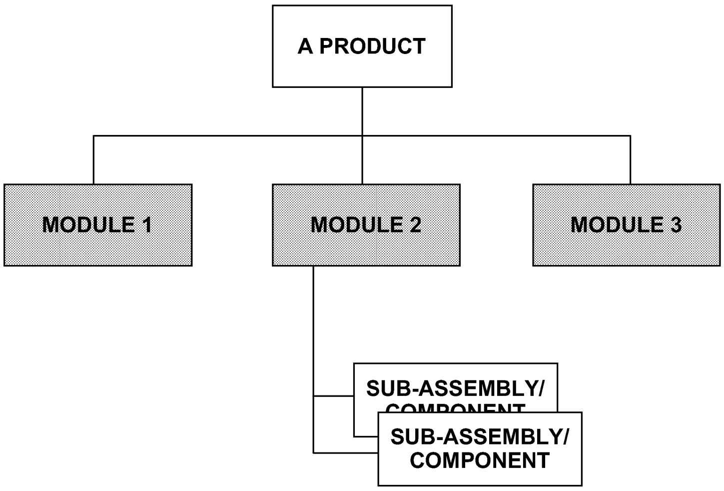

Figure 23. Simplified product structure hierarchy.

To specify quantifiable metrics, the module level of the product structure hierarchy, marked as grey colour, is selected. It means the level that is a natural cost object in the demand-supply chain because operational activities and inventory management are usually done at module level. Second, the view of how a product structure is seen should be defined. There are different views to the product, e.g. design structure has a different meaning from assembly structure. In these metrics, a product structure is understood as a physical assembly structure including main functional (also physical) modules. Packaging and labelling etc. are left out of the product structure.

Simple examples and tests are presented in order to get confidence about metrics meaningfulness, i.e. that they measure how well design principles are applied in a given product. After specifications it is verified that metrics meet the four solution criteria set for the new metrics.

5.2 Number of different physical modules

To measure utilization of "the number of different physical modules", modules are here divided into three categories to clarify their different implications: *Generic modules* mean that there is neither physical nor functional variation in the module. The module is used for all configurations of the same product. *Variable* means that a module has variation in both physical and functional domains. One of the variants is used for one configuration. Finally, *modifiable* means that a module has a standard nature in the physical domain but is variable in the functional domain, e.g. when power of the optional heater of the passenger car can be changed using a switch. The same physical module is used for all configurations of one product but it can function differently in different configurations. The specification of the first metric is:

Number of physical modules = number of generic + variable + modifiable modules.

This metric simply describes the physical variety of the given product structure at module level. It does not include information about the customer offering but it shows how good the physical implementation of the product design is. The fewer different physical modules are developed, the better is the product structure from an inventory and operating cost point of view.

Module categories further emphasize different implications of the modules on demand-supply chain efficiency. In that light, standard modules are the best because the same materials can always be produced and delivered regardless of market demand. In practice, variability is needed when modifiable modules are more efficient than variable modules because they have less implications for material flows in the chain. To keep the design metric simplified enough, module categories are not separated in the metric formula.

Let's take an imagined passenger car as an example. A car could include the following physical module types and the respective number of module variants: engine (5 variants), cabin design (3), suspension (2), interior materials (4), steering wheel (2), seat model (3), and bumpers (2). This example gives a metric value 5 + 3 + 2 + 4 + 2 + 3 + 2 = 22 module variants.

The fewer the different module variants, the more cost efficient is the demand-supply chain. The key point here is that the number of different products should not be reduced, but the number of modules from which a modular product is composed should. To enable comparison of alternative designs, the number of modules should be measured at a consistent level of the hierarchy. In addition, products to be compared should represent the same type of product and roughly the same complexity. Within these limitations, the first metric can be used for evaluation, comparison, and target setting purposes.

5.3 Function-module dependence

When a product is sold, a customer has to select the right options for each variable function. This refers typically to several physical module types. The product's functions' relationship to physical modules can be measured for each *variable function* of a product. If a function is not variable, i.e. it does not have any options (different types of the function), there is always one standard function and a corresponding module or set of modules sold. A *module type* means a core functional module that may have options. Module types are classes of physical modules, one module type may have several different physical module variants.

For instance, in the passenger car, module types could be engine, steering wheel, tyres, etc. When one car is sold, one variant of each module type is selected. It is reasonable to specify dependency at module type level, not at module variant level (whether a steering wheel is genuine leather or plastic covered). The rate of function-module dependency depends on how many physical module types are in interrelation with a certain functional selection. The rate can vary from zero to several modules per function (e.g. the selection of classical or sport style in the passenger car has relations to many modules). At product level, overall dependency can be calculated as module-level dependencies per function. The metric formula is:

> **Dependency Index = Σ (no. of affected modules when changing a functional option) / no. of variable functions.**

Dependency points have to be normalized per function. If not, products with fewer variable functions would have a better dependency index and products with more variable functions would get worse points. This would be a misleading direction, because fewer functions would obviously reduce sales.

The lower the value of the dependency index, the better the product should be from a demand-supply chain point of view. By the index value "3", three physical modules, on average, are affected when changing one functional option from one to another. In the case of a one-to-one function-module relationship, the index value is "1". If the product is fully software configurable, consisting only of modifiable or generic modules, the value would be "0". This is the ideal value for this metric.

Let's now calculate a dependency index value for the passenger car example presented above. There are four variable functions: car style, engine type, interior material, and steering wheel type. A good way to calculate dependency is to use a matrix. A dependency matrix is presented in table 3.

Table 3. An simplified example of a dependency matrix for a passenger car.

Module types	**Variable functions**				
	car style	engine type	inter. material	st. wheel type	
Engine		1			1
Cabin desing	1				1
Suspension	1				1
Interior	1		1		2
Steering wheel	1			1	2
Seat	1	1			2
Bumbers					0
				Dependency points:	9
Number of variable functions	4				

Variable functions are listed in the columns and module types in the rows. The mark "x" is put in the cross of function and module if there is a relationship (for technical feasibility, the number "1" is used instead of "x"). Each relation to a module type gives one dependency point. Finally, the sum of dependency points is divided by the number of variable functions. Therefore, the dependency index in the example is 9/4 = 2.25 which means that 2.25 modules are connected to one function on average.

Practical utility of the dependency index comes from reduced rework in different operations, because functional changes in product configurations reflect less on inventories and cause less changes to orders, manufacturing plans etc. When one function relates to one module only, a product is easy to configure and demand fluctuations have less impact on material flow than in higher dependency products. To improve the dependency index value for a product, the only right way is to develop variable functions that are less dependent on physical modules. It means that a function-module relationship is developed close to the one-to-one relationship, or that variable functions are created using e.g. software modifiable modules. After those improvements, the value of the dependency index would be lower, meaning that the product can offer better functional flexibility without affecting inventories or operational work in the DSC.

In theory, the term "number of variable functions" is another speculative way to potentially improve the index value. If a variable function is changed into the standard functions, then the index value is improved but the customer offering is reduced. Therefore, this does not fulfil the requirements set for the metrics.

When calculated correctly, dependency index values can be used for comparison and target setting purposes as well. There are the same limitations as with the first metric. Products to be compared should represent the same kind of complexity. Often relevant comparisons can be made between the product generations. In that case, target values for new generation products can be defined based on the values of the old generation products. In addition, new product implementation options can be compared, which helps to select the best one to proceed with in the detailed design phase.

5.4 Module commonality

Commonality reduces module variability at the whole product range level. It is independent of the number of different physical modules; they can occur without each other.

Let's assume that product family A has four different power supply variants, which is quite many. If improvement is wanted, there are two dimensions of actions. First, the number of power variants can be decreased to two through a new design in product family A. Second, in addition to that, the commonality concept says that those two power supplies should be designed together with product family B, so that the same two power supplies are used in both product families A and B. At a company level, there are only two different power supplies instead of eight different in the worst case. Therefore, commonality can be measured as module reuse capability between different product families; it should not take into account the number of module variants because it is measured separately in order to separate these two concepts.

Some new parameters are needed to specify a commonality index formula. First, the number of *product families* where the same modules are used is needed. For instance, this means in the autoindustry that a company has four types of passenger cars (sedan, coupe, wagon, and cabriolet). Commonality for module types need to be calculated for each module variant because it may be that power supply variant A is used commonly in the company and power supply variant B has its own implementations in different product families. In that case, some commonality is achieved by using commonly specified power supply variant A. To take this into account, a parameter *share of applicable module variants* is defined. The parameter *number of module types* is now needed for normalisation because commonality points should not improve if a product has more module types; rather, it is better if a product has fewer module types. Then a standard product having only one module would have worse commonality points than a product having more module types with same commonality, although a standard product is better from a demand-supply chain point of view. Therefore, a specification for the commonality index is:

Commonality Index = [Σ (no. of product families where the same module is applicable X share of applicable module variants)] / no. of module types.

Let's assume that a car manufacturer has four product families: sedan cars, coupe cars, wagon cars, and cabriolet cars. To calculate the commonality index for the sedan car family, the sedan modules reuse capability with other car families is calculated. The bigger the value, the better is the product family from a demand-supply chain point of view. In this imagined example, the sedan car consists of seven module types as described above: engine, cabin, suspension, interior, steering wheel, seats, and bumpers. Again, a matrix offers a good aid to calculate the index value. A commonality matrix is presented in table 4.

Table 4. An example of a sedan car's commonality matrix.

Module types & variants	**Product families**				
	Sedan	Coupe	Wagon	Cabriolet	
Engine A	1		1		0.4
Engine B	1		1		0.4
Engine C	1	1	1		0.6
Engine D	1	1			0.4
Engine E	1	1		1	0.6
Cabin A	1				1
Suspension A	1		1		2
Interior material A	1		1		0.67
Interior material B	1		1		0.67
Interior material C	1	1	1	1	1.33
Steering wheel A	1	1	1	1	2
Steering wheel B	1	1	1	1	2
Seat A	1	1	1	1	1.33
Seat B	1		1		0.67
Seat C	1			1	0.67
Bumber A	1	1	1		1.50
Bumber B		1	1	1	1.50
				Commonality points	**17.73**
Number of module types:	**7**				

There are seven sedan car module types with the variants listed in rows. For example, there are five engine variants: A, B, C, D, and E. Commonality points are first calculated for each module variant (each row) separately using the formula: **no. of product families where the same module is applicable X share of applicable module variants.**

Therefore, commonality points for engine A come in the following way. Engine A is used in two product families, sedan and wagon cars. On the other hand, engine A represents one of the five engine variants. Therefore, commonality points are 2 x 1/5 = 0.4. Other engine variants are calculated in the same way. As a subtotal for engine modules, commonality points are 2.4. To get a commonality index, the commonality points are divided by the number of module types. For engines, the commonality index is 2.4 divided by 1 module type, which gives the value 2.4. This means that, on average, one engine variant is used for 2.4 product families.

To calculate the commonality index value for the sedan car family, other modules are handled in the same way. Commonality points of each module are then summed up. That gives total commonality points for the sedan car family. Finally, the commonality index comes out by dividing commonality points by the number of module types. That is: 17.73 / 7 = 2.53. A commonality index of 2.53 means that, on average, one module is used in 2.53 product families.

There are theoretically three ways to improve the commonality index:

1) *Product families.* The first way is to increase the number of product families where the same modules are applicable. This answers the question how many products is this module variant used for. Let's look at the sedan car example. If the engine modules are used for all four car families, then the index value would be 4.0, which is the maximum value.

2) *Share of applicable modules.* Another way is to increase the share of variants of a single module type that are applicable for different products. This answers the question how many variants of the one module type are commonly used. This term improves if more than one module variant is common. A module is common if it is used in at least two product families. This term can not be improved by reducing the number of module variants because then the commonality points of that variant are lost. Let's compare this to the car example, in which some of the module variants

are common and the others are not. This gives an index value of 2.53. If all the modules in table 4. are used for all four car families, then the index value would again be 4.0, which is the maximum value.

3) *Number of module types.* Normalization of the index value is needed, otherwise commonality points can be increased by adding new module types to the product structure or splitting existing modules into smaller entities, which would turn development in the opposite direction than wanted. Some kind of drawback here is that reducing module types affects the commonality index value without changing real commonality. If module types in the sedan car example are reduced from 7 to 6 by integrating steering wheel options with the interior materials, the commonality index changes a little. After this change there are five interior material variants instead of the original three. In addition, interior and steering wheel selections are now coupled, which reduces customer selection. In that case, the commonality index reduces from 2.32 to 2.13. Because that effect is small compared to pure commonality changes, the metric is still meaningful enough.

The usefulness of the commonality index comes from the platform ideas. It measures primarily how many different parallel products the same physical modules can be used for.

The commonality index does not limit the customer offerings in any form. It only deals with the physical implementation of the product design. A quantifiable index value also offers a tool to compare alternative design options in the early phases of the development. Targets can also be set with the same limitations as the earlier metrics. Therefore, the commonality index well meets the requirements for the metrics set at the beginning of the operationalization.

PART III

The purpose of part III is to verify logically that the product structure metrics work. It is shown that different products lead to different metric values, which enables the comparison of goodness of the products from a demand-supply chain efficiency point of view. Metrics are applied to eleven different products, which are later used as cases in simulations.

6 APPLYING PRODUCT STRUCTURE METRICS

6.1 Application environment

Developed metrics are demonstrated using simulation models and case products from the cellular network building industry. That industry was selected because it represents a challenging business from the research problem viewpoint. Products are quite complex high-tech products, and demand-supply chain efficiency is an important competitive advantage. The case product, a telecom network base station, is illustrated in figure 24.

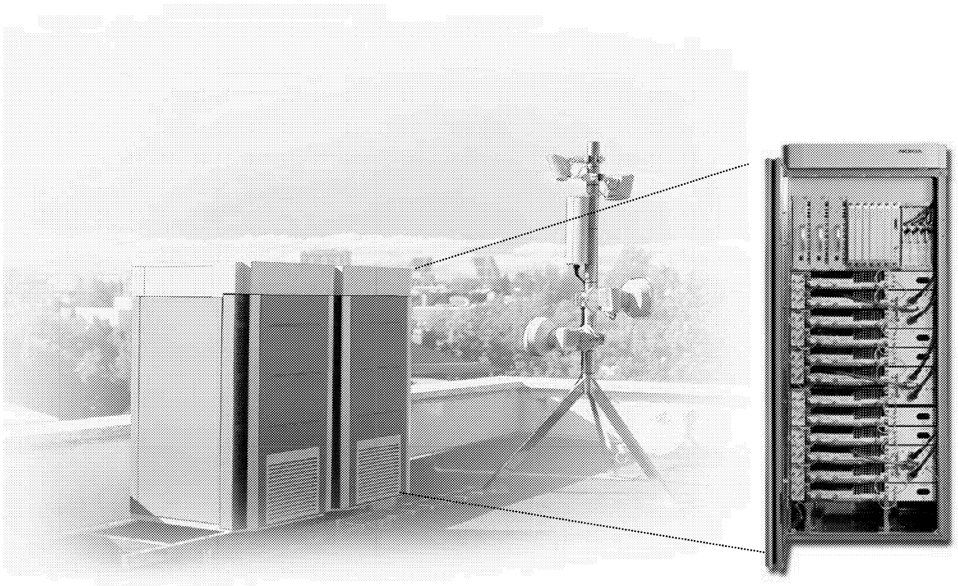

Figure 24. A Base Station (BTS) site and a BTS cabinet from inside. This site consists of two base station cabinets and a pole with antennas and radio transmission.

