5-2014

Implications of additive manufacturing on complexity management within supply chains in a production environment.

Andre Kieviet
University of Louisville

IMPLICATIONS OF ADDITIVE MANUFACTURING ON COMPLEXITY MANAGEMENT WITHIN SUPPLY CHAINS IN A PRODUCTION ENVIRONMENT

By

André Kieviet
Diploma in Industrial Engineering, Vechta, 2001
Diploma in Management Studies, Buckinghamshire, 2005
Master of Business Administration, Osnabrueck, 2010
Master of Science in Industrial Engineering, Louisville, 2010

A Dissertation
Submitted to the Faculty of
the J. B. Speed School of Engineering of University of Louisville
in Partial Fulfillment of the Requirements for the

Doctor of Philosophy

Department of Industrial Engineering
University of Louisville
Louisville, Kentucky

May 2014

IMPLICATIONS OF ADDITIVE MANUFACTURING ON SUPPLY CHAIN COMPLEXITY MANAGEMENT WITHIN SUPPLY CHAINS IN A PRODUCTION ENVIRONMENT

By

André Kieviet

Diploma in Industrial Engineering, Vechta, 2001

Diploma in Management Studies, Buckinghamshire, 2005

Master of Business Administration, Osnabruck, 2010

Master of Science in Industrial Engineering, Louisville, 2010

An Dissertation Approved on

March 31st, 2014

by the Following Faculty Members:

____

Dr. Suraj M. Alexander

____

Dr. William E. Biles

____

Dr. Mahesh C. Gupta

____

Dr. Brent E. Stucker

ACKNOWLEDGEMENTS

I would like to thank my major professor, Dr. Suraj M. Alexander, for his guidance and patience. I would also like to thank the other committee members, Dr. William Biles, Dr. Mahesh Gupta, and Dr. Brent E. Stucker, for their assistance and valuable comments over the past few years. Additionally, I would like to express my thanks to the staff of the Department of Industrial Engineering for all the support they provided me. Finally, I would also like to thank my family and friends for their support and understanding during the last few years.

ABSTRACT

IMPLICATIONS OF ADDITIVE MANUFACTURING ON COMPLEXITY MANAGEMENT WITHIN SUPPLY CHAINS IN A PRODUCTION ENVIRONMENT

André Kieviet

March 31st, 2014

This dissertation focuses on developing a generic framework for using additive manufacturing as an appropriate production method to address the management of complexity in supply chains.

While several drivers such as changing customer demand patterns and intensifying global competition increase product complexity, the available number of product variants and related processes within the supply chain itself increase costs and dilute scale effects. Several concepts and tools like mass customization, modularization, and product platforms have been developed in the past decades, but most of them focus on the product structure. Currently, there is no comprehensive tool set developed in the field of complexity management that incorporates all aspects of supply chain performance (costs, service, quality, and lead time) and evaluates the impacts of additive manufacturing to manage the complexity in the supply chain. This dissertation was developed primarily to address this research gap.

The literature review in this dissertation provides in-depth reviews on specific topics in the field of additive manufacturing production technology, supply chain management, complexity management, and complexity management in supply chains through additive manufacturing.

The dissertation presents the development of a framework for supply chain performance and complexity measurement with a focus on costs and performance depending on production technology. This framework will be the basis for measuring the impacts of additive manufacturing on supply chain performance and level of complexity, by using modeling and reconfiguring supply chain models, and applying complexity management tools in conjunction with additive manufacturing. Based on the findings, a generic framework is developed to identify when and how to apply additive manufacturing to enhance complexity management capabilities in supply chains.

Two case studies will be used to show an application field, where additive manufacturing would require additional time, while another case study suggests the usage of additive manufacturing in the context of supply chain complexity:

A case study of a control panel supply chain will provide an overview of the implications of substituting an injection molding production technology with an additive manufacturing technology on the supply chain and its complexity.

Another case study of teeth aligners shows how additive manufacturing helps to improve supply chain complexity by substituting plaster tools with an additive manufacturing technology.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

1.1. Problem Statement

Competition and customer expectations drive companies to offer a large variety of products and product variants (Smirnov et al., 2006). However, the broad product range makes the entire supply chain complex. A generic supply chain pattern consists of sub-component and component production, assembly, and distribution, and new product variants could increase product complexity at each of these stages (Smirnov et al., 2006). In addition to an expanding product portfolio, other major drivers of complexity include enterprise size, diversification of business units, required internal and external interfaces, product design and portfolio, volatility of supply and demand patterns, and uncertainty of market conditions (Schuh, 2005). The complexity caused by these drivers results traditionally in either stock keeping or long lead times.

Organizations need to decide on a complexity management strategy, so whether to accept, control, reduce, or avoid complexity (Seuring et al., 2004; Wildemann, 2000). Each of these strategies has its own approach and has different implications on supply chain management. Thus, an appropriate strategy should be chosen according to the situation. Kaluza et al. (2006, pp-8-12) define each of the strategies as follows.

> "*Accepting complexity* is a strategy that is suitable when either complexity is fairly limited and does not have a significant impact on supply chain performance or the required measures to manage complexity in the supply chain entail higher costs than

> the resulting inefficiencies. *Controlling* supply chain complexity is an adequate strategy if complexity has a small potential impact […] on supply chain performance and […] does not require significant efforts to manage. This strategy is about monitoring, not manipulating, the complexity. The third strategy, *reducing complexity*, is appropriate when the complexity has a great potential impact […] on supply chain performance and does not require effort for realization. This strategy incorporates all of an organization's tools to mitigate the factors that increase the complexity in the supply chain. The fourth strategy, *avoiding complexity*, is appropriate when complexity has a significant potential impact on supply chain performance and requires significant efforts to manage." This latter strategy uses a comprehensive supply chain design in order to avoid complexity entirely." (Klaus, 2005)

In determining which strategy to choose, two variables are relevant. One is the overall impact that managing the complexity could have on supply chain performance and the other is the cost or effort involved. Several tools have been developed to address these variables.

Most tools for complexity management center on structuring and designing the product to reduce complexity. In general, these tools assume the method of production as a given and often do not take into account new technologies like additive manufacturing (AM). Very little research has been done on how AM could help reduce costs, manage complexity, or improve supply chain performance within a manufacturing environment.

1.2.Objectives

The dissertation aims to analyze the potential impact of additive manufacturing on complexity management in supply chains and to provide a model for determining when additive manufacturing is an appropriate production method to improve supply chain performance or to reduce overall efforts required to manage complexity.

The dissertation will provide a detailed review of the literature on the costs for managing complexity through AM and its potential impact on supply chain performance. Further, the dissertation will analyze drivers of complexity in supply chains and how AM addresses them. Based on this analysis, variables for determining when AM would effectively manage or reduce these complexity drivers will be derived.

1.3.Contribution of the Dissertation

The field of AM has a strong focus on developing and improving production technology as well as on material science. For this reason, limited research has been conducted on commercializing additive manufacturing and integrating it into global supply chain networks. This dissertation aims to provide a framework for when and how to use additive manufacturing to manage complexity in supply chains. It will describe how a supply chain could be reconfigured using additive manufacturing. This theoretical framework is based on currently available additive manufacturing technologies, albeit the technologies partially cope with the problem of ensuring processes are stable and repeatable, and material characteristics properly fulfill all requirements. As these problems have already been solved for some materials and processes by freezing process parameters and utilizing additional quality checks during production, the dissertation assumes that stability and repeatability problem will be solved in the future.

This dissertation aims to determine *how* and *when* to apply additive manufacturing to manage complexity in supply chains.

1.4.Introduction to the Research Approach

1.4.1. Theoretical introduction into research approaches in supply chain management

Before introducing the selected research approach, this section provides an overview of selected research methodologies in the field of supply chain management.

In general, including for supply chain management topics, there are several research methodologies like model building, surveys, case study research, and action science research (Seuring et. al, 2005), all of which will be briefly introduced in the following paragraphs. However, these research methodologies' advantages and disadvantages to the body of knowledge will not be discussed in detail in this section, as they have been already broadly accepted and tested.