The equipped base station outdoor cabinet is considered as a *product* in this study. The term base station used in this study covers several different modules as zoomed in figure 24. *Module types* and the *respective number of module variants* are: *cabinet core (1 variant), application kit (1), base module (1), antenna feeder kit (1), combiner modules (7), receiver multicoupler modules (2), transceiver modules (4), duplexer modules (8), rectifier module (1), battery module (1), connection module (1), cabinet control module (1), power supply module (2), transmission module (6), heater module (1), AC filter module (1), bridge kit (1) and air filter kit (1).*

In the case study, eleven different product structure alternatives are compared in terms of product structure metrics and demand-supply chain efficiency variables. Cases are developed by improving the product structure of the original case product. The target in creating alternative product structures, cases, is to find design solutions that are better according to the proposed product structure metrics and, on the other hand, are technically feasible alternatives.

There are two sets of cases, the first seven (A1-A7) are to simulate product structures having different values in the number of physical modules and dependency index. The second set (B1-B4) with four alternatives includes another product family in order to study the total efficiency of two product families. The main focus is on commonality index values. All the cases include the same functions of the products with 84 configurations (combinations of functional options), but the way they are physically implemented varies. Functions include the following options: frequency band (7 options), power feeding (2 options), and transmission type (6 options). Product structures are illustrated using bill-of-materials (BOM) lists that are placed in the appendices of the thesis.

6.2 Single Product Family Cases

Seven cases are derived inside the presented example product family, a cellular network base station. The idea is to create different designs leading to different values in the number of physical modules and the dependency index.

The original product structure, case A1, is presented in appendix 1. Basically every functional option (variant) is implemented in a separate module variant. Therefore, there are seven frequency variants of transceiver, duplexer, and combiner modules. Multicoupler modules also are frequency band dependent, but they include only two module variants, for lower frequencies are integrated into one module and higher frequencies are integrated into another module. Transmission modules have six physical module variants, as there are six variations required by the market because of different transmission network standards in different markets.

The value for the metric "number of different physical modules" is a sum of all physical module variants listed in the BOM (appendix 1). Therefore,

Number of physical modules = 41

To calculate a dependency index for the base station, a dependency matrix is needed. It is shown in table 5.

Table 5. The case A1 dependency matrix.

Module types	**Variable functions**			
	Frequency	Power	Transmission	
Cabinet Core				0
Application Kit				0
Base module				0
Antenna Feeder Kit				0
Combiner	1			1
Multicoupler	1			1
Transceiver	1			1
Base Band				0
Duplexer	1			1
Rectlifier		1		1
Battery		1		1
Connection module		1		1
Cabinet control module		1		1
Power supply module		1		1
Transmission			1	1
Cabinet Heater				0
AC Filter		1		1
Brige Kit				0
Air Filter Kit				0
			Dependency points:	11

Number of variable functions	3

Module types are listed in the left paragraph, variable functions are defined at the top of the matrix. Relationships between variable functions and physical modules are mapped by adding "1" to the cross if the variable function has a relation to a certain module type. This means that if an option of a variable function is changed then the respective module types must also be changed. The fewer relations there are, the better is the one-to-one dependency. Dependency points are calculated as a sum of all dependencies, and then normalized per variable function. This is done by dividing the dependency points by the *number of variable functions*. Therefore, the value for this metric is:

Dependency index = 11/ 3 = 3.67

Now every function relates to 3.67 modules on average. When relationships from variable functions to physical modules are reduced, the value of the dependency index is also reduced. In a preferred situation, each of the three variable functions of the base station should refer only to one physical module. Then the value of the dependency index would be one, meaning that on average every function relates to one module only. This structure has the following metrics values:

Case A1 values:
Number of physical modules = 41
Dependency index = 3.67

The second case, A2, is created by integrating non-variable mechanical modules. This is often possible, for customers usually buy the same kinds of basic configurations in terms of secondary features like mechanical structure around the core modules. This kind of restructuring can be done by small design changes. It affects the number of physical modules but not the dependency index. The revised BOM is presented in appendix 2. An outdoor kit, base module, and antenna feeder kit are integrated into the cabinet core, as well as a bridge kit and air filter kit, which are handled as one module with the cabinet heater module. The number of different physical modules is a sum of the rows in the BOM. Therefore,

Number of physical modules = 36

A reduction of this value comes from the integration of several mechanical modules into one functional set as described in the BOM list. Because these changes do not affect function-module dependencies, the dependency index value remains the same.

These changes improve metric values in the following way:

Case A2 values:
Number of physical modules = 36
Dependency index = 3.67

Next, hypothetical improvements are focused on the core modules. At the beginning, physical variability is reduced by integrating low frequencies into one physical module and high frequencies into another module. Seven frequency variants of transceiver, combiner, and duplexer modules are integrated into two variants, low frequencies and high frequencies. A separate common part of duplexer and base band modules remains the same as in case A1.

These design changes only reduce the number of physical module variants but they do not affect function-module dependency because frequency selection still has an impact on transceiver, combiner, and duplexer modules as illustrated in table 5 (A1 dependency matrix). There are at least two potential ways to technically implement these changes: 1) to expand the operating area of frequency-related submodules, and 2) to duplicate some design blocks when it is not possible to do it in another way. It is not exactly known how much duplication is needed, but an estimate is that direct material costs would increase by 15% in these modules, which means some percentage in the direct material cost of the whole product. The revised BOM is presented in appendix 3. Combiners are implemented into two physical module variants, transceiver modules into two physical module variants plus a common part, and duplexers into two physical module variants plus one common module. These design changes affect the metric values in the following way:

Case A3 values:

Number of physical modules = 30

Dependency index = 3.67

The number of physical modules again improves but the dependency index remains the same.

In the next scenario, the dependency index is improved by using multiband modules in transceiver and duplexer modules. The revised BOM is described in appendix 4. Duplexer modules (7+1 frequency variants) are replaced by one generic module and transceiver modules (3 + 1 frequency variants) are replaced by one generic module. This means that there are no variations of these modules in the demand-supply chain. In addition, combiner modules are implemented as in the first scenario, i.e. they have seven variants. Finally, a function's "power type" relationship to the connection module and cabinet control module are removed, for they are always included in the configuration. Integration of frequency variants in frequency band related modules improve the first metric values considerably. The new value is

Number of physical modules = 31

The dependency index improves through the following actions: first, the frequency band does not have relations to the transceiver and duplexer because they are generic. Second, power feeding options do not have a relation to the connection module and cabinet control module as in the first scenario. These two modules are now always delivered regardless of the power feeding option. The value of the dependency index is illustrated in table 6.

Table 6. Dependency matrix for case A4.

Module types	**Variable functions**			
	Frequency	Power	Transmission	
Cabinet Core				0
Application Kit				0
Base Module				0
Antenna Feeder Kit				0
Combiner	1			1
Multicoupler	1			1
Transceiver				0
Duplexer				0
Rectlifier		1		1
Battery		1		1
Connection module				0
Cabinet control module				0
Power Supply Module		1		1
Transmission			1	1
Cabinet Heater				0
AC Filter		1		1
Brige Kit				0
Air Filter Kit				0
			Dependency points:	7

Number of variable functions	3

Dependency points are reduced to seven, while the number of variable functions remains the same. Therefore,

Dependency index = 7 / 3 = 2.33

which is radically better than the index value of the earlier cases. Today, multifrequency functions are technically more challenging if only a small direct cost increase is allowed. If this was done today, the direct material cost of a transceiver could increase by tens of percentage points due to duplication of certain design blocks in analogue signal processing. In digital signal processing, these types of changes are much easier to implement already today, but the current architecture defines boundaries in which scenarios are created. These improvements give the following metric values:

Case A4 values:

Number of physical modules = 31

Dependency index = 2.33

This is the first scenario in which both metrics values are improved from the reference scenario.

In case A5, design is improved one step further by adding changes to the mechanical modules of case A2 also in case A4. The BOM list is presented in appendix 5. Reducing mechanical module variants improves the number of physical modules as follows:

Number of physical modules = 26

As in case A2, the dependency index does not change from these mechanical changes in the product structure. Hence, the combination of improvements in cases A2 and A4 gives the following metric values:

Case A5 values:

Number of physical modules = 26

Dependency index = 2.33

Case A6 takes one step further from case A5. The BOM list is presented in appendix 6. Now combiner modules are also changed in a multiband module, all the seven module variants are implemented in one generic module that operates through all the frequency bands. The technical feasibility for this is not studied at a detailed level so far, but it is the goal of one R&D project to achieve this kind of architecture and physical structure for future products. The same trade-offs as in case A4 play a key role in the design work.

In addition to this change, four transmission module variants, those having an E1 connection, are integrated into one module. These are quite near each other in terms of technical implementation. Integration requires that interfaces are extended and additional connectors are placed on the same printed circuit board, which in turn requires a new layout design in order to get enough room on the board. Now both metrics change:

Number of physical modules = 17

The number of different physical modules reduces because combiner modules do not have physical variations for different frequency variants. One generic module is assumed to operate on all the seven frequencies. On the other hand, E1 transmission modules are integrated into one physical module. Changes in combiner implementation also affects the dependency index as illustrated in table 7.

Table 7. The case A6 dependency matrix.

Module types	**Variable functions**			
	Frequency	Power	Transmission	
Cab.Core & outd.kit & base mod. & feeder kit				0
Combiner				0
Multicoupler	1			1
Tranceiver				0
Base band module				0
Duplexer				0
Rectlifier Unit		1		1
Battery Backup		1		1
Connection Unit A				0
Cabinet control module				0
Power Supply		1		1
Transmissions			1	1
Cabinet Heater & bridge & filter kit				0
AC Filter		1		1
			Dependecy points:	6
Number of variable functions	3			

Dependence index = 6 / 3 = 2.00

Hence, metric values for case A6 are:

Case A6 values:
Number of physical modules = 17
Dependency index = 2.00

The number of physical modules is improved considerably, whereas the dependency index makes only a small improvement. The values improve further, for a multiband combiner reduces module variants by six and E1 transmission integration reduces variants by three. Dependency improves because of a frequency-independent combiner module.

To evaluate the effect of a pure dependency index, let's define case A7. The product structure is roughly the same as in the original structure, but the function-module dependency is improved. The BOM is presented in appendix 7. From the reference scenario it is possible to reduce the power feeding selection's dependency to physical modules. AC power-related modules, AC filter and rectifier, can be integrated into an AC power supply module to be always delivered with the AC power option. Direct material costs for integrated modules are simply summarised. In addition, battery back-up, a connection module, and cabinet control module can be integrated into one physical module when the total direct material cost can be reduced by 30% for this module. Hence,

Number of physical modules = 37

The number of physical modules is reduced by four compared to the first scenario. The improvement comes from integrated mechanical modules. The changes are presented in table 8.

Table 8. Dependency matrix for case A7.

Module types	**Variable functions**			
	Frequency	Power	Transmission	
Cabinet Core				0
Application Kit				0
Base module				0
Antenna Feeder Kit				0
Combiner	1			1
Multicoupler	1			1
Transceiver	1			1
Base Band				0
Duplexer	1			1
Battery Backup & connection & control module		1		1
Power Supply & AC filter & Rectifier module		1		1
Transmission			1	1
Cabinet Heater				0
Brige Kit				0
Air Filter Kit				0
			Dependency points:	7
Number of variable functions	3			

Dependency index = 7 / 3 = 2.33

Therefore, metric values for case A7 are:

Case A7 values:

Number of physical modules = 37

Dependency index = 2.33

The cases represent different metrics values, which should indicate that they have different efficiency implications on the DSC. Case A6 seems to be the best product according to the metrics.

6.3 Commonality Cases

In order to create cases with varying commonality, another product family is needed in the picture. Product family X represents products covered in cases A1-A7, and product family Y represents another product family with which commonality of family X modules is analysed. The base station product family Y is designed for different types of cellular networks. There are three frequency band variations in the functions of family Y products. The new products all have the same module types, but frequency-related modules have variants for three new frequency bands, 380 MHz, 420 MHz, and 800 MHz, instead of seven variants of transceiver, duplexer, and combiner in the first product family. In reality, there are a couple of other modules also in product family Y, but light simplification is done to make analysis more comparable.

The first case, B1, is a pure duplication of all the modules from product family X based on the situation in case A2. To make a commonality study simpler, integration of some mechanical modules is included in case B1 as a starting point (as it was in case A2). The BOM list (and the commonality matrix) is presented in appendix 8. Family X modules are marked in black, while family Y modules are shadowed in grey. In case B1, non-frequency-related units are purely duplicated, and frequency-related units cover, in total, ten module variants for ten different frequency bands. The total number of physical modules comes as a sum of all the modules listed in the BOM (left paragraph of the commonality matrix in appendix 8):

Number of different physical modules = 63

The dependency matrix is presented in table 9.

Table 9. The dependency matrix of case B1.

Module types	Variable functions			
	Frequency	Power	Transmission	
Cab.Core & outd.kit & base mod. & feeder kit	1			1
Combiner	1			1
Multicoupler	1			1
Tranceiver	1			1
Base band module	1			1
Duplexer	1			1
Rectlifier Unit	1	1		2
Battery Backup	1	1		2
Connection Unit A	1	1		2
Cabinet control module	1	1		2
Power Supply	1	1		2
Transmissions	1		1	2
Cabinet Heater & bridge & filter kit	1			1
AC Filter	1	1		2
			Dependecy points:	21
Number of variable functions	3			

Dependency index = 21 / 3 = 7.00

The commonality matrix is presented in appendix 8. All the modules are dedicated to one product family only, which means no commonality between families X and Y.

Commonality index = 15 / 15 = 1.00

Metrics values are:

Case B1 values:

Number of physical modules = 63

Dependency index = 7.00

Commonality index = 1.00

The metric values indicate that these two product families may not have good DSC efficiency together because of separate product designs. The consequences are suffered at company level anyway. To defend the lack of commonality, it should be mentioned that different types of network and slightly different types of purpose make it difficult to implement commonality in core functional modules.

To improve commonality in this product range, the first step is to implement it with cheaper secondary units that are mechanics, power supplies, and transmission units. The BOM and the commonality matrix are presented in appendix 9. The base station cabinet with related modules, power supplies, and transmission units is used commonly in case B2. Thanks to improvement actions, the total number of physical modules is now improved as follows:

Number of different physical modules = 46

The number of different physical modules reduces concurrently with the commonality because module variants are calculated now as a total number. Table 10 describes the dependency matrix for case B2.

Table 10. Dependency matrix of case B2.

Module types	**Variable functions**			
	Frequency	Power	Transmission	
Cab.Core & outd.kit & base mod. & feeder kit				0
Combiner	1			1
Multicoupler	1			1
Tranceiver	1			1
Base band module				0
Duplexer	1			1
Rectlifier Unit		1		1
Battery Backup		1		1
Connection Unit A		1		1
Cabinet control module		1		1
Power Supply		1		1
Transmissions			1	1
Cabinet Heater & bridge & filter kit				0
AC Filter		1		1
			Dependecy points:	**11**
Number of variable functions	**3**			

Function-module dependencies are reduced so that new frequency variants of family Y do not require another set of mechanical modules as in case B1 (e.g. frequency vs. rectifier and battery backup). The index value is as follows:

Dependency index = 11 / 3 = 3.67

Module variants are reduced in places that cover ten different frequency variants. Even first-step commonality improvements offer a significant improvement to the index value:

Commonality index = 25.66 / 15 = 1.71

In practice, these changes are not a question of technical possibilities, merely a question of mindset change and operational issues. Metric values for case B2 are:

Case B2 values:
Number of physical modules = 46
Dependency index = 3.67
Commonality index = 1.71

The next step in commonality improvement is to partially develop common core modules between the product families. This is done in case B3, which is a continuation from B2. The BOM and the commonality matrix are listed in appendix 10. Combiner modules are improved to be partially common with families X and Y. A new 800 MHz frequency band is combined with the existing 900 MHz band and two new band variants (380 & 430) are implemented in one physical module. Small changes are also made in relation to multicouplers, transceivers, and duplexers. The new value for the number of modules is as follows:

Number of different physical modules = 29

The dependency index remains the same because function-module relationships are the same. E.g. the frequency band affects the transceiver module regardless of whether there are two or five physical variants of that module type.

The commonality index is improved because less combiner, multicoupler, transceiver, and duplexer modules are required to cover the market needs of both product families. As seen in appendix 10, the commonality index value is as follows:

Commonality index = 27.33 / 15 = 1.82

These changes also challenge technological thinking because two different network types require slightly different transmit power from the transceiver module. It may mean that more components need to be duplicated when a direct cost increase would be more than in the modifications made for modules inside the same standard. Metric values for case B3 are:

Case B3 values:
Number of physical modules = 29
Dependency index = 3.67
Commonality index = 1.82

Now metric values are much better, for variable frequency related units are developed as partly common modules.

For the last case, B4, transceiver and duplexer units are developed to be full common, and other modules remain as in case B3. This design change is a kind of ultimate goal and it is technically more challenging than the changes in the earlier cases. The corresponding BOM and the commonality matrix are presented in appendix 11. Calculated from that, the number of modules is as follows:

Number of different physical modules = 23

The reduction comes from functional combination of frequency variants in transceiver and duplexer modules. Naturally, this affects function-module relationships, which is seen in the dependency matrix, illustrated in table 11.

Table 11. The dependency matrix of case B4.

Module types	**Variable functions**			
	Frequency	Power	Transmission	
Cab.Core & outd.kit & base mod. & feeder kit				0
Combiner	1			1
Multicoupler	1			1
Tranceiver				0
Base band module				0
Duplexer				0
Rectlifier Unit		1		1
Battery Backup		1		1
Connection Unit A		1		1
Cabinet control module		1		1
Power Supply		1		1
Transmissions			1	1
Cabinet Heater & bridge & filter kit				0
AC Filter		1		1
			Dependecy points:	9
Number of variable functions	3			

Because transceiver and duplexer module types do not have a relation to frequency band, the dependency index is as follows:

Dependency index = 9 / 3 = 3.00

The change also means that all the transceiver and duplexer modules are shared between the two product families, which gives a better commonality index value.

Commonality index = 24.67 / 13 = 1.90

The number of module types is now 13 instead of 15 in cases B1-B3. The reason is that transceiver and duplexer modules included separate common part and additional variable parts.

Because physical variations are not used any more, common parts are not needed separately. Therefore, case B4 metrics are:

Case B4 values:
Number of physical modules = 23
Dependency index = 3.00
Commonality index = 1.90

This change has a considerable impact on all the metrics. These metric values are near the best case of set A (case A6), which means that when commonality is good, additional products do not necessarily increase complexity.

All the metrics work in a quantification of design principles because they offer comparable power. They can potentially reduce demand-supply chain inventory and operating costs without reducing the number of end-product variants offered to the markets. All parameters used in the metric formulae are well known already in the product concept design phase. At least adequate assumptions can be set. Therefore, metrics can be used for design option comparison purposes before making final decisions.

PART IV

The purpose of part IV is to develop utility for the product structure metrics through capturing their relationship to DSC efficiency. Evidence is built up on simulations and is supported by partial real data validation. Eleven product structure cases are simulated in terms of operating cost and inventory value, and three real products are studied in terms of actual manufacturing and order handling process efficiency.

7 SIMULATED IMPLICATIONS ON DSC EFFICIENCY

The research question Q2 asks what is the effect of changing a product structure on demand-supply chain efficiency. To get rational evidence for answering the question, eleven case products are simulated in terms of inventory value and operating cost. Two simulation models were developed, one to measure dependent variable V1 (inventory value) and another to measure dependent variable V2 (operating costs). The inventory value simulation model is based on the real business process of the case company. Rules and capacity limitations were captured from real life. Hence, model reliability compared to empirical data is high. The operating cost simulation is built up by applying activity-based costing. Again, real business processes with actual volume and cost data from the case company are used as a basis. Both models are described in more detail later in this chapter. Eleven case products are used as input to the simulations.

7.1 Simulation Design

The purpose of the simulations is to point out utility for the metrics through finding relationships between the product structure metrics and the dependent variables. The original product structure of the example product of the case company represents the baseline DSC efficiency. The other ten products potentially represent better DSC efficiency. The simulation environment, the process model, and the demand model are kept fixed all the time. Simulations are done separately for each product. Results are then compared as an efficiency improvement percentage of the original product structure.

It is studied whether product structure metrics have a relationship to the dependent variables. The eleven case products offer comparative data to analyse product structures' effect on DSC efficiency. The set-up used is described in figure 25.

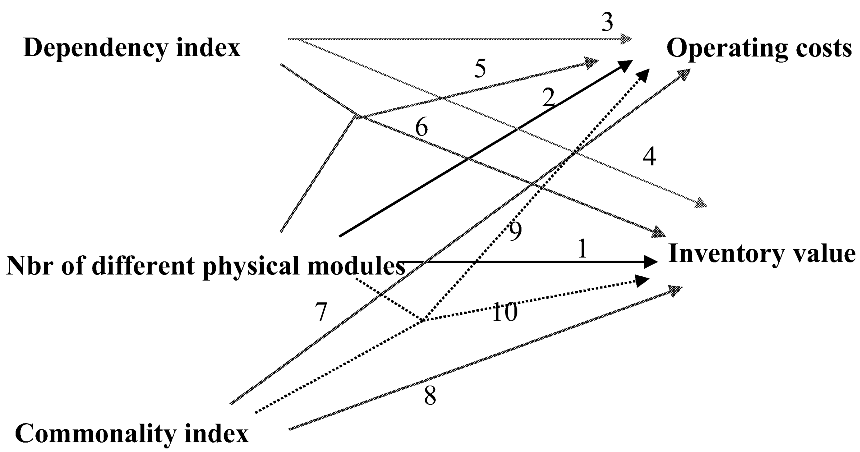

Figure 25. Relationships studied in the simulation.

Ten relationships are studied as illustrated in figure 25. The number "1" describes the relationship between the metric value "no. of physical modules" and V2. The number "2" describes the relationship to the inventory value. Corresponding relationships 3 and 4 are studied for the metric "dependency index", and relationships 7 and 8 for the commonality index. Joined effects of the number of physical modules and the dependency index are studied in relationships 5 and 6, marked with a red line in the figure. Joined effects of the number of physical modules and the commonality index are marked with the numbers 9 and 10. Joined effects of the metrics dependency index and commonality index are not studied because there was no such feasible redesign option available.

Anyway, the eleven case products are very representative because there is clear variation in all the product structure metric values between the cases.

Generally, the demand-supply chain is composed of downstream processes (from manufacturer to customers) and upstream processes (from suppliers to manufacturer). Because variability of the product structure mainly influences downstream processes, it is set a limitation in this study. This corresponds to the limitation in the product structures, for complexity of the product structure from modules to final products has to be managed in downstream processes, between the module manufacturers and the final customers. Potential efficiency effects of different process structures are excluded from this study.

7.2 Inventory value simulation model

The inventory simulation process model consists of factory operations and distribution center (DC) operations. Customer orders are shipped from the distribution center to the customer's delivery drop-off point, from where they are taken to the installation process. Factory operations fulfil replenishment orders daily to the DC. Supplier operations are excluded, as well as processes in the customer interface. Continuous collaboration is assumed to work so that components are always available. Therefore, materials resource planning (MRP) is not used. Delivery problems in the model are possible, for high demand peaks and capacity constraints can cause stock-outs according to the model rules.

Real operating rules and capacity limitations were captured in the process model. For the parameters that were not available in an explicit form, the experts were interviewed to get the most useful approximation that corresponds to real life operation and people behaviour in the process.

Figure 26 shows the elements included in the simulated process model.

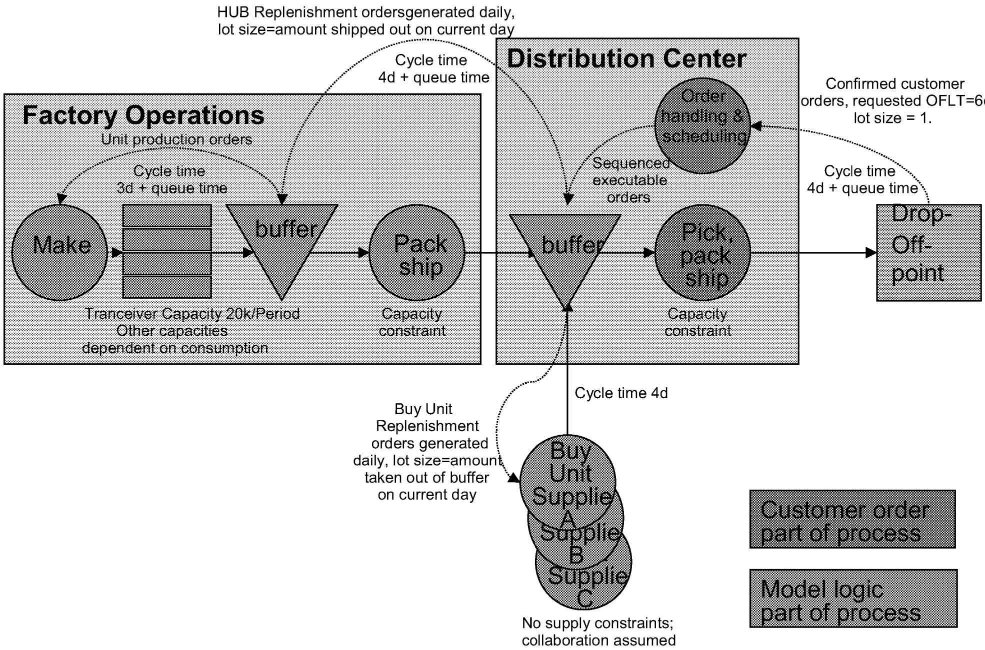

Figure 26. The order fulfilment processes in the simulation model.

In reality, factory operations are located in Finland, mainly in the Oulu area. The DC operations are located in Tillburg, Netherlands. The idea is that the distribution center's picking, packing, and shipping responds directly to customer orders by sending the requested product configuration to the drop-off point as quickly as possible. The required order fulfilment lead-time is 6 days, which means time from order triggering to receipt at the drop-off point (DOP) of the customer's network building project. Six days consists of a 4-day cycle time plus queue time, depending on actual demand and the location of the DOP. If the demand exceeds strongly the average demand for a long time period, delivery delay may occur. Shipping in the DC has a capacity constraint that is dimensioned according to monthly demand and manufacturing capacity. Capacity of tranceiver modules was used in dimensioning (20 000 pcs/month).

The factory side is systematically driven by inventory replenishment rules. Modules are divided into "make" or "buy" modules. Four module types, transceivers, base band modules, base modules, and combiners, are make units in own manufacturing. Replenishment orders are sent daily to the factory according to the amount shipped out on the actual day. The cycle time of 4 days corresponds to the average order-delivery cycle time from the Oulu area to the Tillburg DC. The factory module buffer is fulfilled according to usage. The module manufacturing cycle time of 3 days also corresponds to average values in practice.

Manufacturing of buy modules is outsourced to suppliers. The module suppliers deliver their modules to the DC using the pull principle. Buy module replenishment orders are placed daily from the DC according to the amount shipped out on the actual day. A standard cycle-time of 4 days is defined for this process based on expert interviews. It is a practical average for these types of buy modules used in the example product.

The capacity in the factory's packing and shipping process is balanced with the factory's make process. The DC's picking, packing, and shipping process has 30% flexibility in its capacity. The flexibility is needed, because otherwise it would be impossible to fulfil all orders on time. From an inventory point of view this means that during peak loads the DC's process is able to consume the inventory faster than the factory is able to fulfil it. The customer demand in the model was adjusted according to the production capacity of the model. This is a typical property in all successful supply chain simulation projects. The average volume of simulated customer orders was almost the same as the production capacity of the factory. This means that the capacity of the simulation model was quite highly utilised.

The demand data consists of individual order lines that enter the model during the simulations. The demand data was self-generated using random factors to a certain extent. Namely, flexibility limits were specified for confirmed customer orders according to the real environment. The flexibility limits are the following:

- Maximum volume of confirmed orders ***per day*** is 1.5 x daily capacity (+50% flexibility)

- Maximum volume of confirmed order ***per week*** is 1.3 x weekly capacity (+30% flexibility)

Demand data, i.e. the set of orders used in the simulations, was created by generating the type of orders and the weekly and daily volumes separately. The length of the simulations was chosen to be 20 weeks. This is long enough to reveal the effects of demand fluctuations and other dynamics, but short enough to keep the simulations reasonably short.

The product configuration (=order type) was generated using the three following functional parameters:

1= Frequency band	Demand mix	**2= Transm.**	Demand mix	**3= Power supply**	Demand mix
A=1800 full	20%	A=E1	20%	A=AC	50%
B=1800 A	20%	B=E1/T1	30%	B=DC	50%
C=1800 B	20%	C=E1-B	20%		
D=1900 full	10%	D=RRI	10%		
E=900 stand.	10%	E=STM-1	10%		
F=900 H	10%	F=FC E1/T1	10%		
G=900 J	10%				

Frequency band includes seven options used for different countries and customers. Transmission type includes six options, the first three for copper networks in the US and Europe, option D for wireless transmission, and options E and F for optical transmission. Power supplies include typical alternating and direct current options. Each of the three properties is generated independently using random factors, and this guarantees that the demand really complies with the distributions.

The volume fluctuation was performed in two steps: first, the weekly volume was generated, and then the weekly volumes were split to days within the weeks. The steps in volume generation were the following:

- The weekly volume was generated using an even distribution between 153 and 542 customer orders per week. The upper limit of 543 orders per week represents the 30% flexibility at weekly level. The lower limit was chosen so that the average capacity utilisation remains reasonably high (>80%).

- The randomly generated weekly volumes were manually sorted so that for every 4-week period, demand volume is the same or smaller than the production capacity of that period.

- For each week, the volume was randomly allocated to the 5 working days using an even distribution. This means that for each order, the probability is the same to become situated on any working day. However, the randomness causes daily volume fluctuations.

Figure 27 shows a diagram of the volumes of an example demand set that was generated as described earlier.

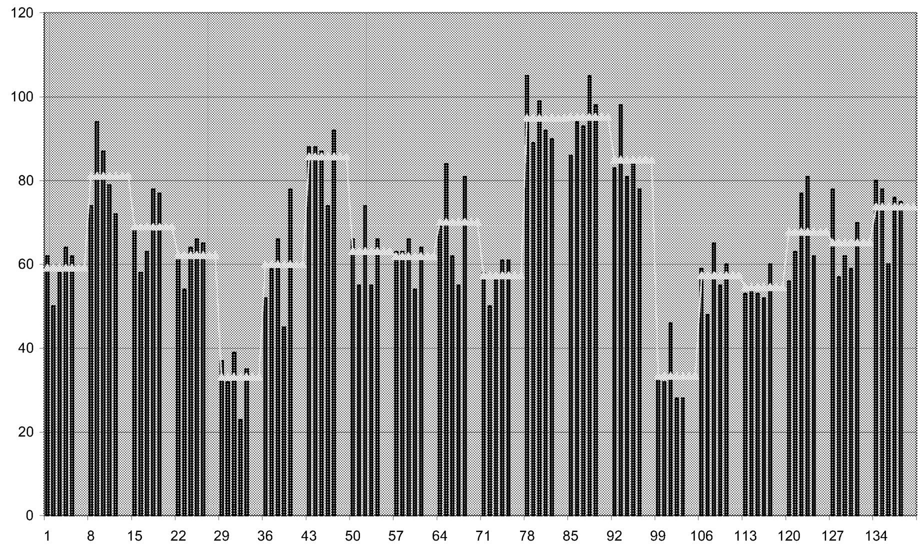

Figure 27. Demand pattern used in the simulation model.