Model building

This description of model building is based on Reiner's (2005) review of quantitative modeling in a supply chain management context. Although quantitative modeling was intended to provide an analog solution to action research, real-world problems, it is now also used for quantitative model-driven research. There are two classes of model building—one focusing on the ideal model (axiomatic research) to prove theorems and logic, and another used to derive empirical findings and measurements. The model should therefore be linked as much as possible to actions in reality in order to yield an optimal solution (Reimer, 2005). According to Reimer (2005)

> "the research type used can be descriptive or normative. Descriptive empirical research is interested in creating a model that describes the causal relationships that may exist in reality and leads to improved understanding of the process mechanics, e.g., systems dynamics research (Forrester, 1961), and clockspeed in industrial systems (Fine, 1998). In this sense, simulation is more than a faction of axiomatic quantitative research and can be used in the second class of model based research, too. A further type is the normative empirical quantitative research that is interested in developing policies, strategies, and actions so as to improve the current situation. There is a wide spectrum of literature about the validation and verification of models." (Reimer, 2005, p. 435)

Survey research

According to Kotzab (2005)

> "survey research plays an important role in many disciplines when it comes to collecting primary data (Zikmund, 2000). Choosing a survey strategy allows the collection of large amounts of data in an efficient manner. Typically, this is done by using questionnaires with which researchers bring together standardized data that can be compared easily (Saunders et al. 2004). Surveys, for example, are very important for marketing research as they are 'normally associated with descriptive and causal research situations' (Hair, et al. 2003, p. 255)." (Kotzab, 2005, pp. 126)

Case study research

Seuring (2005) provides a comprehensive definition of case study research:

"'A case study is an empirical enquiry that (1) investigates a contemporary phenomenon within its real life context, especially when (2) the boundaries between phenomenon and context are not clearly evident' (Yin, 2003, p. 13). Case studies are used as a research method if contextual factors are taken into account, but at the same time limit the extent of the analysis (Eisenhardt, 1989; Voss et al., 2002). This allows in-depth insights into emerging fields (Meredith, 1993), yielding a basic comprehension of fuzzy and messy issues (Swamidass, 1991). The strength of the case study method rests on its ability to capture conceptual developments (Meredith et al., 1989; Meredith, 1993), while not immediately proposing broad theories (Weick, 1995; Swamidass, 1991; Wacker, 1998). Therefore, it is particularly appropriate if new fields of research are emerging (Yin 2003). The advantage of the case study approach is its ability to address 'Why?' and 'How?' questions in the research process. (Yin, 2003, p. 1; Ellram, 1996, p. 98; Meredith, 1998, p. 444)" (Seuring, 2005, pp. 238)

Action research

Action research is a consultancy approach for praxis problems. Müller (2005) describes action research in the context of supply chains:

"Action research started with praxis problems, and the change of reality is a central aspect of pragmatism. In action research, the planning and implementation of change in companies is fundamental. The core of action research is the integration of the praxis as a component of social science research (see Krüger et al., 1975, p. 8). The methodology of action research implements the result of the research during the science process. Science finally engages into practice (Gunz, 1986). […] The main characteristics of action research are summarized as follows (Coghlan, 1994; Argyris et al., 1985; Greenwood & Levin, 1998; Gummesson, 2000;

McDonagh & Coghlan, 2001): the process of action research started by praxis problems; action research takes action; action research is discourse-oriented; action research is embedded in the field; the researcher is an agent of change; [and] action research is mainly based on a dialectical theory." (Müller, 2005, pp. 353–354)

According to Müller (2005), Coughlan and Coghlan developed a three-step process for action research. In the first step, the context and purpose of the action research project is described. In the second step, the research is implemented with a set of six sub-processes (data gathering, data feedback, data analysis, action planning, implementation, and evaluation). Finally, in the third step, the research is monitored. This process is applied if a problem is highly unstructured and the results are achieved by a series of actions that is described in the research. This research focuses on understanding and learning from the change the actions achieve.

1.4.2. Selected research approach

The dissertation will utilize model building, action-, and case study research to enhance the theoretical research. Figure 1 illustrates the dissertation's chosen approach.

First, a literature review on the technology and cost of AM, supply chain models, supply chain performance evaluation, and complexity management is presented (Chapters 2 and 3). Next, the development of a new remodeling approach for supply chains utilizing additive manufacturing to manage complexity, based on combining the established tools, processes, and methodologies currently used in supply chain management; additive manufacturing; and complexity management, is described. A typical supply chain network model will be described, and relevant performance drivers will be defined. Based on this model, all relevant complexity management drivers and traditional tools that could be used to manage complexity and how AM could address these drivers will be discussed. Following this discussion, the supply chain model will be

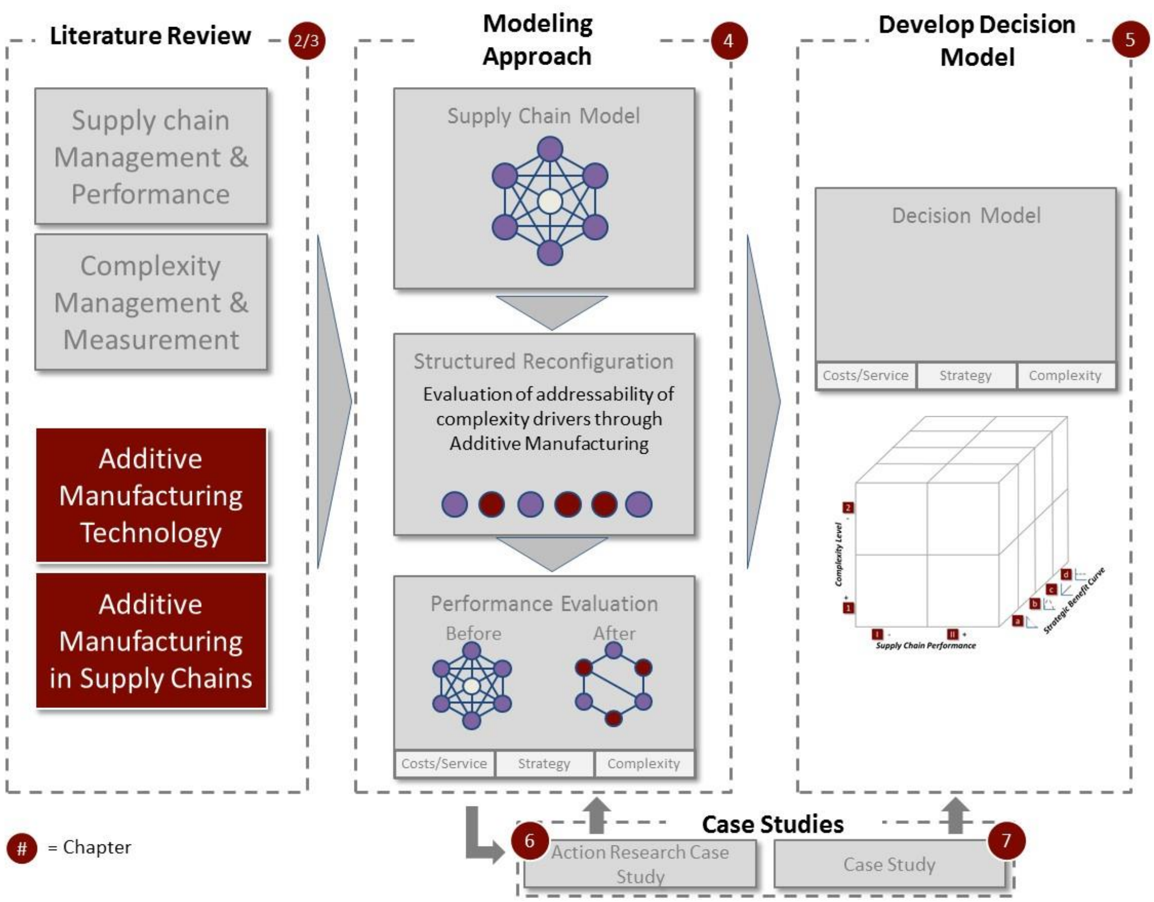


Figure 1: Research approach

reconfigured and performance differences will be evaluated. The remodeling approach will be completed by an evaluation to measure supply chain and complexity performance (chapter 4). The remodeling process provides a tool that future research in quantitative model building could refer to.

Based on the findings in Chapters 2, 3, and 4, a decision model will be developed to determine in which situations additive manufacturing could provide considerable benefits to an organization (chapter 5).

The process (Chapter 4) and the decision model (Chapter 5) will be supported by findings from two case studies. In Chapter 6, the action-based research case study will be introduced, that is, the praxis problem will be analyzed and solved using the remodeling process developed in Chapter 4.

In Chapter 7, a theoretical case study will demonstrate the successful utilization of additive manufacturing using the process in Chapter 4.

2. LITERATURE REVIEW

2.1. Introduction to Additive Manufacturing

2.1.1. Technology overview

The term additive manufacturing is relatively new. The concept of rapid prototyping or manufacturing, which is widely used in many industries, has the same underlying technology as additive manufacturing; however, the name is limited to the production of prototypes. In contrast, additive manufacturing focuses on technology (e.g., adding materials one after another to produce a part) and manufacturing, which goes beyond prototyping to producing parts (Stucker et al., 2010). ASTM International defines additive manufacturing as "the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies. Synonyms: additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, and freeform fabrication" (ASTM F2792-10 Standard Terminology for Additive Manufacturing Technologies, pp. 1).

2.1.2. Additive manufacturing technology classification

AM can be classified in several ways based on criteria like raw material input (e.g., photopolymers, metals) and technology used (e.g., laser, printer). Technology can be divided into several sub criteria such as in the classification introduced by Pham and Gault (1998), which classifies AM based on how dimensions X and Y are used to produce a layer (Stucker et al., 2010). The classifications in the literature mainly consider technology-driven aspects and are used to describe the feasibility of the desired products. For example, Chua et al. (2010) classify additive manufacturing based on the raw material's state of aggregation or form, specifically, whether they are liquid-, solid, or powder-based raw materials.

2.1.3. Decision variables for choosing production methodologies

Several variables can be used to determine the right production technology. In addition to identifying the appropriate AM methodology to produce the desired product (see section 2.1.2), this dissertation will also determine the factors relevant to investment decisions (Domschke et al., 1997). Investment decisions in the field of production planning focus on minimizing costs by optimizing production factors (e.g., capital, equipment, labor) to produce the required amount of products (Woehe, 1996). Other factors such as time, productivity, costs, health and safety requirements, environmental impact, quality, flexibility, and inventory are also important in production planning decisions (Fritz and Schulze, 1998).

In evaluating the application of additive manufacturing from a technology perspective, Cormier and Harryson (2002) state that the factors speed, selective coloring, material composition, and material properties should be considered. In addition to these material- and production-related capabilities, two further elements should be incorporated into the decision model for applying AM: shape and material complexity. *Shape complexity* reflects the product design and refers to the capability to produce "lot sizes of one," provide customized geometries, and enable shape optimization and hierarchical multiscale structures (Chu et al., 2008). On the other hand, *material complexity* reflects material requirements and refers to the capability to use “one point, or one layer, at a time” to “manufacture parts with complex material compositions and designed property gradients” (Chu et al. 2008, pp. 1).

Based on the comparison of production processes, a decision-making model should consider a combination of commercial factors (e.g., time, productivity, costs) and technical factors (i.e., shape and material complexity).

2.1.4. Status of additive manufacturing

2.1.4.1. Overview of additive manufacturing technologies

ASTM (2012) provided seven new standard categories for additive manufacturing, based on type of technology: *binding jetting*, *direct energy deposition*, *material extrusion*, *material jetting*, *powder bed fusion*, *sheet lamination*, and *vat photopolymerization*.

Currently, there are seven methods available for additive manufacturing: photo polymerization, powder bed fusion (PBF), extrusion, printing, sheet lamination, and powder spray. Table 1 provides an overview of the available methods, used materials, and structural design limitations that might require additional support material for each technology chosen. The technologies will be discussed in detail in the following sections.

Table 1: Overview of additive manufacturing technologies

Method	ASTM F2792-12a Terminology Process Categories	Sub-Method	Materials							Support Required
			Organic/Wax	Paper	Ceramic	Photopolymers	Polymeric	Metallic	Sand	
Photopoly merization	Vat Photopolymerization	Stereolithography - Vat				X				Yes
	Material Jetting	Projection Systems -Vat				X				Yes
	Vat Photopolymerization	Mask Projection				X				
	Vat Photopolymerization	Selective Laser Sintering (SLS) - Laser				X				
Powder Bed Fusion	Powder Bed Fusion	LSP			X		X	X	X	
	Powder Bed Fusion	SLS, Electron Beam Melting (EBM)				X	X	X	X	
	Powder Bed Fusion	High-Speed Sintering - Line/Layer						X		
	Powder Bed Fusion	Selective Inhibition Sintering - Line/Layer					X			
	Powder Bed Fusion	Selective Mask Sintering - Line / Layer					X	X		
	Powder Bed Fusion	Fused Deposition Modeling (FDM)								
Ex-trusion	Material Extrusion	Direct			I		X	I		Yes, always
Printing	Material Jetting	Printing Processes	X			X				yes
	Binder Jetting	Binder Printing								No
Sheet Lamination	Sheet Lamination	Laminated Object Manufacturing (LOM); bond then form		X						full block used
	Sheet Lamination	Offset Fabrication; form then bond		X	X		X	X		
	Sheet Lamination	Computer Aided Manufacturing of Laminated Engineering Materials (CAM-LEM)								
	Sheet Lamination	Ultrasonic Consoldiation						X		
Beam Deposition	Direct Energy Deposition	Lens - YAG Laser						X		
	Direct Energy Deposition	POM - CO2 Laser						X		
	Direct Energy Deposition	More accurate accufusion						X		
	Direct Energy Deposition	AEROMET CO2						X		

2.1.4.2. Vat photopolymerization

The process of vat photopolymerization is limited to photopolymers—special radiation curable plastic resins that usually react to ultraviolet wavelengths. This production process is conducted in a vat by patterning a light source. There are different laser construction methods available: vector scanning; two-photon laser methods, which are usually point-by-point approaches; and masking, which covers a full area on a layer. Photopolymerization within the vat usually does require supports to attach the part to the baseplate (Stucker et al., 2010).

2.1.4.3. Powder bed fusion

In contrast to photopolymerization, PBF is based on selective laser sintering (SLS) technology, which uses a thermal source such as a laser or an electron beam to heat and fuse small material particles. In addition to the thermal source, PBF requires two elements: a unit to spread the powder across the building area (i.e., the power bed) and the building area itself. The unit spreading the powder is usually a leveling roller or blade that allows building very thin layers (normally ~0.1 mm). For PBF and SLS, several materials are available; thus, in addition to plastics and metals, the process can be used for materials in powder form like sand. Depending on the building material, support material may be required, especially for metals. Sometimes, chemicals are added to force reactions between the powders and atmospheric gases (Stucker et al., 2010).

2.1.4.4. Material extrusion

Because extrusion is a traditional production technology, it can also be applied as an AM technology. Extrusion is a process where semi-liquid materials are usually stored or pre-treated in a reservoir, pressed through a special nozzle at a constant pressure rate, and then allowed to cure. The most common approach in extrusion is to pre-heat the materials in the reservoir or in the nozzle so that curing is based on a cool-down effect. In this process, chemical reactions like hydration in the case of concrete (Buetzer, 2009) as well as other chemical reactions (Stucker et al., 2010) can occur. With this process, a “road” of material could be built in any required length with the shape of the nozzle. As an AM technology, the extrusion process is conducted on a layer-by-layer basis to build the desired product, during which the material should remain in shape. To improve the material characteristics and strength of the part being built, a layer must not fully solidify before the next layer is added so that the two layers could solidify together (Stucker et al., 2010).

The Fused Deposition Modeling (FDM) machine is an extrusion-based technology developed by the company, Stratasys. It uses the extrusion process for polymers, which are pre-heated within an internal heating chamber (Stucker et al., 2010).

Plastic materials like acrylonitrile butadiene styrene (ABS) and polycarbonate (PC) are widely available for the extrusion process in AM. However, there are also other materials available for extrusion, like concrete and rubber (Stucker et al., 2010).

Due to the free-form nature of this process, supports may be required depending on the complexity of the design. Having a system with at least two nozzles would allow using a secondary material as support material to reduce the finishing work required.

2.1.4.5. Binder jetting

There are several approaches for 3D printing. 3DP uses a regular ink-jet printer head. This printer is used to print bonding materials like glue on powder-based raw material layer by layer (binder jetting). The powder is stored on a powder bed. The use of raw material powder is virtually unlimited, and thus, is used for ceramics, cermets, and plastics (Mansour and Hague, 2003). When using a powder bed, a support is not necessary.