The columns indicate the daily volumes and the line with markers shows the 5-day average of each week. The vertical scale is the number of customer orders.

During the simulations, DC's module buffer's unitary levels were calculated every hour, from which the average module inventory level was used. Following logic was applied in calculating unitary inventory level and the respective inventory value:

- Starting inventory level [Inventory (max1)] of each module was set so high that stockouts will not occur.
- By running the simulation (generated demand file), inventory level range for each unit was monitored and calculated. The range means the difference between the starting inventory level and the minimum inventory level during the simulation. This range is refered as [Inventory (max1)-Inventory (min1)].
- Then the lowest possible starting inventory level [Inventory (max2)] was found for each module (so that there are just enough modules in the buffer throughout the simulation). Because the service level and the inventory size are typical trade-off variables, it was decided to keep the service level constant during all the simulation rounds. The target On-Time-Delivery (OTD) of the simulations was set to 98%, which corresponds to an acceptable level in the business area the products represent. The higher OTD percentage would increase inventory values exponentially while offering only an incremental improvement at service level. Therefore,

  Inventory (max2) = 0.98 * [Inventory (max1)-Inventory (min1)]

  Inventory (max2) was found by iterations so that the OTD requirement of 98% is fulfilled. Simulations were run and the effect of modules' stock-outs on OTD was monitored. Test runs were repeated until a "minimum" required level was found for all the modules in all eleven cases in order to just reach the OTD of 98%. Because product functionalities in different product structures were implemented differently, each of eleven cases led to unique values of Inventory (max2).

- In final simulation cases, Inventory (max2) for each module was used as a starting point. Hence, actual unit inventory level was calculated every hour. For the first hour, it is calculated as follows:

  Inventory (actual) = Inventory (max2) – (modules shipped out during the hour + received replenishment modules during the hour).

  This result was then used to calculate the next Inventory (actual) and so on, until 20 days was run. Because of differencies in product structures, inventory (actual) values for each module type were unique in each simulation case. E.g. modules with higher commonality are used more requlary which lead to lower inventory (actual) values.

- Finally, average inventory level was calculated based on Inventory (actual) levels over 20 days. To get inventory value, the average inventory level was multiplied by the direct material cost of each module.

7.3 Activity Based Costing simulation model

The purpose of the Activity Based Costing (ABC) simulation model is to predict future costs of demand-supply chain process activities caused by the product structure. Process costs are estimated for the five-year delivery life cycle of the products. The basic idea is the same as in the inventory simulation, to compare alternative product structure scenarios. The scope of the model includes activities needed to run DSC operations in the European business region of the case company.

The demand-supply chain processes include configure & price & quote, order handling, manufacturing, purchasing, distribution, and demand-supply planning processes. These processes and their activities are illustrated in the process diagram in figure 28.

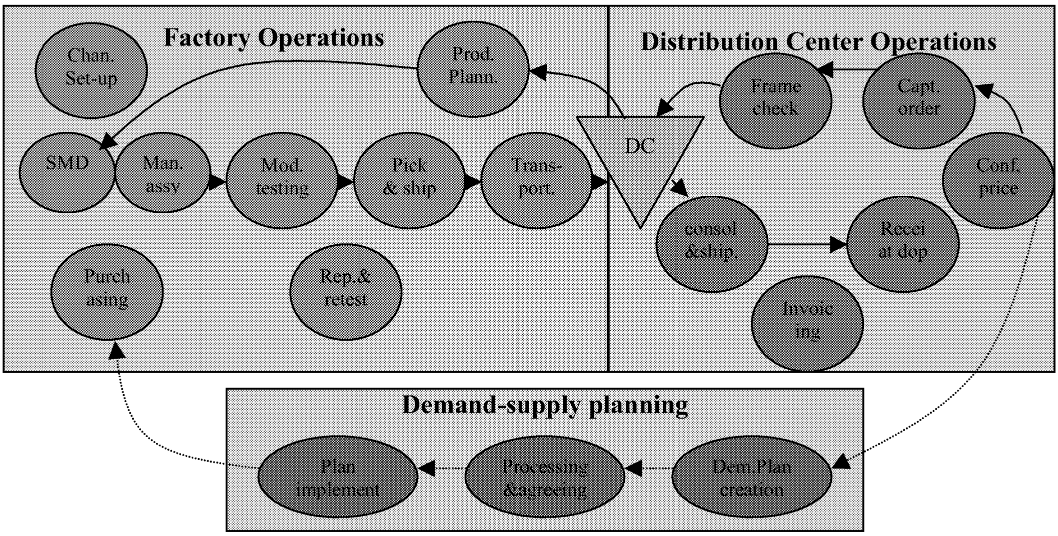

Figure 28. Demand-supply chain activities included in the simulation model.

Activities that operate at module or product level are taken into account. Going into more detail would not increase the accuracy to overcome additional complexity. Defined activities determine the processes closely enough to real life system behaviour. This solution ensures that the level of aggregation is consistent with the product structures and inventory value simulation model. The ABC model consists of following processes, which include the activities listed in table 12:

Table 12. Activities classified into the five processes and their activity drivers and cost driver formulae.

PROCESSES & ACTIVITIES	ACTIVITY DRIVER	COST DRIVER FORMULA
Configure & Price & Quote	# of reservation/order lines	Volume/lotsize x # of different sales items
Customer Order Management		
Internal & external invoicing	# of order lines	sales item volume/lotsize x # of different types of sales items
Capture customer order & confirmation	# of order lines	sales item volume/lotsize x # of different types of sales items
Frame Check	# of order lines	sales item volume/lotsize x # of different sales items
Manufacturing		
Purchasing & Vendor management	# of order lines	# of diff. components x comp. cycle speed + # of BUY units X 365
Production planning	# of manufacturing order lines	sales item volume/ production lotsize x # of MAKE units
Machine assembly	# of components	sales item volume x average number of components per module
Changing setups	# of manufacturing lots	sales item volume/ production lotsize x # of MAKE units
Manual assembly	# of work hour	# of work hours per product x sales volume
Module testing	# of machine hours	# of machine hours per product x sales volume
Retesting & repairing	yield %	(1-yeild) x 3 x (assy+test cost)
Distribution		
Picking & packing & shipping in plant	# of order lines	volume/lotsize x nbr of different sales items
Transportation, Air	volume (m3)	volume x product volume
Delivery consolid. & Shipping from the HUB	# of order lines	sales item volume/lotsize x # of different types of sales items
Receiving at DOP or site	# of order lines	sales item volume/lotsize x # of different types of sales items
D/S Planning		
Demand plan creation and handling	# of different planning items	# of planning items x nbr of handling times
Processing information & agreeing plan	# of manufacturing items	# of different sales items x nbr of handling times
Decisions & supply plan implementation	# of different planning items	# of different planning items x nbr of handling times

Every activity has an activity driver that defines the principal factor, which describes resource usage in a certain process activity, and a cost driver formula that defines the final relationship between the product structure and the resource usage. The following phases were used to develop the ABC simulation model:

- A cross-functional group of experienced people was collected, representing the needed stakeholders as process experts from each process included, the financial department, and the IT department, to get access to the legacy systems.

- Existing process descriptions were analysed and the first activity grouping was done. In official process models there were roughly one hundred activities, which is too much for this kind of simulation model. The target was to combine such activities that may have the same activity driver and the same organisations doing those activities. This was done in a one-day cross-functional workshop.

- Another one-day workshop was held to continue the activity, combining and finding out such activity drivers that 1) describe well enough the workload of each activity, and 2) have historical data available in legacy systems to get the amount of transactions to calculate activity unit cost. Activity driver selection requires some assumptions to be made, for none of the activity drivers is perfectly correct. It has to be assumed that resources are consumed linearly along the driver quantity increases. To get good enough accuracy in selecting activity drivers, two drivers with most potential were selected. The aim was to base assumptions in the selection process as much as possible on empirical experiences of the team members. Two options were tested and the better one was selected according to team members' empirical understanding.

- Activity grouping and activity driver selections were finalised in the third workshop. Calculative cost drivers were also defined together with the cross-functional team. This was very much an iterative process taking four weeks. The target was that the cost driver behaves close to the way that costs behave in real life. The same method was used to define cost driver formulae, parameters that link product structure to process costs. The principle in assessing parameters was that they are both based on an expert's opinions in the workshop and the direct experiences of the team members. Some interviews were also used to validate assumptions. This enabled most exceptional solution ideas to be filtered out. The most sensitive parameters in the model are the number of module types, the number of module variants (corresponds to sales items), the customer order lot size, and the volume.

- After cost driver definitions were made, organisation charts were analysed and activities were connected to organisations. Then questionnaires were developed to ask what percentage of working time people normally use for each activity. Questionnaires were sent to experienced representatives of each organisation.

- Total costs of the corresponding organisations were captured from legacy systems as well. Costs of supporting functions were first allocated to the main activities according to cost share from the total cost of the organisation. Then appropriate parts of each organisation's costs were collected for the defined activities. The amount of activities was also collected from legacy systems. The data came from the first quarter of the year 2000. It is assumed that three months is long enough to describe average operations. From that data, activity unit costs were calculated. Results were used to build up the first draft of the simulation model in Microsoft Excel.

- Dimensional consistency of the model was checked. It means that each variable has the units of measure in place, every parameter is in place in the calculation formulae, and there are no arbitrary scaling factors that have no real world meaning. All the costs are in euros.

- A structural assessment test was done in order to check that the overall structure of the model is consistent with the understanding of real life processes. A group of process experts was collected from the headquarters' process development unit, who checked the model and accepted it as accurate enough for the purposes it was developed.

- A numerical sensitivity analysis was also carried out for the whole model. An example product was taken and parameters were typed in. After the basic scenario, the worst case and the best case were created and calculated. This test pointed out that relatively big change in input parameters led to increased inaccuracy in the results. The most sensible input parameters are: number of different sales items and customer order lot size; both relate to the product structure.

Table 13 presents input parameters that are used in cost driver formulae that in turn give costs of an activity by multiplying this result by an activity unit cost. Parameters not painted remained fixed in these simulations. The table here presents the parameters of scenario A1.

Table 13. Input parameters for calculative cost drivers.

Parameters per year	Year 1	Year 2	Year 3	Year 4	Year 5
Product sales volume (pcs.)	1667	1667	1667	1667	1667
Total nbr of different sales items (pcs.)	41	41	41	41	41
Nbr of different types of sales items (pcs.)	18	18	18	18	18
sales item volume (pcs.)	113356	113356	113356	113356	113356
Customer order lotsize (pcs.)	68	68	68	68	68
Production lotsize (pcs.)	20	20	20	20	20
# of different planning items	6	6	6	6	6
# of different BUY units	29	29	29	29	29
# of different MAKE units	12	12	12	12	12
# of different components in MAKE units	2500	2500	2500	2500	2500
Average # of components in MAKE units	2000	2000	2000	2000	2000
Production yield for MAKE units (%)	75%	75%	75%	75%	75%
# of manual assebly hours per product	4	4	4	4	4
# of testing hours per product	6	6	6	6	6
Product volume (m3)	1.6	1.6	1.6	1.6	1.6
# of D/S Planning times per year	48	48	48	48	48

Let's have an example of an activity "order confirmation". The cost driver formula of this activity is "sales items volume/ lot size x number of different types of sales items" as presented in table 12. The first term defines the number of orders and the second term the number of order lines in the one order, when the total number of order lines comes out. Parameter "sales item volume" is calculated from the BOM by summing up the quantity of each module for one configuration. This is 68 modules x product sales volume (base stations), which is 68 x 1667 = 113356 modules per year. Parameter "lot size" means customer order lot size (quantity of all modules in the order) in distribution center operations. This parameter depends on the product structure, it is a quantity of modules required for one product configuration. The "lot size" parameter is 68 in these cases, which means that every product required in the network building project is ordered separately for its installation site. This is the consistent logic with the inventory simulation model. "Number of different types of sales items" is 18, which means that one product includes 18 different types of modules that are selected from 41 different modules in the configuring phase (=value of the metric "number of physical modules"). Therefore, the driver quantity for this activity is 113 356 / 68 x 18 = 30 006 transactions. If the activity unit cost was 5 euros, the total cost of this activity in year 1 is 30 006 x 5 euros = 150 030 euros.

7.4 Simulation method

There were two simulation rounds. The first was to study the relationship between the two first metrics, number of physical modules and dependency index. Product structure cases A1-A7 were simulated by the inventory simulation model described earlier. Same cases were then simulated by the ABC simulation model as it was described earlier. Required input parameters for cost driver formulae come from the product structure cases: the number of different types of sales items, total number of different sales items, customer order lot size, and sales item volume. The rest of the model parameters were constants. Because every case was different, this led to unique inventory levels in the inventory model and unique activity costs in the ABC model.

The purpose of the second simulation rounds was to study effects of the commonality index through product structure cases B1-B4. Simulations were done so that another product family with the same volume was added to the demand model, and the process model in the inventory simulation was balanced with the new demand so that the results are comparable. The total demand and capacity of activities are the same, for it was equally divided for both product families.

8 EMPIRICAL VALIDATION

Three real products are taken under the study by calculating product structure metric values and then following their process performance in manufacturing, distribution, and order handling.

8.1 Scope

The purpose of empirical validation is to complement the data used in the simulation models because the simulation models already include data from real operations. Therefore, the scope of pure empirical data can be limited to the most important and informative parts. The most questionable thing is accuracy of the operating cost simulation model. Using the ABC method for product structure simulations is a novel idea. The critical thing is how well the selected cost drivers describe the resource usage caused by the products.

Inventory cost plays an important role in total process costs, but it was impossible to get real inventory data because business environments were not comparable. Internally, demand-supply chain operating models, legacy systems, and DC locations were under a change process for new products. Externally, demand for new products has not ramped-up as forecasted because of telecom operators' economic slowdown. The customers are not sure whether to invest in new technology and in which one. Therefore, empirical validation is focused on feasible parts of operating costs only.

Because there is no ABC system in use, empirical metrics can not be very exact. Traditionally, product cost is formed as a sum of material cost, direct labor, and overhead. Overhead costs can not be fairly allocated for different products. Hence, process performance metrics include both indirect and exact metrics.

8.2 Operating Cost Metrics

The operating cost simulation model includes five activity categories: configure & price & quote, order handling, manufacturing, distribution, and demand-supply planning activities. In a total cost sense, configure & price & quote and manufacturing activities are the biggest and equal in magnitude. Order handling and distribution are considerably lower but meaningful activities. Demand-supply planning activities represent only minor costs and are not so interesting in the empirical validation. Therefore this is left out from the scope of the empirical part.

Configuring & pricing & quoting activities are very decentralized in the case company and there are no good ways to capture data from these activities. There are also various country-specific ways to do these activities, which would lead to non-coherent and speculative results whatever the data collection method. Options would be to organize interviews in numerous places or to send questionnaires. The problems in the first one are unwillingness of the salesmen to participate in such research, inaccuracy of the data because of a country-specific nature, cost, and time, whereas questionnaires are very challenging to get filled in by busy business people in the customer interface. Therefore, configure & price & quote activities are left out from the empirical validation.

Manufacturing activities can be better followed, because factories have quite sophisticated information systems to control and steer direct labor costs associated with the products. Because a lot of data about process efficiency of the factories is available, this data can be used.

Order handling and distribution represent much lower relative operational costs than the manufacturing process. Because of limited data availability, only factory parts of the order handling and distribution processes can be considered. As a result, selected manufacturing processes and the factory part of distribution and order handling processes represent roughly 50% of the total operating costs in the simulation model, which provides enough confidence in how product structure affects operating costs.

Selected processes do not have ready efficiency metrics to enable the comparison of efficiency from a product perspective. There are plenty of metrics used in the case company to measure and follow manufacturing and distribution processes but they are more process phase oriented than product oriented. Hence, it is necessary to specify appropriate metrics from the data available. For manufacturing and distribution processes, combined direct labor cost metrics can be formulated. For order handling, it is necessary to use indirect efficiency metrics. The metrics and their taxonomy are presented in table 14.

Table 14. Empirical operating cost metrics and expected relationship to the product structure metrics.

MEASURED PROCESSES	**OPERATING COST METRICS**	**IMPACTING PRODUCT STRUCTURE METRICS**
Manufacturing and distribution processes	Manufacturing labor cost	Number of different modules Commonality index
Order handling process	Percentage of changed orders	Number of different modules Dependency index

Manufacturing labor cost describes efficiency because it measures resource usage for certain manufacturing output. Manufacturing labor cost is calculated in the following way:

Manufacturing labor cost = (Work time X Cost of man hour) / Number of subscribers

Measured work time is manually measured standard work time in manufacturing and distribution for a certain product with a certain configuration. The cost of a man hour is calculated using paid salaries divided by used man hours for the certain product. To allow fair comparison between case products, the labor cost figure is normalized per subscriber, which describes a comparable capacity unit in all the case products. Hence, bigger product configurations will not suffer from bigger workload.

Product structure potentially affects manufacturing efficiency in two ways: first, it defines how many batch level tasks are needed in all the process phases. Fewer different items in manufacturing enables more repeat times per one item when work time per output naturally reduces, i.e. the share of non-value added work versus value added work improves. Second, it drives a learning curve effect in all the tasks.

The scope of manufacturing labor cost includes activities from the beginning of the production line (starting from paste printing) to the delivery creation (ending with truck loading). Direct value added work and related control activities like set-up times are included in man hour figures. Support and management functions of the factory, as well as global operations, are not included in this metric. Included process phases are: SMD, submodule testing, depaneling, screwing, work a robot, hand assembly, module testing, base station integration and testing, packaging, and shipping.

It is expected that the product structure metrics *number of different physical modules* and *commonality index* describe the manufacturing labor cost. The first one defines the number of different modules in the manufacturing process, except for some submodule tasks that are done at the beginning of the manufacturing. The second one affects how many different items are manufactured at company level. Inaccuracy here comes from the outsourced "buy" modules that are not seen in the factory under the study. Buy modules come into the process in the base station integration phase, whereas earlier activities cover only "make" modules.

Measuring the efficiency of the order handling process is more complicated than in the case of the manufacturing process. Because there is no product-specific worktime or cost follow-up for order handling activities, labor cost metrics cannot be used in that case. Therefore, order changes are used to evaluate process efficiency indirectly.

Changes in customer orders are common in the cellular network industry. How much these changes are reflected in the physical configuration of modules, depends on the functional flexibility of the product structure, which can be measured by the dependency index.

The percentage of changed orders per product reflects the efficiency of the order handling process in two ways: first, order mistakes require changes afterwards. The number of mistakes depends on how many selections are needed when configuring the product. Also, if selections and options are the same as in the other products, it is potentially more evident to make the right order first time. The number of different modules describes that phenomenon. Second, changes in physical configuration after the original order has been placed. The more dependent are the functions on the physical modules, the more functional changes reflect orders in the factory, which require the reorganization of many activities. This phenomenon can be roughly measured by the dependency index. The metric is calculated in the following way:

Percentage of changed orders = (Number of changed orders/Total number of orders X 100)

The number of changed orders includes only changes in the product configuration. The number of modules is changed, or the type of modules is changed, or modules are either removed or added.

The changes in order header information, such as customer name, delivery address or delivery date, are filtered out.

The major drawback of this efficiency measure is inaccuracy caused by equally valued order changes. In practice there are smaller and bigger order changes that affect rework time differently. Because it can be assumed that all the case products involve both smaller and bigger changes, the measure is good enough for comparison purposes.

8.3 Case Products

Three base station products that have a comparable process model are selected. The first product, A, is a high volume base station product currently in the ramp-down phase. No DSC design principles were used when this product was originally developed. The second product, referred to as B, is the follower of product A, where new design principles were partially applied but which is still far from an ideal product in that sense. The third product, C, has the same functions as products A and B, but is designed for smaller installations. This product has been designed at the same time as product B and therefore design principles have been somehow considered but not from the beginning of the project.

The basic functions in all the products are the same and the functional modules correspond to the modules presented in the simulation case. Only basic full size base station cabinets are studied here because there is better data available since the basic base station is the most often delivered entity. Site support cabinets that include battery back-up and possible cross-connection panels etc. are excluded. They are additional stuff that are rarely delivered. Also antennas, radios, and locally managed installation materials are excluded because the demand-supply chain processes of those auxiliary items vary depending on the product and the country of the customer. Products compared here differ from each other in physical implementation of base station functions, function-module dependency, and module commonality. Therefore, each product will have unique product structure metric values that describe demand-supply chain efficiency of the product structure.

Product A is commonly held to be quite a complex product among the experts in the case company. A large number of different modules direct the same message. Its module types and number of physical variants are: Cabinets 4, Antenna filters 13, Transceivers 2, Combiners 6, Multicouplers 4, Transmit boosters 2, Transmissions 4, Heat controls 8, Plinths & roofs 4, Power supplies 4, Cable sets 23, and other mechanical modules/items 41.

There are 6 variable functions in product A: Cabinet application, Frequency band, Power feed, Combining, Filter type, and Transmission type. It includes 43 modules types, each designed for this product only.

Product B makes some steps forward in improving the physical product structure. It has the following module types and number of variants: Cabinets 1, Duplexer filters 7, Transceivers 4, Combiners 7, Multicouplers 4, Transmissions 4, Heat controls 2, Power supplies 2, and other mechanics 15. Variable functions include: Cabinet application, Frequency band, Power feed, Combining, and Transmission type.

The third product, C, has the following physical module types and number of variants: Cabinets 1, Transceivers 5, Transmission 5, Power supplies 4, and other mechanics 6. This also has 5 variable functions but they differ a little from other case products: Cabinet application, Frequency band, Power feed, Filter type, and Transmission type. Smaller configurations done by this product require fewer module types in the product structure. Therefore, the metrics values for the case products are presented in table 15:

Table 15. Product structure metric values for the case products.

	PRODUCT A	PRODUCT B	PRODUCT C
Number of different modules	115	49	21
Dependency index	6.8	4.0	0.8
Commonality index	1.0	1.26	1.16

In product A, the large number of different physical modules is not the only bad thing. Variable functions are also quite much coupled with the physical modules. Especially different cabinet applications have a lot of dependencies with mechanical items and cables. Because product A has long been the only product of that type, there are no commonalities with other product families. According to the product structure metric values, product A represents a product that should not be demand-supply chain efficient.

In product B, the number of different physical modules is reduced by more than half. The dependency index and commonality index are improved. The major reasons behind the improvements are: 1) mechanical structures are simplified and cables are integrated into functional modules, 2) more functions are integrated into fewer modules, 3) some frequency bands are combined into one physical module, and 4) some modules are shared with the new generation products. It is expected that product B would have better demand-supply chain performance that product A.

In product C, the dependency index is now even below one, which means that there are some functions changeable without affecting any physical modules. The main reasons for the improved value are: 1) A standard cabinet that works inside and outside, no other sizes offered; 2) frequency-related modules integrated into one module. For better commonality, transmission modules are shared with product B.

All three case products have the same kind of process models in the phases that are under study, even if the whole DSC design may differ. Product A most clearly utilizes the DC mode of operation. Product B is new and volume ramp-up is ongoing. Because of internal process development actions and low volumes so far, the process model has been mainly direct delivery from factories without DC buffers. Product C is also new but it uses the same DC process model as the product A.

Manufacturing of some modules is outsourced and the suppliers deliver replenishment orders daily to the DC using the pull principle. The outsourcing level is the same across the products and they cover the same module types. Inhouse manufactured modules also use the pull principle with daily replenishments. After all, the process model corresponds to the simulation models presented earlier.

8.4 Data Collection

The target in data collection is to capture comparable process performance data for the three products. Anyhow, different life cycle phases make data capturing challenging because demand is usually unstable during ramp-down and ramp-up phases, which end up with varying cost structures for the products. Absolute volume figures also affect data comparability. On the other hand, internal process development projects disturb comparison of data. The overall status of life-cycle phases of the case products is illustrated in figure 29 below.

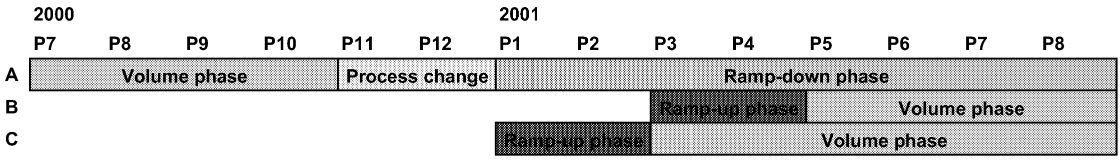

Figure 29. Life cycle phases of the case products.

Product A is under the ramp-down process during the first half of the year 2001. The manufacturing process of that product faced considerable changes from period 11 onwards. Between period 7 and period 10 in the year 2000, delivery volumes have been stable and process structure fixed. Therefore, manufacturing labor cost and percentage of order changes are collected between those periods. Four months (periods) is estimated to be enough for comparison purposes. It reveals normal trends even if there are some peak values.

For products B and C, data collection is started from the beginning of the volume phase. Product B is in the ramp-up phase during months three and four. Volume phase data can be collected from period five to period eight. During that time the manufacturing and order handling processes correspond to the processes of product A. Product C has passed its ramp-up phase by the end of period two. Normal volume phase data can be collected between periods three and six. Monthly volumes are only 1/7 of the volumes of the other products.

Data for manufacturing labor cost, paid salaries, and used work time, can be collected monthly from the legacy systems of the case company. Standard work time is a fixed value during the whole data collection period because neither products nor processes changed. It tells how much work time is associated with the certain model configuration for each work phase on average. Products A and B utilize the same size of model configuration. Product C has smaller model configuration. To make these equal, labor cost per configuration is divided by the number of subscribers.

To collect data about the percentage of order changes, transactional databases were used. First, all the customer orders were classified according to what products were ordered. Second, original orders were compared to the final ones in orders to find out whether the orders have been changed or not. This phase was done using a computer because there is a footprint of order changes in the database. Third, orders that include changes in some header information instead of product configuration, were cleaned up. That phase was done manually, because it was too challenging to automate comparison of order contents. Finally, the number of changed orders was divided by the total number of orders to get the percentage of changed orders.

9 RESULTS

9.1 Simulation Results

Product structure metrics' relationships to the dependent variables were simulated with the inventory value and operating cost simulation models. Ten relationships studied are illustrated in figure 25 (chapter 7.1). Simulations included eleven cases, cases A1-A7 to study relationships 1-6 dealing with the metrics dependency index and the number of different physical modules, and cases B1-B4 to study relationships 7-10 dealing with the commonality index. The data from the first simulation round, cases A1-A7 is presented in table 16.

Table 16. Data of the first simulation round.

	Product Structure Metrics			Inventory	Operating cost
Case #	Design changes	# of modules	Dependency	reduction	reduction
VARIABILITY & DEPENDENCY SIMULATION					
Case A1	Basic architecture, current base station	**41**	**3.67**	**0%**	**0%**
Case A2	Mechanical modules integrated to reduce module types.	**36**	**3.67**	**0%**	**7%**
Case A3	Tranceiver, duplexer, combiner half generic	**30**	**3.67**	**-2%**	**12%**
Case A4	Tranceiver & duplexer generic	**31**	**2.33**	**20%**	**19%**
Case A5	Tranceiver, duplexer generic & integrated mechanics	**26**	**2.33**	**20%**	**26%**
Case A6	Tranceiver, dupl., comb., and E1 generic and mechanics integr.	**20**	**2.00**	**22%**	**34%**
Case A7	Basic architecture, mechanics changed.	**37**	**2.33**	**1%**	**8%**

Direct simulation results are presented as an inventory value reduction percentage and operating cost reduction percentage. Values of the number of different physical modules and the dependency index are presented in columns 3 and 4. Case A1 as a reference intuitively represents an average product in the field. Almost all variable functions are physically implemented in separate module variants, which lead to a high number of physical modules (41). Function-module relationships have not been a design target as such, which means quite dependent relationships.

In case A2, the number of different physical modules is improved but the dependency index is the same. It shows that if mechanical modules are integrated in bigger standard combinations, it does not reduce inventory values because the same amount of material is still buffered. Instead, it reduces operating costs by 7% through having fewer items to be handled in processes.

In case A3, inventory costs do not decrease while operating costs do because of fewer different modules. There are two reasons why inventory cost did not reduce. First, direct material cost for the changed modules was hypothetically increased by 15% in the simulation model. In reality this increase could be less or nothing because component duplication is not necessarily needed. Exact information would require very detailed investigation, which was not possible in this study. If the direct material cost had been kept the same, then inventory cost would have been reduced further. Second, originally transceiver, duplexer, and combiner modules have 7 frequency variants plus one generic base band module. Now frequency variants were reduced from 7 to 2 but the separate generic module of each module type was still left as such. Two frequency variants and one generic module remained. Integrating these would have probably reduced both operating costs and inventory costs because of having fewer different modules.

Case A4 includes generic (multiband) transceiver and duplexer modules so that frequency variants do not exist any more in these two module types. The direct material cost was increased by 30% in changed modules. This action improves both metric values. Considerable benefits come from inventory value reduction (20%) and operating costs reduction (19%). The reason for this is that the function-module relationship is closer to the ideal value simultaneously with the reduced number of physical modules. A better dependency index influences flexibility benefits towards demand fluctuations between product configurations. The most significant flexibility benefit comes from independency of frequency band variants in the functional domain.

Case A5 again points out that integrated mechanics does not reduce inventory values even if it reduces operating costs. Demand fluctuations still affect materials, regardless of whether modules are integrated or not. Operating cost cares whether modules are integrated or not.

In case A6, combiner modules were also changed to full generic, and four E1 transmission module variants were implemented in a generic module. According to the same logic as in case A4, now both inventory cost and operating costs are further decreased.

In case A7, function-module dependencies are reduced to 2.33, which makes only a 1% reduction in inventory value but a considerable 8% reduction in operating costs. The reduction in operating costs is achieved because reducing function-module dependencies requires a reduction in the number of different module types. In addition to the number of different physical modules, the number of module types is an important driver in processes like order handling and distribution.

Table 17 presents results from scenarios B1-B4, which were used to validate the commonality index's relationship to the dependent variables.

Table 17. Results data of the second simulation round.

	Product Structure Metrics				Inventories	Operating cost
Case #	**Design changes**	**# of modules**	**Dependency**	**Commonality**	**reduction**	**reduction**
COMMONALITY SIMULATION						
Case B1	Case A2 + 3 new products,	**63**	**7.00**	**1.00**	**0%**	**0%**
	no common modules					
Case B2	Cheap modules common, mech.	**46**	**3.67**	**1.71**	**10%**	**14%**
	part, transm., power etc.					
Case B3	More commonality in tranceiver,	**29**	**3.67**	**1.82**	**15%**	**32%**
	duplexer and combiner					
Case B4	Tranceiver and dupl. full common	**23**	**3.00**	**1.90**	**33%**	**43%**
	and generic					

At the beginning, a new product range including two product families was created. It was assumed that there is a company having just these two product families. The metric values are now measured at product range level instead of single product/product family.