2.1.4.6. *Material jetting*

Another recent technology for 3D printing is acrylate photopolymers, where liquid monomer droplets are deposed through a print head and then exposed to UV light (Stucker et al., 2010) (material jetting). Another typical material for material jetting is wax (ASTM, 2012, pp. 1). When using acrylate photopolymers, a support may be required. Using two printer heads allows the use of a different material to create the support structure.

2.1.4.7. *Sheet lamination*

The sheet lamination process is a mix of different production technologies. The basic principle of the process is using different sheets of materials, for example, paper, and cutting the form on a sheet-by-sheet basis and bonding the sheets together by a bonding material like glue or by a sintering, welding or clamping process. Sheet lamination allows the insertion of cooling channels within complicated geometries (Zäh, 2006).

2.1.4.8. *Directed energy deposition*

The directed energy deposition processes (formally known also as beam deposition, metal deposition or powder deposition process) uses either powder or wire material as feedstock. The material will be melted through a high-energy laser or electron beam. A nozzle will typically feed the material while the beam will melt the material and deposit layer by layer. Figure 2 provides a schematic overview of the process.

There are several beam deposition systems available. These systems differ mainly according to the laser beam used (e.g., CO_2 laser, YAG laser), feeding type, and size of the build chamber.

According to Stucker et al. (2010), the process could be used for several materials, but is mainly used for metallic materials.

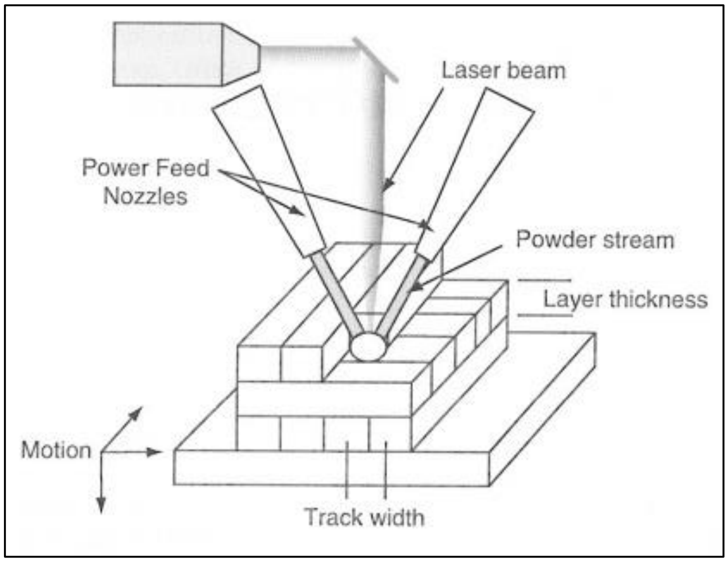


Figure 2: Schematic of a typical beam deposition process (Stucker et al., 2010)

2.1.5. Additive manufacturing costing

2.1.5.1. Cost elements

There is limited research on comprehensive cost models for additive manufacturing. So far, existing studies have focused on the comparisons of two production technologies. However, Hopkinson and Dickens (2001) identified relevant cost elements in order to compare application fields for additive manufacturing and injection molding. Other researchers elaborated on Hopkinson and Dickens' work. For example, in Germany, Jahnke and Lindemann (2012) developed a cost model that covers the overall product life cycle on a specific metal part. Additionally, Lindemann et al. (2012) developed a life cycle cost model that incorporates life-cycle costs like weight reduction, but they did not consider the supply chain and supply chain network.

Additive manufacturing is primarily a manufacturing technology. Thus, in this dissertation, only the elements of the production process relevant to manufacturing will be considered. This is a focused view and does not incorporate all other relevant information required to derive the most value-adding decisions. However, incorporating the production cost elements in a comprehensive supply chain cost model provides a complete view of the total cost of the supply chain.

For calculating production cost, Zäh (2006) identified four relevant elements: pre- and post-processing of the machine, production of the part, post-processing of the part, and material costs. The cost elements from these steps are machining and labor and material costs (Zäh, 2006; Hopkinson, et al. 2003).

Currently, there is no general holistic cost model for additive manufacturing processes. However, researchers like Ruffo et al. (2005) have developed more detailed cost models for specific technologies. For example, Ruffo et al. (2005) have analyzed laser sintering costs and divided them into direct and indirect. This dissertation assumes that the relevant cost elements do not differ between the various additive manufacturing technologies; only the characteristics of the cost elements may differ.

Figure 3 gives a systematic view of the cost model. The model provides a somewhat simplistic view of manufacturing costs because like Zäh (2006), it only takes labor and direct costs into account, not all overhead costs. However, for the dissertation's purposes, it might be sufficient to assume that these other costs equal those of other production technologies.

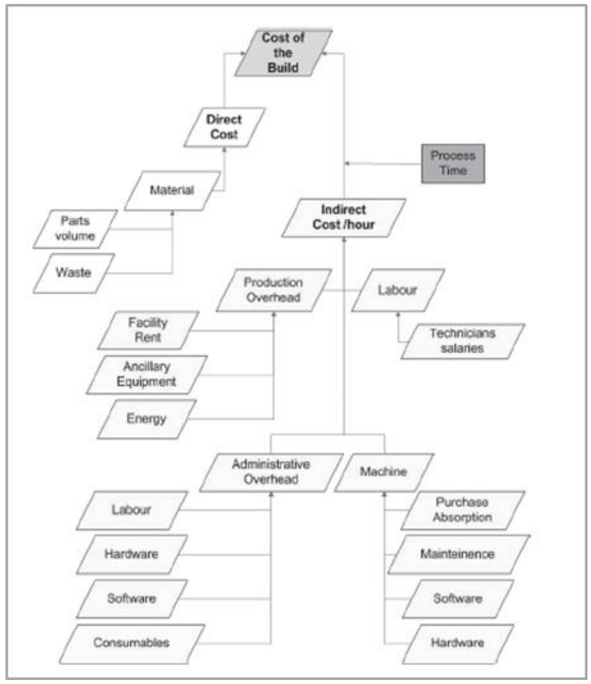


Figure 3: Schematic of cost model (Ruffo et al., 2006, pp. 1421)

2.1.5.2. Machining cost

The calculation of machining cost is independent of the type of production process, so using established definitions might be sufficient. Olfert (1987) defines machining cost as follows:

$$Machine\ hour\ cost: C_{Ah} = \frac{K_A + K_Z + K_I + K_R + K_E}{U}$$

where

- K_A: Calculated depreciation – Purchase price divided by the expected usage time

$$K_A = \frac{Purchase\ Price}{Years\ of\ Usage}$$

- K_Z: Calculated interests – Interests from the machine financing

$$K_Z = 0.5\ x\ Purchase\ Price\ x\ Interest\ rate$$

- K_I: Maintenance costs – All costs involved to maintain and repair the machine including required consumables like lubricants
- K_R – Space costs – Costs for the space required by the machine

$$K_R = Space\ required\ in\ sqm\ x\ Calculated\ rent\ per\ sqm\ p.a.$$

- K_E – Energy costs – All utility costs like for gas, electricity, and water p.a.
- U: Utilization – Amount of time the machine is effectively used to produce parts in hour p.a.

Thus, the total machining cost is the amount of time the machine is used, multiplied by the hourly rate of the machine:

$$\text{Machining cost } C_A = C_{Ah} * t_A$$

where t_A is the amount of time for which the machine is reserved for setup, processing, and post-processing.

2.1.5.3. Labor cost

According to Woehe (1996), labor cost consists of the direct and indirect costs related to labor compensation, including base wage, benefits, and social contribution costs. In exchange for compensation, a person must devote a defined amount of time to working. There are several types of compensation. For this dissertation's purposes, I use the most common approach, which is compensation based on time, specifically, the use of hourly rates. In addition to region- and industry-related factors, the level of payment is mainly driven by required experience and the level of difficulty of the task (Woehe, 1996).

Little research has been conducted to determine whether a higher skill level is required to perform additive manufacturing processes compared to subtractive production processes. Due to this lack of research, in this dissertation, the level of qualification is assumed to be similar to that of conventional production processes. Zäh (2006) assumed higher hourly rates for the additive manufacturing production process compared to those for subtractive processes. However, in a more industrialized environment, this assumption might not hold if workers become more used to the technology. Thus, Ruffo et al. (2006) assumed the same labor rates (c_{lh}) between the two types of processes for their comparisons.

In this dissertation, I follow Zäh's assumption. The overall labor cost in the production process is determined by multiplying the process duration with the hourly rate. The time consumed is categorized into the following elements:

- t_d: Time used for designing and converting design files
- t_s: Time used for preparation of machine
- t_{pp}: Time used for post-processing of parts
- t_{pm}: Time used for post-processing of machine

Thus, the overall cost function for labor can be defined as follows:

$$\textit{Labor cost function } (C_l) = c_{lh} * (t_d + t_s + t_{pp} + t_{pm})$$

where c_{lh} is the hourly labor cost rate (Zäh, 2006).

2.1.5.4. *Material cost*

Slack et al. define material cost as “the money spent on the materials consumed or transformed in the operation” (Slack et al., 2001, pp. 55). Material cost can be calculated by multiplying the amount of material used with the material cost per unit (Woehe, 1996):

$$C_{M=}c_{mu} * m_u$$

where

- C_M: material cost
- c_{mu}: material cost per unit (e.g., kg)

  m_u: material used in units (e.g., kg)

Table 2: Material cost calculation by technology

(Hopkins and Dickens, 2003, pp. 35)

	Source of cost	
	Variable	Obtained by
Number per platform	*N*	Maximum possible in one build
Material costs for SL		
Material per part including support (kg)	SLMass	Weighing finished parts
Material cost per kg	SLcost	Quote = 275.20 euros
Material cost per SL part	SLMCP	SLMAss × SLcost
Material costs for FDM		
Material per part (kg)	FDMPM	Weighing finished parts
Support material per part (kg)	FDMSM	Weighing finished supports
Build material cost per kg	FDMPC	Quote = 400.00 euros
Support material cost per kg	FDMSC	Quote = 216.00 euros
Material cost per FDM part		(FDMPM × FDMPC) + (FDMSM × FDMSC)
Material costs for LS		
Material cost per kg	LSC	Quote = 54.00 euros
Mass of each part	LSM	Weighing finished parts
Volume of each part	VP	Found with Magics software
Total build volume	TBV	$34 \times 34 \times 60\,\mathrm{cm}^3$
Mass of sintered material per build	LSMS	*N* × LSM
Mass of unsintered material per build	LSMU	(TBV − *N* × VP) × 0.475*
Cost of material used in one build	LSMC	(LSMU + LSMS) × LSC
Material cost per LS part	LSMCP	LSMC/N

* Published density of unsintered LS powder is $0.45–0.5\,\mathrm{g/cm}^3$ [**11**].

This simplified cost function seems suitable to the context of additive manufacturing; however, it might provide an imbalanced view because of the difference between how subtractive and additive manufacturing define material used. The major advantage of most additive manufacturing technologies is that they mainly use the material required for producing the component itself and create no or limited waste depending on the technology used and geometry produced. These two factors influence the material cost in terms of the waste produced by the main raw material (technology) and that by the support material (geometry/partially by technology). Hopkins and Dickens (2003) suggest three approaches for calculating material cost depending on the technology used (see also Table 2):

- Building and support are from the same material (e.g., stereolithography or SL)
- Building and support are from different materials (e.g., fused deposition modeling (FDM))
- Building material waste is created from the production technology (e.g., laser sintering (LS))

Contrary to Hopkins et al., it might be appropriate to include waste from support material or from building material as material cost, as well as any income generated from waste disposal and recycling. A metric ton of aluminum, for example, generates an income of approximately €1,100 (as of February 2012; Entsorgungs Punkt DE, 2012). For the purposes of this dissertation, other advantages brought about by waste disposal and recycling, such as social, environmental, and ecological advantages, will not be considered (Kaseva and Gupta, 1996).

Considering Hopkins et al.'s calculation and incorporating recycling income, the material cost function can be extended as follows:

$$C_{M=}(c_{muB} * m_{uB)} + (c_{muS} * m_{uS}) - ((I_{muB} * m_{rB}) + (I_{muS} * m_{rS}))$$

where

C_M : material cost

c_{muB}: building material cost per unit (e.g., kg)

c_{muS}: support material cost per unit (e.g., kg)

m_{uB}: building material used in units (e.g., kg)

m_{uS}: support material used in units (e.g., kg)

I_{muB}: building material recycling income per unit (e.g., kg)

I_{muS}: support material recycling income per unit (e.g., kg)

m_{rB}: building material for recycling in units (e.g., kg)

m_{rS} : support material for recycling in units (e.g., kg)

2.1.5.5. Overall cost function for additive manufacturing

The total cost function (TC) could be described as follows:

$$Total\ cost: (TC) = C_M + C_L + C_A$$

2.1.5.6. Critical review of current cost models

The existing cost models focus only on production costs, which may lead to an inaccurate comparison between traditional and additive manufacturing processes due to two major reasons:

- Additive manufacturing is not as industrialized as eroding production processes, resulting in limited scalability and economies of scale. For example, a kilogram of ABS for a 3D printer costs approximately €23–50 (irapid.de, 2012) while regular ABS like Lustran H801 costs €1.80–2.00 per kilogram (A.T. Kearney, 2009).
- Supply chain costs (i.e., costs for transportation, buffering, warehousing, and managing complexity) are not included in the cost function.

Thus, in this dissertation, I will incorporate other cost elements outside of the supply chain and complexity to allow for a more comprehensive view and comparison of total costs.

2.1.6. Benefits of additive manufacturing

Additive manufacturing provides benefits that traditional manufacturing methodologies do not. According to Stucker et al. (2010), the three major benefits are less time requirement, increased design complexity capability, and no tool requirement.

AM provides a time benefit for new product development, as the products will be designed in a CAD environment and will be built immediately after file conversion in a "what you see is what you build" manner (Stucker et al., 2009, pp. 8). AM also allows “full product customization with complete flexibility in design and construction of a product” (Petrovic et al., 2009, pp. 4).

Another benefit of AM is the capability of the technology to build parts in one step regardless of the design complexity, while other technologies require multiple and interactive stages. It also provides the benefit of easy implementation of design changes; with traditional methods, even a minor design change might result in significant efforts to adapt. One additional benefit of AM, which is not mentioned explicitly by Stucker et al., (2009) in this context is that compared to several other traditional manufacturing methodologies like injection molding, AM does not require any tool to be built prior.

Finally, Petrovic et al. (2009) identified two other benefits: savings through reduced waste and partial density improvements. Unlike traditional production methodologies, AM even enables material savings because it adds material rather than subtracts material, which produces waste. According to Reeves (2008), for some applications, AM reduces waste by up to 40%. Further, in comparison to other powder based methodologies, AM can produce parts without residual porosity, that is, the parts have full density (Petrovic et al., 2009).

2.2. Supply Chain Management

2.2.1. Supply chain models and process definitions in a production environment

The term “supply chain” has different definitions. For example, Stevens (1989) defines a supply chain as a model in which different activities form a network through various participants, from the suppliers in production to the end customers. On the other hand, Chopra and Meindl define a supply chain as follows: “A supply chain consists of all parties involved, directly or indirectly, in fulfilling a customer request. The supply chain includes not only the manufacturer and supplier, but also transporters, warehouses, retailers, and even customers themselves” (Chopra and Meindl, 2007, pp. 3). This definition is fairly specific but not limited to the actors and functions in the process chain involved.

Since there is no one general supply chain for all products, Chopra and Meindl’s definition must be extended by incorporating the network aspect of Stevens’ definition; within a supply chain, there are usually different tiers of suppliers that require various types of interactions and management activities. For the purposes of this dissertation and in the context of additive manufacturing, all other steps involved in addition to manufacturing must be reviewed.

Based on this extended definition, the relevant activities and processes involved in a supply chain must be identified. The Supply Chain Council developed the Supply Chain Operations Reference (SCOR) model as a reference model that applies to all types of supply chains. The SCOR model identifies five distinct management processes:

- *Plan*: Coordination and planning of supply, production, and customer demand
- *Source*: Sourcing of raw materials or intermediates that are required to produce the product
- *Make*: Production of a product
- *Deliver*: Notification and physical delivery of goods to the location where the product is required

- *Return*: Notification and physical return of goods

Although this model illustrates a sequence of processes for a company, the sequence is repeated several times in the entire supply chain, as illustrated in Figure 4 (Thaler, 2001).