Case B1 was formed by adding another base station product family together with the case A2 product family. As a result there are two product families having the same basic functions but different options and totally different physical implementation options. The results of case B1 are reference values which other cases are compared to.

Case B2 includes a commonality improvement from 1.00 to 1.70. It means that the number of different physical modules is reduced at the product range (company) level. Also the dependency index is improved. These metric values lead to 10% and 14% improvements in inventory and operating costs. Inventory reduction is quite small because the module types in which improvements were made represent a relatively small share of the total direct material cost.

In case B3, commonality of the modules is increased by partially sharing transceiver, duplexer, and combiner module variants with the two product families. Corresponding improvements in the product structure metrics are followed by reduced inventory values and operating costs.

In case B4, commonality is further improved by sharing one full generic transceiver and one generic duplexer with all the product variants of both product families. The rest of the modules are partially shared. As expected, this case has the best efficiency improvement: inventory value is reduced by 33% and the operating cost even by 43%.

The presented simulation case results provide answers to the relationships between the product structure metrics and the dependent variables. Let's have a look at each relationship from number 1 to number 10. Cases A2 and A3 argue that relationship number one (R1), the number of physical modules vs. inventory cost, is not necessarily true. Two reasons are behind that result: 1) if direct material cost increases over a certain threshold it may overcome benefits of fewer module variants; 2) module variants are reduced in the module types that have a lot of variations. Reducing many variants of one module type by one or two variants is not so meaningful because the function-module relationship still remains. Despite that phenomenon, operating costs reduce because fewer variants cause less operative work in the order fulfilment process. Therefore, R2, number of physical modules vs. operating cost is true. That is shown from cases A2 and A3. The more the reduction in the number of physical modules, the more reduction in operating costs will follow.

R3, dependency index vs. operating cost, can be analysed based on cases A3 & A4 and A2 & A7. In case A4, there is roughly the same number of physical modules as in case A3, but the dependency index is better (2.33 compared to 3.67). That change has influenced a huge change in inventory costs and also a considerable change in operating costs. Comparison of cases A2 and A7 confirms the same phenomenon. The dependency index has loose positive correlation to operating cost.

Cases A3 and A4 suggest that R4, dependency index vs. inventory value, is true. The dependency index has been improved in case A4, which reduces inventory value. In case A7, the dependency index is improved through reduced function-module relationships in cheap mechanical modules. Therefore, the correlation with inventory value is weaker than in case A4. It can be argued that the dependency index has relationships to inventory costs, and that the amount depends on the relative value of the modules in which improvements are made.

R5 studies the joint effect of the number of physical modules and the dependency index on the operating cost, and R6 on the inventory cost. Cases A4, A5, and A6 offer data for conclusions. In the all these cases the dependency index is good, and the number of physical modules is gradually improved from case A4 to case A6. It is clearly seen that both dependent variables show considerable reduction percentages. The more the number of modules is improved, the more reduction is seen in operating costs. If only the dependency index was improved then both reduction percentages would be lower as in the cases from A1 to A3. Therefore, a joint effect on the operating cost is strong as well as on the inventory cost. This shows that the dependency index, together with the reduced number of physical modules, ensures that the module variant reduction is focused in the places that have the biggest influence. To clarify the joint effect on the inventory costs, figure 30 is shown.

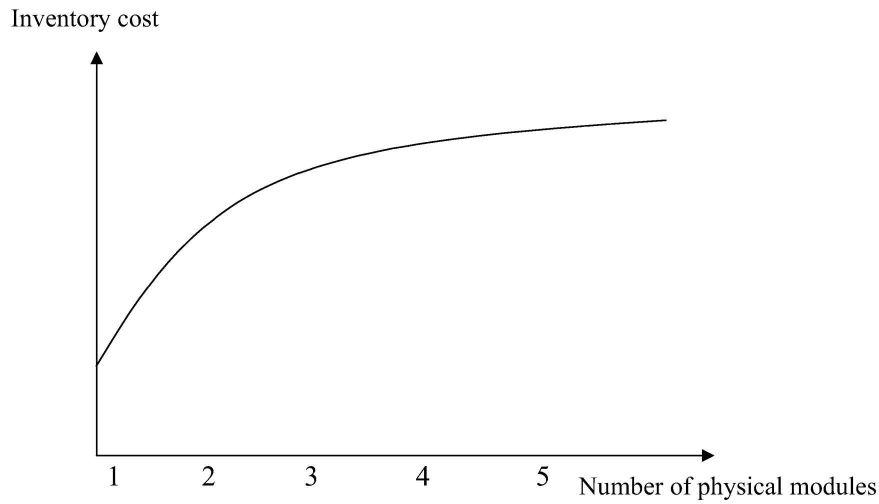

Figure 30. Effect of the number of physical modules on inventory costs.

As seen in the figure above, if a module type has five variants then a reduction to four variants is not as valuable as the reduction from two to one generic module. In the first alternative, the dependency index does not improve but in the second alternative it improves. Therefore, joint improvement of both metrics is important. On the other hand, the joint effect on operating cost is also important. When the number of physical modules is improved, the operating cost is always improved. But when the dependency index is also improved it means some reduction in the number of module types in the product family, which is the second moving factor in the dependency index. The number of module types is seen in several places in the demand-supply chain operations. For instance, it normally defines how many order lines there are in one customer order and it also defines the number of invoice rows to be handled.

The second simulation round with cases B1-B4 was to study relationships 7-10. R7, commonality index vs. operating cost, can not be directly seen from the case results because there is no case in which only commonality would have been improved. It seems that the reduction in the number of physical modules occurring simultaneously mainly causes a reduction in operating costs. Because operating costs are measured only through single product order-delivery activities, operating cost does not care whether the same modules are used sometimes in another delivery situation. Therefore, there is no direct relation between the commonality index and operating costs.

R8 says whether the commonality index affects inventory value. The commonality in this study measures not the part commonality within the product, but the rate of reuse of the same modules for several product families. Cases B2-B4 gradually improve the commonality index of product family X by increasing the percentage of shared modules with product family Y. Along with a commonality increase, corresponding inventory reduction increases. Hence, the commonality index can be argued to have a relationship to inventory costs.

R9 studies the joint effect of the commonality index and the number of physical modules on operating cost and R10 on inventory cost. It becomes clear from cases B2 and B3 that the joint effect is positive on the inventory cost because the dependency index remains the same in both cases. The number of physical modules itself reduces the inventory costs of product family X and the shared modules further increase the inventory cost reduction by reinforcing inventory rotation. For common modules, the same modules can be used from the buffer regardless of the final demand on product family X or Y. The commonality index and the number of physical modules both affect inventory cost.

Finally, the commonality index and the number of different physical modules' joint effect on operating costs is analysed. In case B3, commonality is increased in transceiver, duplexer, and combiner modules. The number of physical modules is reduced from 46 to 29, which mainly causes the huge reduction in operating cost (from 14% to 32%). The commonality index does not improve so much. Therefore, the joint effect correlates positively with the operating cost even if the cause is more the number of physical modules than the commonality index.

Figure 31 represents the findings about the relationships between the product structure metrics and the dependent variables.

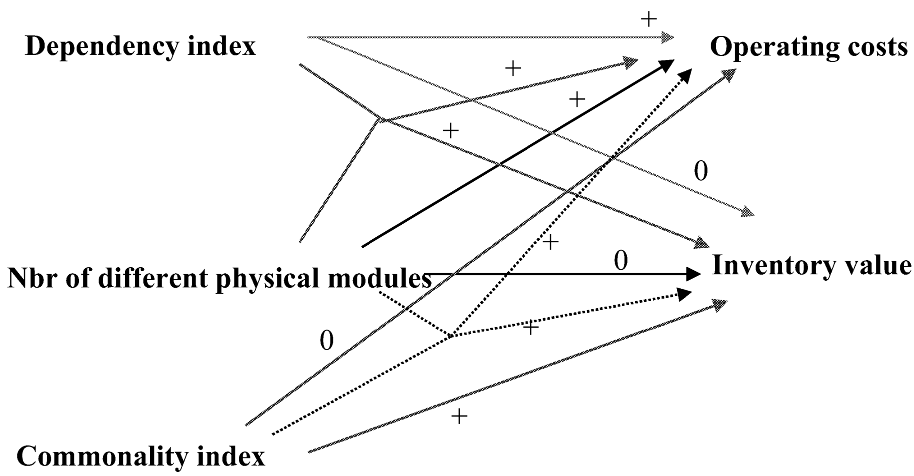

Figure 31. Relationships between the product structure metrics and the dependent variables.

In the figure above, a plus mark "+" is used to point out that the relationship is true. The mark zero "0" is used to point out that the relationship is not self-evident, or it may vary depending on other factors such as direct cost issues or process structures or volumes.

According to the specified simulation models, new product structure metrics seem to work. The results point out that the product structures having better metric values end up with lower inventory levels and lower operating costs. This can be claimed to be effective through the products' volume phase life cycle because inventory behaviour was studied over 20 weeks and operating costs over five years, which are long enough periods to see the implications of normal demand fluctuations.

It becomes clear from the results that when all the metrics are improved, both efficiency measures are improved. Therefore, the key message from the results is that to get benefits in both inventory value and operating costs, all the metrics should be improved simultaneously. It does not necessarily improve the efficiency if only one product structure metric value is improved, because the action should be focused on the places that are the most critical in terms of DSC efficiency. The most critical places are the module types having lots of variants, high direct material costs, and which are consumed in relatively high volumes, even in a fluctuating demand environment.

9.2 Empirical Study

To keep the data and work amount within manageable limits, the study was limited to manufacturing and order management processes only. Inventory cost is left out because different operating models in the distribution do not allow feasible comparison of inventory data between the case products. The lack of an activity-based accounting system considerably limits availability of useful data to validate operating costs of all the DSC processes. *Manufacturing labor cost per subscriber* directly describes the efficiency of the manufacturing process and factory side of the distribution process. *Percentage of changed orders* was used to describe efficiency of the order handling process through illustration of value added versus non-value added work in the order handling process. The same four-month period was analysed for both metrics. The results are presented in table 18.

Table 18. Values of manufacturing labor cost per subrscriber (normalized values) and percentage of changed orders, presented for products A, B, and C.

	Jul.00	Aug.00	Sep.00	Oct.00	Mar.01	Apr.01	May.01	Jun.01	Jul.01	Aug.01	Ave.
Man. labor cost A	100	80	85	78							**86**
Man. labor cost B							44	48	48	48	**47**
Man. labor cost C					27	27	27	27			**27**
% of changed orders A	15	13	10	9							**12**
% of changed orders B							10	9	13	14	**12**
% of changed orders C					1	9	4	13	9	8	**7**

Product A is presented in the first row, values meaning average values for each month. For instance, manufacturing labor cost for product A is 78 units on average during October 2000. Labor cost is reduced by roughly 40% from product A to product B, and again by 40% to product C. Evidently the main reason is that the complexity of product A, measured by the product structure metrics, is the highest. More batch level tasks are needed in order to get certain output, which reduces the share of value added work. On the other hand, because the same modules are handled quite rarely, the learning curve does not develop as fast as in the other products. One major cause of these effects is the values of the product structure metrics. The number of different physical modules describes that phenomenon.

The commonality index describes the same phenomenon at a higher level. If the commonality index is lower, the total non-value added work in all manufacturing lines is reduced. This finding confirms simulation results where the relationship between the number of different physical modules and operating cost was found to exist, as well as between the commonality index and operating cost.

The results from the order handling process, in respect to the situation, are promising. For example, 15% of product A customer orders in July 2000 include configuration changes. In turn, 10% of product B customer orders in May 2001 include the same kind of changes. The latest months of product B show that changes have increased, which may happen because of the novelty of the product design. Design changes often lead to changes in the open order base as well. The first period of product C orders shows only 1% changed orders, but they have also increased a little because of few design changes to the product. Anyhow, according to monthly average values, the trend seems to be that product C is the most efficient in terms of order handling efficiency. Fewer selections in ordering activities, fewer things to ensure, and fewer function-module dependencies lead to more efficient handling of customer orders. Therefore, product C results support the view that the number of different physical modules and the dependency index have a relationship to the percentage of changed orders.

Therefore, it can be argued that the number of different modules and the commonality index have a relationship to manufacturing and distribution efficiency. For the number of different modules and the dependency index, the relationship to order handling efficiency is promising but not airtight. Because real data cases provided supportive results rather than contradictory ones, there is illuminating confidence that new metrics can be used to indicate DSC efficiency of given products.

10 DISCUSSION

10.1 Review of the Results

Research problem

The research problem was: *Is it possible to measure a product structure's goodness in terms of demand-supply chain efficiency already in the new product development phase?* According to the results, when a certain number of product variations are required by the market, it is possible to measure a product structure's goodness in terms of DSC efficiency, measured by operating cost and inventory value. The metrics *number of different physical modules, dependency index,* and *commonality index* were developed because existing findings did not enable the measurement of that property of product structures. Results point out that all of the three metrics should be used together, each of them describing its own kind of drivers of DSC performance. These metrics are findings of this single research work, influenced by the industry studied and experiences of the researcher. They are a representative list of necessary metrics but not by any means a complete and sufficient list of metrics.

Research question 1

Question Q1 asked *how can the demand-supply chain efficiency of product structures be measured.* There was an intention to have a quantifiable tool to compare alternative design proposals. Operationalization of the design principles into the three metrics made it possible to measure DSC efficiency of the alternative designs. Metrics application in eleven cases verified that they offer comparable information about the goodness of product structure alternatives.

Product structure's effects on DSC efficiency were validated through operating cost and inventory value simulation models using eleven cases as input data. Because many unmanageable factors affect DSC performance in practice, a simulation method was selected as a primary validation method. Relationships between the product structure and DSC efficiency were also validated using real data cases as a second source.

The original idea in this study was to validate also inventory value implications and most of the operating costs through real data in a living environment, but it was found impossible. First, new product ramp-ups did not go as planned, for the market situation in the telecommunication industry was very uncertain which led to postponements of operator investments on new technologies. Second, there were internal process development projects going on which changed the operating model information management tools in the processes under study. These factors would have interfered too much with the data.

In ideal validation, all the processes in the operating cost simulation model would have been validated fully empirically, as well as inventory value implications in the real distribution center of the case company. If much more time had been used for this work, inventory validation could have been possible, for some of the showstoppers could have been removed. But operating cost validation would still have been a big challenge, for there was little data available.

The number of different physical modules measured how many different physical modules a product structure includes. The number of different physical modules referred to operating and inventory costs, for most of the operative activities in the outbound chain were done at module level. Both simulation models as well as real data cases were used to validate the relationships.

The dependency index was an important measure of function-module dependency, referring to modularity of the product structure. It was shown that demand changes in the products having high dependency index values related to increased operating and inventory costs. And vice versa, low dependency offered flexibility towards demand fluctuations, leading to lower costs. Both simulation and real data validations were used to study these implications.

The commonality index measures common use of the same physical modules between the product families. The commonality index clearly referred to inventory costs having less impact on operating costs. The effect was validated in simulation models with eleven cases having different commonality index values.

Research question 2

The second research question asked *what is the effect of changing a product structure on DSC efficiency*. The simulation and real case results offered evidence that bigger changes in the metric values led to bigger reduction percentages in inventory and operating costs. Validations also showed that improvement in one or two product structure metrics does not ensure efficiency improvements. When all the metrics were improved, efficiency was improved as well.

The amount of improvement potentially depends on many things: First, demand variability may affect this. Second, design of demand-supply chain processes (places of inventories, process activities, lead-times, operating rules of the people, information management systems, etc.) can affect the magnitude of the implications.

The product structure metrics and DSC efficiency relationship depends on the product structures under study. Configurable relatively complex products often cover considerable differences in metric values and respective cost efficiency from one product family to another, whereas compact consumer products tend to have quite a standard structure with few modules when improvement potential may be lower. This generalizability issue is discussed in more dept in the external validity section later on.

It should also be noticed that in practise there might be some counterproductive effects and trade-offs involved when relying on the product structure metrics. The basic question is the balance between optimising internal efficiency of the product business and external market compatibility of the new products. It seems that when the market requirements are challenging and unclear, it is more difficult to get room for internal efficiency issues in the companies because major efforts are required to get market acceptance and to find right functionality to be fulfilled. On the other hand, there might be a risk of focusing too much on too small product structure issues that consume R&D resources of the company. It is important to evaluate total cost/benefit ratio of the activities, and to find feasible management and engineering focus to efficiency improvement through product structure development.

10.2 Contribution to the Theory

Regardless that the interface of a new product and the manufacturing process is quite a well-covered area in the current literature, it still needs to be better understood how to take into consideration the whole demand-supply chain cost implications, not only the manufacturing part of it, in new product development. On the other hand, it is necessary to take a new approach to the market-defined number of product variations required. It is not feasible to optimize the number of product variations from internal perspectives. One of the basic arguments is that in order to keep market leadership, markets define the offering required, and to maximize profitability, a single company has to adjust to the market-defined number of variations at the best possible cost structure. Quantifiable metrics to evaluate alternative technical solutions already in the concept design phase are little discussed in the existing literature.

Even if modularity and reuse are often mentioned as means to improve efficiency of the company, operation management literature has not offered good enough instruments to quantify how good a product is in relation to DSC efficiency. In this research, quantification of product structure goodness is analysed from multiple perspectives and it is linked to the extended quantification of costs of delivery operations of an industrial enterprise. The area where implications are analysed is extended from traditional manufacturing and inventory management to the whole order fulfilment cycle. This enables the introduction of a new set of metrics that together describe DSC efficiency drivers of the product structure. Therefore, the presented results offer new epistemic utility for the problem area.

The results are also mostly in line with the earlier studies. The results expand the body of knowledge of the problem area by operationalizing new aspects of the product structures that drive DSC efficiency. Operationalization is empirically validated by linking new metrics to real efficiency measures.

Results support the findings of Ulrich (1995, 1998), Lee (1995, 1996, 1999) and Erixon (1994) that commonality reduces inventories. They also support the findings of Foo et al. (1990) and Dowlatshahi (1996) that the number of physical variations affects manufacturing costs. Because extended quantification of operational benefits was used, the results point out that these product design actions could also considerably reduce operating costs throughout the DSC. On the other hand, the results provide a new light on the relationship between the number of module variants and inventory costs. According to the results of this study, inventory costs depend not only on commonality and the number of variants, but also on function-module dependency.

This study makes its contribution mainly to design for "X" literature by the following points:

First, a new approach of enabling a market-defined number of product variations instead of limiting them is presented (Sharman 1984, Martin and Ishii 1996, Dowlatshahi 1996).

Second, Lee (1996, 1999), Stoll (1990), Foo (1990) and Dowlatshahi (1996) have requested quantifiable tools to evaluate products' goodness in terms of DSC performance. In this research, instead of generic design guidelines, a combination of concrete metrics is introduced to evaluate product structure's goodness. New performance factors were operationalized and they were empirically linked to real efficiency measures, whereas the earlier metrics of Martin and Ishii (1996), Erixon (1994) and Galsworth (1995) have relatively weak linkage to empirical reality.

Third, the effective area of product structure metrics was extended from manufacturing cost and inventory cost to cover a bigger part of the DSC processes. An activity-based costing method was linked to the product structures, which represents a new way to evaluate product structures' cost implications for business processes. This provides new information compared to earlier studies by Lee (1995, 1999), Martin and Ishii (1996), Erixon (1994) and Galsworth (1995).

Fourth, understanding of product structure's efficiency implications has been increased through a case study in the cellular network industry, which represents a quite uncertain business environment with complex configurable products. The earlier mentioned studies have mainly been made in the PC industry, automobile industry, and consumer electronics.

10.3 Quality of Research Designs

Any research should have a research design that is correct enough to ensure the result's epistemic utility. The constructive research approach has relatively weak tests to analyse the quality of the study. A market test, when some external instance introduces a new construct, does not necessarily mean that the construct is useful. Therefore, Robert Yin's (1989) tests to judge research designs' quality are additionally applied to this thesis. Four tests are used: construct validity, internal validity, external validity, and reliability. They are originally based on case study research, especially used in quantitative case studies. Because this thesis includes quantitative concepts and relationships, these tests complement normal validation methods of the constructive research well. (Yin 1989)

Construct validity

Construct validity means that established operational measures are correct. Metrics for product structure goodness and for DSC efficiency were used in this study.

Product structure goodness in terms of DSC efficiency was measured through three concepts that were discovered and operationalized in this study. Impacting factors as physical modules, function-physical module dependency, and module commonality were embodied in the metrics. All the concepts behind the three metrics were based on existing literature. Some of them already had empirical evidence about the relationship to the manufacturing and inventory costs. The product structure metrics were also verified to provide feasible results through applying them to eleven cases. A potential weakness in these metrics is that the concepts were operationalized through the cellular network industry's base station products, meaning that they may not behave similarly with other types of products.

The number of different physical modules is potentially a valid measure of a product structure's goodness in terms of DSC efficiency because operative activities in the DSC processes are managed at module level. A physical module is an object for doing in most activities.

The dependency index operationalized function–module dependency in the product, which was argued to represent modularity in the current literature. In turn, modularity was argued to improve the efficiency of an industrial enterprise. The more independent the functions of the product, the better can demand information flow be separated from physical material flow. The value can be calculated exactly using a matrix, and the result is normalized by the functions of the product.

The commonality index operationalized how well the same physical modules are used for different product families of the company. The value was calculated for each module type of a product in a matrix, and an average commonality per module type came out.

The DSC efficiency measures, inventory value, and operating cost were operationalized in simulation models that were strongly based on real business processes in the case company. In addition, logical correctness of the model was tested and verified through expert assessment. The process model, the demand model, capacity constraints, and cycle times in the inventory simulation were real average values from normal operations. In operating cost simulation, total costs of the activities and volumes were built up on actual information collected from legacy systems in real life.

Inventory value is a commonly known efficiency measure in the operations management literature. In this study, distribution center inventories that were kept at module level were considered. To follow inventory behaviour of different products, a simulation model was built using real business processes as a basis. It was visible that changes in physical modules in the product structure led to changes in inventory value, while all the model rules were constant. A potential weakness here is that the inventory value was measured only on the distribution center inventory.

Operating cost represented costs caused by the physical modules manufactured and delivered or demand-supply information handled. The cost was a sum of costs of process activities in the operating cost simulation applying the ABC method. Process activities included real data as a basis, but cost drivers represented an approximation of the product structure – process cost relationship.

That is reasonable because the same approximations in process cost parameters were used for each simulated product structure, while input values came from the product structure cases. The simulation model excluded some potential cost implications in the areas that were out of the scope of this study or that were difficult to quantify. They were qualitative or not related to a single order-delivery. First, overall manufacturing and NPD management and business development would be easier due to more simple products, e.g. business planning and management and product management would be easier, resulting in better financial steering and efficiency. Second, potential implications on the whole supply network (including all the suppliers) could be notable.

Other operating cost measures were established in real case validation because the ABC method was not in use in the case company to the required extent. Real data measures represented pure empirical reality and exact actual figures were available. A challenge was that there were other factors that might potentially have affected the results. For instance, a new product's readiness (design changes), process readiness, and relative volumes might have caused unlinearity in the results.

Manufacturing labor cost was a direct measure of efficiency of the manufacturing process and the factory end of the distribution process. This measures efficiency because it was normalized per subscriber, meaning also the number of physical units coming out from the process. If labor cost is higher for the same output, more non-value added activities have been done in the process, which means lower efficiency.

Percentage of changed orders implied workload in order handling, but it was not a direct measure of efficiency. Because this was the best practical way of measuring the phenomenon, that metric was established. There could have been causes other than percentage of changed orders affecting order handling workload.

Internal validity

Internal validity means causality of the phenomenon under study, here meaning the relationship between the product structure and DSC efficiency. Causality is the strongest type of relationship. According to Eloranta (1999), probabilistic causality exists (c is the cause of e) if 1) c is of type C and e is of type E, 2) c is prior to e, 3) $P(E|C) > P(E)$, and 4) no event d (of type D) that $P(E|(C\&D)) = P(E|D)$.

Compared to this definition, there is causality in the simulation models between the product structure and operating cost, as well as between the product structure and inventory value. That is because 1) simulation inputs, product structure cases, represented one instance of product structure metric values, and each simulation result represented unique values of cost figures; 2) product structure metric values were known before the corresponding simulation results; 3) the probability of getting the same simulation results without the same product structure metric values is lower than without the values; and 4) no other variables were changed in the simulations that could have affected the results.

According to these criteria, cause-effect relationships in the simulation models are valid. The idea is that simulation models measure how much physical modules cause inventories and process costs. These costs depend on the number of different physical modules, function-module dependency, and module commonality, which are properties of the product structure.

In real data cases, relationships between the product structure and manufacturing labor cost, and between the product structure and percentage of changed orders are not causal, because there can be other variables that could have affected the results.

External validity

External validity means definition of domains in which results can be generalized. Generalizability depends on analogies in the concepts and in the experiment environment. The basic concepts used in the metrics were quite common, a product family, a product, configuration, a module type, a physical module variant, and a variable function. They can be found in many industrial enterprises, but their relative importance varies from an industry and a company to another.

In this study the goodness of product structures was measured on product range/product family level, which is relevant when the company has several product families. A base station product is a component of a system or solution sales. The whole system includes many types of products that typically represent different product families. In this kind of situation, a major share of overhead costs lie on the product range/family level. But if a company has only one product family or only single product, then proposed three metrics are not all so valid. The number of different modules and the dependency index are then potentially suitable metrics to evaluate modularity. Usefulness still depends on complexity of the single product/product family, whether there are lot of configurations or only one standard configuration. In case of one product and standard configuration, benefits from these metrics will be only incremental. In the most imaginary case a company could sell single product that might have a standard structure and it might run a single function that is always the same. Then there is no need to separate the terms a product, a module type, a module variant, and a variable function, and it is not even possible to optimise operative cost efficiency through product structure development.

In general, applicability of the presented metrics can be estimated by analysing following three questions: A) How wide range of customer selections and the respective product items exist on each level of the hierarchy? B) How many process activities, and how frequent, a company does in each level of the product hierarchy over the business processes? C) How many inventory phases and how long process lead-times exist in the company's demand-supply chain processes? The more selections and items on each level, the more activities on many levels, and the more complex the DSC, the more potential benefits can be achieved by introducing the proposed product structure metrics.

When applying the product structure metrics to an new environment, it is required to define each parameter of the product structure metrics again in its new context. Meanings for these parameters can vary from company to company, especially in spoken language.

It is argued that the product structure metrics are potentially applicable for an industry in which a wide range of high volume products has to be offered to the markets, products represent average or high complexity in terms of the number of building blocks and the number of configurations, and the DSC structure is analogue to the process model presented in this study, and it's operations represent a relatively big share of the company's total costs. Potential industries that apply to these criteria could be many machinery industries, auto industry and some sections of construction industries.

On the other hand, the metrics the number of different modules and the dependency index could be applicable to wider range of industries that do not necessarily manufacture and deliver the system products. Some consumer product industries could benefit from more flexible internal structure of the products. Such industries could be personal computers and domestic appliance industry. Also, some design intense industries that have pressures to vary the outlook of the products, could benefit from clear function-module mapping.

Reliability

Reliability aims at minimizing the errors and bias in a study. The idea is that another investigator could get the same results by conducting exactly the same research phases. A fundamental issue in reliability of the study is that the results are not only based on step-by-step model development but also on innovative steps. The new construct, the product structure metrics are results from a literature study and innovative work that is influenced by the personal experiences of the researcher. Another researcher could find a different set of metrics for the product structure goodness and for DSC efficiency.

On the simulation model side, it is possible to build up the models in the same way as described in this thesis. Anyhow, there are some assumptions made in the operating cost simulation model that affect the reliability of the results. First, availability of new resources at the same cost. It was assumed that when the number of transactions increases, new resources are automatically available, which is not the case in the real life. In practice, there are certain cost steps, because the same number of people can do more transactions and the same machines can do better throughput to some extent. When new investments are made, costs increase rapidly. Therefore, there is linearity in the ABC model that is not true in the real world. Second, a potential weaknesses lie in the definition of cost driver formulae. Different people could have ended up with different kinds of cost drivers. Because consensus opinions among experts were used, there is confidence that the results are accurate enough.

A significant issue affecting real data results is the market situation during which the study was carried out. With different demand and supply levels, labor cost figures as well as percentage of changed orders could have provided different values.

10.4 Market Tests

Kasanen and Lukka (1993) emphasize the role of market tests as a validation for a new construct. The idea is that when an external stakeholder introduces the construct, it confirms its usefulness.

Weak test

Three of the NPD projects that applied the metrics were used as a weak market test.

Product alfa was taken as a case project when radio access generations developed from GSM (global system for mobility) to GPRS (general packet radio system) technology. Product alfa also represented a new category of base stations (BTS) designed for cities to offer high capacity (number of subcribers) within a small coverage area. The architecture and the functioning of the product were almost similar to the earlier GSM product. The demand-supply chain processes corresponded to the models used in the simulations.

The product structure metrics were applied in the new project in order to maximize demand-supply chain performance of the GPRS base stations while offering the required amount of product variations. Network building projects required high flexibility in terms of changing product configurations during the project. Changes happen because the success of the permission process in authorities varies a lot. When some of the permissions are not given, a new place for the BTS need to be found, which potentially requires different functional options.

The product structure metrics were sold to the hardware design manager responsible for physical implementation of the requirement specifications. They were used to evaluate which of the design options would be the most appropriate in terms of the DSC efficiency.

Product beta was a control server in the IP (internet protocol) radio access network product portfolio. It controls that the data transmission and resource management work properly. The idea has been to develop a modular platform architecture that enables continuous new product introductions using carry-over physical modules. To affect DSC efficiency, minimization of the number of physical modules and maximization of the module commonality were feasible targets. The product structure metrics were used by a hardware development manager who was responsible for implementation of the intended simple modular architecture.

Product gamma was a digital cross-connection node for high data capacity purposes used in the SDH (synchronous digital hierarchy) type of fixed transport networks. The functioning and the physical architecture of the product differ from the two earlier examples. Anyway, the product is a complex system offering plenty of different configurations in relation to cross-connection capability and interface requirements to other parts of the network. The program manager accepted the metrics to be used. He thought that a simple measure of DSC efficiency would be a good guide in the concept development phase. Target values for the metrics were set based on existing products. Alternative design solutions were also analysed by these metrics, and options were discussed in monthly program management team meetings. The metrics helped to estimate and show the cost implications of different design alternatives over the product life-cycle.

Strong tests

A strong market test means that positive results have been achieved because of applying the new construct. Products B and C in the real data cases presented in chapter 8 (Empirical validation) were used as a strong market test. The product structure metrics were applied to these NPD projects, but the commonality concept was not operationalized yet. The results of manufacturing, distribution, and order handling process efficiency (see table 18 in chapter 9.2) pointed out that products B and C performed better than product A, in which none of these design principles or metrics were applied.