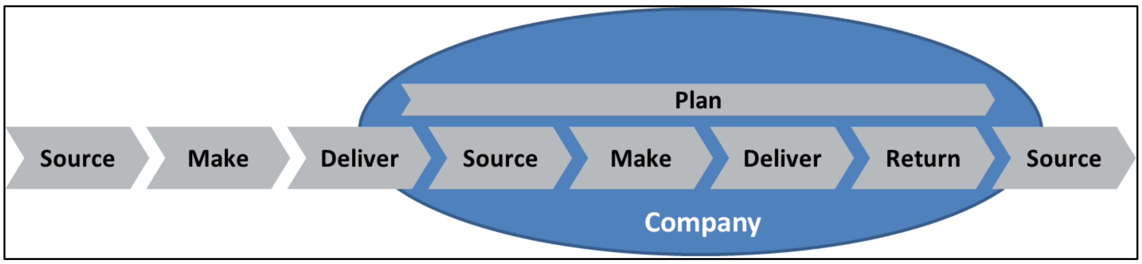


Figure 4: SCOR Model (adapted from Thaler, 2001, pp. 47)

Because the SCOR model focuses on a single company, the entire value chain may behave like a network where manufacturing plants are geographically distributed (Saiz et al., 2006). The network consists of not merely one but several different players. This network can be differentiated for original equipment manufacturers (OEM) and suppliers in different tiers. Saiz defines supply networks (SN) as “a network that performs the function of materials procurement, transformation of these products into intermediates and finished products, and the distribution of those products to the final customers” (2006, pp. 163). Saiz adds that a supply network includes “production units (manufacturing and assembly processes, and inventories for temporary stocking) and storage points (distribution centers), connected by transportation of goods and by exchange of information, as well as their corresponding planning and control system” (2006, pp. 163).

Figure 5 provides an overview of a supply chain network, where each organization has a finite number of first-tier suppliers and customers, and each supplier has a finite number of suppliers. Thus, a supply chain consists of different parties with several interfaces. Childerhouse et al. (2011) describe the upstream and downstream processes in a supply chain of an organization, showing a finite number of interfaces.

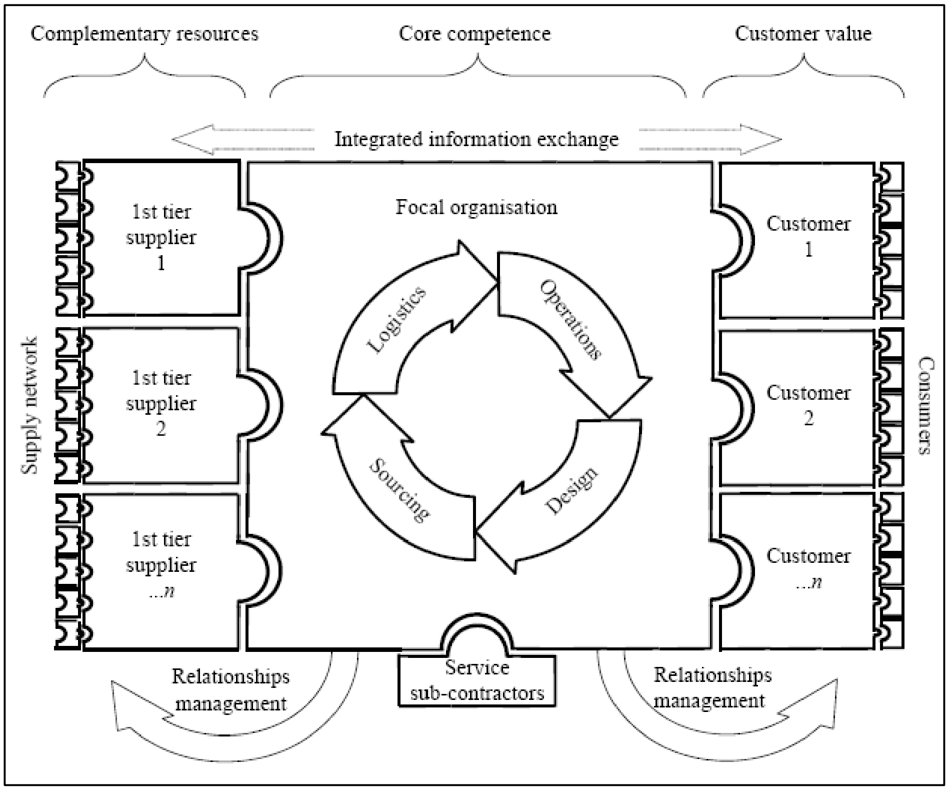


Figure 5: Supply chain integration (Childerhouse et al., 2011, pp. 531)

The automobile industry has started to rank its supplier base according to different tiers, assuming that an automotive OEM as a focal organization has three tiers of suppliers. Pavlinek and Janek describe first-tier suppliers as those delivering “pre-assembled autonomous subsystems or components” and second-tier suppliers as those providing “smaller and less complex components from smaller parts” (2007, pp. 140). Based on these definitions, the main difference between first- and second-tier suppliers is that the former is autonomous; second-tier suppliers supply first-tier suppliers with components and directly supply OEM with smaller parts if the OEM produces the components (e.g., engines) itself.

A third-tier supplier produces "simple components with low value-added in production" (Pavlinek and Janek, 2007, pp. 140). Although this automobile industry model helps to manage the supply chain and supplier base, it is not as accurate as it should be because it does not consider other elements (e.g., raw material supply) that might play a significant role in the context of additive manufacturing. In this dissertation, therefore, this model will be extended by considering raw material supply.

An important part of SCM is logistics. Although these terms are often used synonymously, they are different. Logistics focuses on the coordination of logistical activities of supply. On the other hand, SCM is the management of the "interconnectivity of information technology, logistics process, and customer support" and refers to "alliances with supply chain partners, lean processes, and end-to-end integration of key business processes," where "the enabling technology is information" (Russell, 1997, pp. 63).

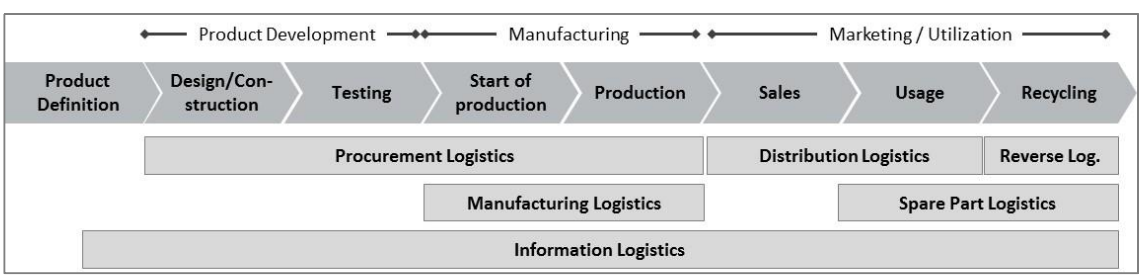


Figure 6: Logistics across a product life cycle

(adapted from Kersten et al., 2006, pp. 327)

The Council of Supply Chain Management Professionals provides a widely accepted definition of major logistics activities:

> "Logistics management activities typically include inbound and outbound transportation management, fleet management, warehousing, materials handling, order fulfillment, logistics network design, inventory management, supply/demand planning, and management of third party logistics services providers. To varying degrees, the logistics function also includes sourcing and procurement, production planning and scheduling, packaging and assembly, and customer service. It is involved in all levels of planning and execution—strategic, operational and tactical. Logistics management is an integrating function, which coordinates and optimizes all logistics activities, as well as integrates logistics activities with other functions including marketing, sales manufacturing, finance, and information technology." (n.d.)

Major logistics activities could be clustered along the life cycle of a product. There are many product life cycle definitions; across Europe, the product lifecycle is divided into the stages of market research, product and process planning, development and construction, sourcing, production, testing, packaging and storing, sales, installation and usage, product observation, technical support, and recycling or re-usage (Binner, 2002). However, Kersten et al. (2006) suggest a more simplified life cycle definition as shown in Figure 6. In this life cycle, Kersten et al. cluster logistics activities into procurement logistics, distribution logistics, manufacturing logistics, spare parts logistics, reverse logistics, and information logistics. Although other researchers like Binner (2002) include sales and development logistics as logistics processes in their definition, a more complicated definition of life cycle like this one may not be appropriate in the context of this dissertation, as such definition has a negligible linkage to the manufacturing technology.