10.5 Future Research

This research expands understanding of the product structure's impact on operative efficiency, but it is not in any form final understanding. The reliability of the results could be improved within the same industry by improving the accuracy of the simulation models and by performing wider empirical studies about the metrics relationship to efficiency. On the other hand, the reliability of the results could be improved by further quantifying potential benefits, such as many management functions and improved customer service through better product quality or better DSC performance.

There is also a lot of room for new research to further improve result validity. So far, these results are based on one sample configuration of the process and demand models, and the products. How would relationships change when some of the factors are changed? Which one would be the best combination of the process model and the product structures, and in which kind of demand environment? Practical utility would be higher if it was possible to make comparisons with different DSC processes, which enables decision-making on product structures and delivery process structures simultaneously.

Testing applicability to other industries is also a green field. It is quite obvious that the basic mechanism will work in a similar way but what are the potential differences? On the technology development side, there is room for new research to find better technical solutions to handle functional variability, especially to develop technologies to design multifunctional modules and products without a direct cost increase.

10.6 Conclusions

To be able to guarantee good customer service at a reasonable cost level, along with an ever-expanding product range, product structures' implications for DSC efficiency will have increasing importance in the industries that are in tornado or in main street phase of their life cycle. Developing only product functionalities and operative processes ignores one significant driver of the cost efficiency, namely product structures.

This study has introduced a concrete tool to manage DSC efficiency through better product structures. The metrics presented help the use of modularity and other means for better products. The new metrics combine functional and physical views of product structure, and guide the improvement of products in physical implementation of the design, not restricting product variations in the function domain. That is a novel contribution to the body of knowledge. The study has a more holistic and practical view than many earlier studies in the area, and therefore it makes a clear contribution to the management in industry.

The metrics have significant managerial implications. It is useful for managers in NPD organizations to include these metrics in their toolbox, because the metrics enable concrete evaluation and comparison of alternative design solutions, in terms of operative efficiency, before decision-making. Trade-off situations between design requirements often require quantification of design implications. The best results are achieved when understanding is shared between many disciplines and design options are evaluated cross-functionally.

By setting targets for new products, an important driver of demand-supply chain efficiency is taken into account already in the early design phase. Used in this way, the metrics are a handy way to contribute to a company's profitability through DSC efficiency. When used properly, metrics are a good guide in concept design and a good aid in improving cross-functional co-operation.

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12 APPENDICES

APPENDIX 1 – The case A1: The Bill-Of-Materials (BOM) list of the base station.

Cabinet Core
Outdoor Application Kit
Base module
Internal Antenna Feeder Kit
Combiners Standard 900
Combiners Filter H 900
Combiners Filter J 900
Combiners 1800 A
Combiners 1800 B
Combiners 1800 full
Combiners 1900
Receiver Multicoupler GSM 850/900
Receiver Multicoupler GSM 1800/1900
Transceiver 1800
Transceiver 1900
Transceiver 900
Base band module
Duplexer 1800 A
Duplexer 1800 B
Duplexer 1800 full
Duplexer common module
Duplexer 1900 full
Duplexer 900 Standard
Duplexer 900 H
Duplexer 900 J
Rectlifier module
Battery backup
Connection module
Cabinet control module
Power Supply AC
Power Supply DC
Transmission FC E1/T1
Transmission FXC E1
Transmission FXC E1/T1
Transmission FXC RRI
Transmission FXC STM1
Transmission E1-B
Cabinet Heater Unit (Outdoor Kit)
AC Filter
Bridge Kit
Air Filter Kit

APPENDIX 2 – The Case A2 BOM list.

Cab.Core & outd.kit & base mod. & feeder kit
Combiner Standard 900
Combiner Filter H 900
Combiner Filter J 900
Combiner 1800 A
Combiner 1800 B
Combiner 1800 (full band)
Combiner 1900
Multicoupler GSM 850/900
Multicoupler GSM 1800/1900
Transceiver 1800
Transceiver 1900
Transceiver 900
Base band module
Duplexer 1800 A Band
Duplexer 1800 B Band
Duplexer 1800 Full Band
Duplexer common module
Duplexer 1900 Full Band
Duplexer 900 Standard
Duplexer 900 Filter H
Duplexer 900 Filter J
Rectlifier Unit
Battery Backup
Connection Unit A
Cabinet control module
Power Supply AC
Power Supply DC
Transmission FC E1/T1
Transmission FXC E1
Transmission FXC E1/T1
Transmission FXC RRI
Transmission FXC STM1
Transmission E1-B
Cabinet Heater & bridge & filter kit
AC Filter

APPENDIX 3 – The Case A3 BOM list.

Cabinet Core
Outdoor Application Kit
Base module
Internal Antenna Feeder Kit
Combiners, Generic 900
Combiner, Generic 1800/1900
Multicoupler 850/900
Multicoupler 1800/1900
Transceiver, Generic 1800/1900
Transceiver 900
Base band module
Duplexer, Generic 1800
Dual Band Duplexer
Duplexer, Generic 900
Rectlifier Unit
Battery Backup
Connection Unit A
Cabinet control module
Power Supply AC
Power Supply DC
Transmission FC E1/T1
Transmission FXC E1
Transmission FXC E1/T1
Transmission FXC RRI
Transmission FXC STM1
Transmission E1-B
Cabinet Heater
AC Filter
Bridge Kit
Air Filter Kit

APPENDIX 4 – The Case A4 BOM list.

BTS Cabinet Core 12 TRX
Outdoor Application Kit
Base Operations and Interface
Internal Antenna Feeder Kit
Combiner Standard 900
Combiner Filter H 900
Combiner Filter J 900
Combiner 1800 A
Combiner 1800 B
Combiner 1800 (full band)
Combiner 1900
Multicoupler 850/900
Multicoupler 1800/1900
Tranceiver, Generic module
Duplexer, Generic module
Rectlifier Unit
Battery Backup
Connection Unit A
Cabinet control module
Power Supply AC
Power Supply DC
Transmission FC E1/T1
Transmission FXC E1
Transmission FXC E1/T1
Transmission FXC RRI
Transmission FXC STM1
Transmission E1-B
Cabinet Heater
AC Filter
Bridge Kit
Air Filter Kit

APPENDIX 5 – The Case 5 BOM list.

Cab.Core & outd.kit & base mod. & feeder kit
Combiner Standard 900
Combiner Filter H 900
Combiner Filter J 900
Combiner 1800 A
Combiner 1800 B
Combiner 1800 (full band)
Combiner 1900
Multicoupler 850/900
Multicoupler 1800/1900
Tranceiver, Generic module
Duplexer, Generic module
Rectlifier Unit
Battery Backup
Connection Unit A
Cabinet control module
Power Supply AC
Power Supply DC
Transmission FC E1/T1
Transmission FXC E1
Transmission FXC E1/T1
Transmission FXC RRI
Transmission FXC STM1
Transmission E1-B
Cabinet Heater & bridge & filter kit
AC Filter

APPENDIX 6 – The Case 6 BOM list.

Cab.Core & outd.kit & base mod. & feeder kit
Combiners, Generic module
Multicoupler 850/900
Multicoupler 1800/1900
Tranceiver, Generic module
Duplexer, Generic module
Rectlifier Unit
Battery Backup
Connection Unit A
Cabinet control module
Power Supply AC
Power Supply DC
Transmission, Generic E1 options
Transmission FXC RRI
Transmission FXC STM1
Cabinet Heater & bridge & filter kit
AC Filter

APPENDIX 7 – The Case A7 BOM list.

Cabinet Core
Outdoor Application Kit
Base module
Internal Antenna Feeder Kit
Combiner Standard 900
Combiner Filter H 900
Combiner Filter J 900
Combiner 1800 A
Combiner 1800 B
Combiner 1800 (full band)
Combiner 1900
Multicoupler 850/900
Multicoupler 1800/1900
Transceiver 1800
Transceiver 1900
Transceiver 900
Base band module
Duplexer 1800 A Band
Duplexer 1800 B Band
Duplexer 1800 Full Band
Duplexer common module
Duplexer 1900 Full Band
Duplexer 900 Standard
Duplexer 900 Filter H
Duplexer 900 Filter J
Battery Backup & connection & control module
Power Supply & AC filter & rectifier
Power Supply DC
Transmission FC E1/T1
Transmission FXC E1
Transmission FXC E1/T1
Transmission FXC RRI
Transmission FXC STM1
Transmission E1-B
Cabinet Heater
Bridge Kit
Air Filter Kit

APPENDIX 8 – The BOM and the commonality matrix of the Case B1.

	Product X	Product Y	Commonality points
Cab.Core & outd.kit & base mod. & feeder kit		1	0.5
Cab.Core & outd.kit & base mod. & feeder kit	1		0.5
Combiner 380		1	0.1
Combiner 430		1	0.1
Combiner 800		1	0.1
Combiner Standard 900	1		0.1
Combiner Filter H 900	1		0.1
Combiner Filter J 900	1		0.1
Combiner 1800 A	1		0.1
Combiner 1800 B	1		0.1
Combiner 1800 (full band)	1		0.1
Combiner 1900	1		0.1
Multicoupler 380/430		1	0.333333
Multicoupler 800/850/900	1		0.333333
Multicoupler 1800/1900	1		0.333333
Tranceiver 1800	1		0.166667
Tranceiver 1900	1		0.166667
Tranceiver 900	1		0.166667
Tranceiver 380		1	0.166667
Tranceiver 430		1	0.166667
Tranceiver 800		1	0.166667
Base band module	1		0.5
Base band module		1	0.5
Duplexer 1800 A Band	1		0.1
Duplexer 1800 B Band	1		0.1
Duplexer 1800 Full Band	1		0.1
Duplexer common part X	1		0.5
Duplexer common part Y		1	0.5
Duplexer 1900 Full Band	1		0.1
Duplexer 900 Standard	1		0.1
Duplexer 900 Filter H	1		0.1
Duplexer 900 Filter J	1		0.1
Duplexer 380		1	0.1
Duplexer 430		1	0.1
Duplexer 800		1	0.1
Rectlifier Unit	1		0.5
Rectlifier Unit Y		1	0.5
Battery Backup	1		0.5
Battery Backup Y		1	0.5
Connection Unit A	1		0.5
Connection Unit A Y		1	0.5
Cabinet Control Unit	1		0.5
Cabinet Control Unit Y		1	0.5
Power Supply AC	1		0.25
Power Supply AC Y		1	0.25
Power Supply DC	1		0.25
Power Supply DC Y		1	0.25
Transmission FC E1/T1	1		0.083333
Transmission FC E1/T1 Y		1	0.083333
Transmission FXC E1	1		0.083333
Transmission FXC E1 Y		1	0.083333
Transmission FXC E1/T1	1		0.083333
Transmission FXC E1/T1 Y		1	0.083333
Transmission FXC RRI	1		0.083333
Transmission FXC RRI Y		1	0.083333
Transmission FXC STM1	1		0.083333
Transmission FXC STM1 Y		1	0.083333
Transmission E1-B	1		0.083333
Transmission E1-B Y		1	0.083333
Cabinet Heater & bridge & filter kit	1		0.5
Cabinet Heater & bridge & filter kit		1	0.5
AC Filter	1		0.5
AC Filter Y		1	0.5

APPENDIX 9 – The BOM and the commonality matrix of the case B2.

	Product X	Product Y	Commonality points
Cab.Core & outd.kit & base mod. & feeder kit	1	1	2
Combiner 380		1	0.1
Combiner 430		1	0.1
Combiner 800		1	0.1
Combiner Standard 900	1		0.1
Combiner Filter H 900	1		0.1
Combiner Filter J 900	1		0.1
Combiner 1800 A	1		0.1
Combiner 1800 B	1		0.1
Combiner 1800 (full band)	1		0.1
Combiner 1900	1		0.1
Multicoupler 380/430		1	0.333333
Multicoupler 800/850/900	1		0.333333
Multicoupler 1800/1900	1		0.333333
Tranceiver 1800	1		0.125
Tranceiver 1900	1		0.125
Tranceiver 900	1		0.125
Tranceiver 380		1	0.125
Tranceiver 430		1	0.125
Tranceiver 800		1	0.125
TRX Base Band GSM	1	1	2
Duplexer 1800 A Band	1		0.090909
Duplexer 1800 B Band	1		0.090909
Duplexer 1800 Full Band	1		0.090909
Dual Band Duplexer	1	1	2
Duplexer 1900 Full Band	1		0.090909
Duplexer 900 Standard	1		0.090909
Duplexer 900 Filter H	1		0.090909
Duplexer 900 Filter J	1		0.090909
Duplexer 380		1	0.090909
Duplexer 430		1	0.090909
Duplexer 800		1	0.090909
Rectlifier Unit	1	1	2
Battery Backup	1	1	2
Connection Unit A	1	1	2
Cabinet Control Unit	1	1	2
Power Supply AC	1	1	1
Power Supply DC	1	1	1
Transmission FC E1/T1	1	1	0.333333
Transmission FXC E1	1	1	0.333333
Transmission FXC E1/T1	1	1	0.333333
Transmission FXC RRI	1	1	0.333333
Transmission FXC STM1	1	1	0.333333
Transmission E1-B	1	1	0.333333
Cabinet Heater & bridge & filter kit	1	1	2
AC Filter	1	1	2

APPENDIX 10 – The case B3 BOM and the commonality matrix.

	Product X	Product Y	Commonality points
Cab.Core & outd.kit & base mod. & feeder kit	1	1	2
Combiner 380-430		1	0.333333
Combiner Standard 800-900	1	1	0.666667
Combiner 1800-1900	1		0.333333
Multicoupler 380/430		1	0.333333
Multicoupler 800/850/900	1	1	0.666667
Multicoupler 1800/1900	1		0.333333
Tranceiver 1800-1900	1		0.333333
Tranceiver 800-900	1	1	0.666667
Tranceiver 380-430		1	0.333333
Base band module	1	1	2
Duplexer 1800-1900	1		0.333333
Duplexer common part	1	1	2
Duplexer 800-900 Standard	1	1	0.666667
Duplexer 380-430		1	0.333333
Rectlifier Unit	1	1	2
Battery Backup	1	1	2
Connection Unit A	1	1	2
Cabinet Control Unit	1	1	2
Power Supply AC	1	1	1
Power Supply DC	1	1	1
Transmission FC E1/T1	1	1	0.333333
Transmission FXC E1	1	1	0.333333
Transmission FXC E1/T1	1	1	0.333333
Transmission FXC RRI	1	1	0.333333
Transmission FXC STM1	1	1	0.333333
Transmission E1-B	1	1	0.333333
Cabinet Heater & bridge & filter kit	1	1	2
AC Filter	1	1	2

APPENDIX 11 – The BOM and the commonality matrix of the Case B4.

	Product X	Product Y	Commonality points
Cab.Core & outd.kit & base mod. & feeder kit	1	1	2
Combiner 380-430		1	0.333333
Combiner Standard 800-900	1	1	0.666667
Combiner 1800-1900	1		0.333333
Multicoupler 380/430		1	0.333333
Multicoupler 800/850/900	1	1	0.666667
Multicoupler 1800/1900	1		0.333333
Tranciever, generic & common	1	1	2
Duplexer, generic & common	1	1	2
Rectlifier Unit	1	1	2
Battery Backup	1	1	2
Connection Unit A	1	1	2
Cabinet Control Unit	1	1	2
Power Supply AC	1	1	1
Power Supply DC	1	1	1
Transmission FC E1/T1	1	1	0.333333
Transmission FXC E1	1	1	0.333333
Transmission FXC E1/T1	1	1	0.333333
Transmission FXC RRI	1	1	0.333333
Transmission FXC STM1	1	1	0.333333
Transmission E1-B	1	1	0.333333
Cabinet Heater & bridge & filter kit	1	1	2
AC Filter	1	1	2