2.2.2. Supply chain objectives

After defining this dissertation's conceptual framework of supply chains in a production environment, it is important to review the overall objectives of supply chains. The overall objectives will be used to define the measures for performance assessment.

Chopra and Meindl (2007, pp. 3) identify a generic objective: "The objective of every supply chain should be to maximize the overall value generated." Chopra and Meindl define value as the difference between the cost of the supply chain and the worth of the product to the customer (i.e., profit). However, such a definition that focuses on costs may not be appropriate, as it does not allow sufficient control of the overall supply chain. Costs will always be the guiding principle, but other detailed and measureable elements should be included to allow an efficient management of the supply chain. Thus, the definition should be expanded to include the generic objectives of logistics, which are the provision of the "right goods and information, in the right quantity, at the right place, at the right time and the right costs" (Thaler, 2001, pp. 43). It is arguable that not everything can be expressed in terms of costs. For example, if a product is not on supermarket shelves, it represents lost sales to a company, which could be measured and expressed in monetary values. Thus, the extended definition helps define performance measures beyond costs to allow a qualitative comparison of the effectiveness and efficiency of technologies.

2.2.3. Supply chain performance measurement

The literature provides several definitions of performance management. Pires and Aravechia provide a comprehensive definition:

> "Performance measurement can be defined as information regarding the processes and products results that allow the evaluation comparison in relation to goals, patterns, past results and with other processes and products. Also, it is important to highlight that a managerial performance evaluation system needs to be focused on results, which should be guided by the stakeholders' interests. (Pires and Aravechia, 2001, pp. 4)

There are other performance measurement definitions and conceptual frameworks like the Performance Pyramid (Gruening, 2001), the Quantum Performance Measurement (QPM) System (Hronec, 1993), and the widely used Balance Score Card (Kaplan and Norton, 1992). What these definitions have in common is the required subject of measurement, a quantifiable item called key performance indicator (KPI), which is also known by different terms depending on the researcher (e.g., Hronec refers to KPIs as "drivers."). In QPM, KPIs are clustered in different categories such as quality, costs, and time (Hronec, 1993).

There are also different approaches to measuring supply chain performance. For example, Chopra and Meindl (2007) suggest measuring performance based on the six major drivers of supply chains:

- *Facilities* – comprises all physical locations within a supply chain network
- *Inventory* – includes all stages in the supply chain and all types of inventories (raw materials, intermediate work-in-progress materials or components, finished goods)
- *Transportation* – encompasses all physical movement of goods
- *Information* – covers all available data within the supply chain and the methods and capabilities to make such data available
- *Sourcing* – covers the selection of who will perform a logistics activity in the supply chain.
- *Pricing* – the amount of money a firm will charge for the goods and services the supply chain is set up for

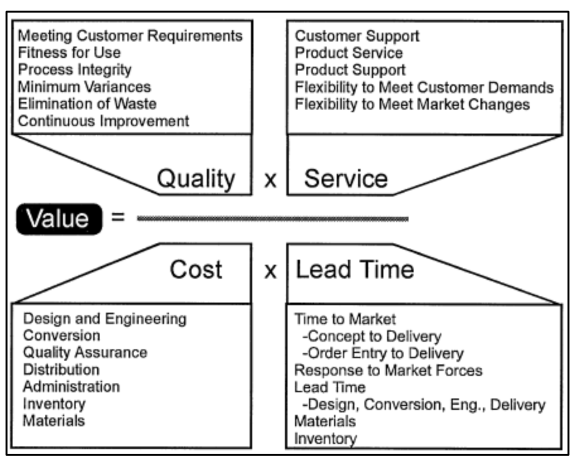


Figure 7: Total value metric

(Johannsson et al., 1993, as cited in Naylor et al., 1999, pp. 109)

Another approach is provided by Johannson (1993) which is focused on supply chain performance as a value created consisting of the four cluster quality, service, cost and lead time. As this is also reflecting the overall supply chain objective chosen by Chopra and Meindl (2007. p. 3) as described in section 2.2.2.

In this dissertation, I will adapt Johannsson's model (1993), shown in Figure 7, to evaluate the performance of traditional supply chains and remodeled supply chains that use additive manufacturing.

2.3. Introduction to Complexity, Complexity Drivers, and Complexity Management

2.3.1. Definition of complexity

Complexity has many definitions. However, before discussing the definitions of complexity, it is important to determine its scope. In general, complexity is related to a system such as a supply chain. A system has three main characteristics: It consists of *several parts* that *differ* from each other and that must be *linked* within an architecture (Vester and Hesler, 1980). There are several other definitions of systems, some of which are more field-specific, like that given by the National Aeronautics and Space Administration (NASA) Systems Engineering Handbook, which states that a system is an interaction "in an organized fashion towards a common purpose" (as cited in Shishko and Aster, 1995, pp. 3). Other descriptions of systems are listed in Table 3.

What these definitions have in common is that they acknowledge that a system consists of different elements or parts interacting in a defined fashion and that removing one part would affect the functionality of the system. This common definition will be used in this dissertation.

Table 3: Various descriptions of systems

Aspect of a system	Reported in
Several Parts Parts are different from each other Parts linked into an architecture	Vester & Hesler 1980
Linked parts Interaction influences system behavior Dynamic Complexity as a parameter of systems	Ulrich & Probst 2001
System represents a technical artifact System is concrete and dynamic Set of ordered and mutually linked elements	Pahl & Beitz 1996
System borders Inputs and outputs as connection to their surroundings	Lindemann 2007
Organized interaction of elements towards a purpose	NASA 1995
Structure as a system attribute	Daenzer & Huber 1999
System element compatible in form, fit and function Interacting elements can accomplish more than stand alone elements System possess uncertainty and risk	Wasson 2006

Source: Lindemann et al., 2009, pp. 23

Having defined a system, I need to point out that the system itself creates complexity or could be affected by complexity. A significant amount of research has been done on the issue of complexity in the context of different scientific disciplines. However, a comprehensive and commonly agreed-upon definition of complexity is not yet available. Saeed and Young (1998, pp. 1) define complexity as "the systemic effect that numerous products, customers, markets, processes, parts, and organizational entities have on activities, overhead structures, and information flows." Ulrich and Probst (1988) refer to complexity as resulting from the number of factors and their interconnectedness. Malik (2003) defines complexity as stemming from the number of different states a system could have. Coming up with a single comprehensive definition of complexity is difficult, as a conceptual definition might not be valuable for further reference. Non-scientific definitions such as by Wikipedia state that complexity is the negation of simplicity (Wikipedia, 2011). In this study, the term complexity is defined in the context of a system, specifically a supply chain, wherein due to the numerous possible states of each element and their interaction, the overall system could have numerous possible states itself, which then impacts management efforts to control the overall system.

2.3.2. Origins of complexity

2.3.2.1. Overview

The literature has different classifications for complexity drivers. In this dissertation, complexity is classified into *complexity clusters* based on how complexity is added to a system and the complexity driver, that is, what causes complexity.

2.3.2.2. Complexity clusters

By using the definition of complexity provided in section 2.3.1, I define a complexity driver as an element that affects the number of states a system could have by changing its

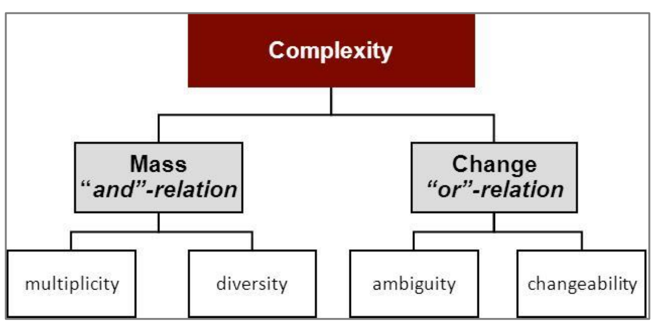


Figure 8: Complexity clusters (adapted from Reiss, 2001, p. 79)

state and interacting with other drivers or factors. Reiss (1993) identifies four major clusters of drivers: multiplicity, diversity, ambiguity, and changeability.

Figure 8 provides an overview of the different clusters defined by Reiss, and Table 4 provides examples of causes for each type of cluster.

Table 4: Four major clusters of complexity drivers, with examples

multiplicity	diversity	ambiguity	changeability
Frequency	Diversity	Ambiguity	Volatility
Volume	heterogeneities	Risk	Growth
Scale	Scope	Uncertainty	Instabilitiy
Openess	Variance	Fuzziness	Learning
Interface Density	Customization	Entropy	Change
....	....	....	....

Source: Adapted from Reiss, 2011, pp. 79

Reiss (2011) further categorized the four clusters into mass ("and" relation) and change ("or" relation). A mass cluster is one in which there is an absolute number of different system states ("and" relation), while a change cluster is one in which there is just one state addressing one element of the system ("or" relation) (Schuh, 2005; Reiss, 2011).

Other researchers in the field of complexity management either refer to Reiss' framework or focus on complexity sources; however, they have not yet developed a comparable comprehensive framework. Meanwhile, some researchers classify complexity clusters using two criteria:

- *Internal* and *external* complexity, that is, whether complexity is caused by the focal organization (*internal*) or caused by demand or other external factors like legislation (*external*) (Lindemann et al., 2009)
- *Dynamic* and *static* complexity, that is, whether complexity is caused by the setup of the system (*static*) or caused by changing parameters for operating the system (*dynamic*) (Frizelle and Woodcock, 1995).

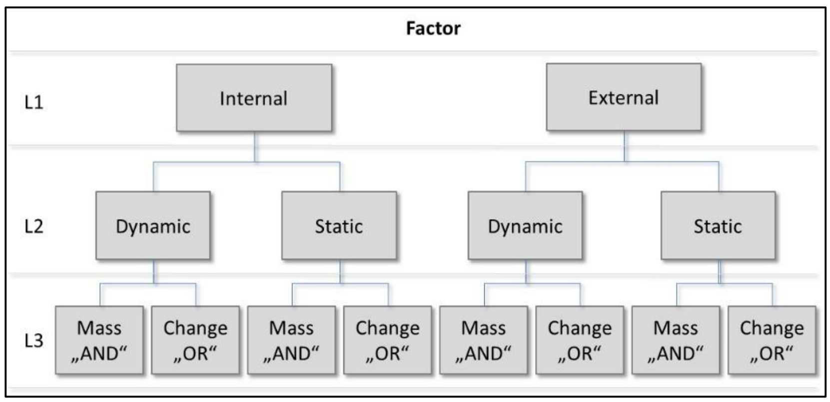


Figure 9: Complexity cluster tree

The above three types of cluster categorization could be used to build a hierarchical complexity tree with three binomial levels, resulting in eight different possible clusters (Figure 9). In this hierarchical order, the *internal* and *external* complexity clusters are at the top of the hierarchy and identify the appropriate strategy to manage complexity, an issue that is discussed in section 2.3.3.2. Next in the order are the *dynamic* or *static* complexity clusters, followed by the mass and change complexity clusters. Generally, the level one and two clusters are potentially interchangeable within the hierarchy, that is, which level comes first could be selected depending on how the complexity should be expressed. However, the basic strategies for complexity management that will be described later in this dissertation use the external and internal complexity clusters, as a major decision variable. This complexity tree has not been used in the existing literature. It is based on the hypothesis that each cluster needs a different set of tools to manage complexity efficiently. Further analysis is used to assess which tools could be supported by additive manufacturing and when to apply additive manufacturing to manage complexity. It is also important to evaluate if the complexity cluster tree described above can be used in determining which situations can adopt additive manufacturing to manage supply chain complexity efficiently.

2.3.2.3. Complexity sources

As described in the preceding sections, various criteria are used to categorize complexity drivers, such as *dynamic* and *static* complexity clusters and *internal* and *external* complexity clusters (Schuh, 2005; Lindemann et al., 2009). Figure 10 gives an overview of the four major areas of complexity inside and outside the organization: *market*, *product*, *organizational*, and *process*. Lindemann et al. (2009) view market complexity as an external complexity area, and product, organizational, and process complexity as internal complexity areas.

External complexity is mainly customer driven and reflects market needs and requirements; however, it could also include legislative and other external factors. In terms of customer driven factors, the main external complexity driver is product variability (Marti, 2007). On the other hand, internal complexity is partially a result of the external requirements. Internal complexity increases when the product life cycle is shortened and the number of product variants is increased (Schuh, 2005; Lindemann, 2009).

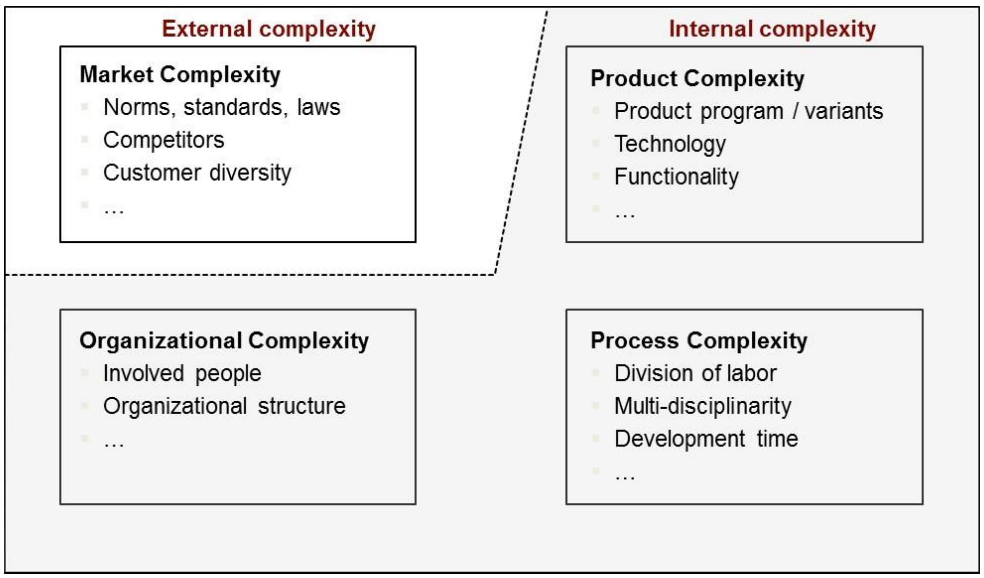


Figure 10: Four fields of complexity and associated sources (Lindemann et al., 2009, pp. 27)

In contrast to the generic view on key complexity drivers, Blecker et al. (2005) classify complexity based on its origin, varying widely from heterogeneous demands and incompatible IT systems to globalization.

Table 5: Supply chain complexity drivers and their origin

(Blecker et al., 2005, pp. 49)

KEY DRIVER CATEGORIES	Internal Organization	Supplier-Customer Interface	Dynamic Environment
Product/ Technological Intricacy	• heterogeneous demands • raising product complexity • new technologies	• non synchronized supply chain planning & control systems • incompatible IT systems	• technological innovations • changing resource requirements • technological customer demands
Organizational Aspects	• process-related deficits • structural deficits	• different strategies • non harmonized decisions & actions • supply chain bottlenecks • information gaps • non-harmonized processes • supplier & customer reliability	• development of business environment • provisions of law • globalization • shortened product lifecycles
Uncertainty	• subjective estimations • changing skill requirements	• demand amplification (bullwhip) • parallel interactions • non synchronized decisions & acting	• general uncertainty of future development • economic trends • decreasing accuracy of forecast
		ORIGIN	

2.3.3. Complexity management

2.3.3.1.Definition of complexity management

Complexity management within a production environment deals with controlling and optimizing the level of complexity. Schuh (2005) defines complexity management as structuring, controlling, and developing varieties (e.g., "products, processes, resources") within the entire value chain. The objectives of complexity management are to optimize overall costs and customer value by choosing the right level of complexity (Saeed and Young, 1998).

2.3.3.2. *Basic strategies*

There are several basic strategies for managing complexity, each of which is comprised of numerous of tools.

Kaiser (1995) identified three major strategies based on the level of internal or external complexity in a system: avoidance, avoidance and control, and control. Figure 11 provides an overview of when each strategy should be applied.

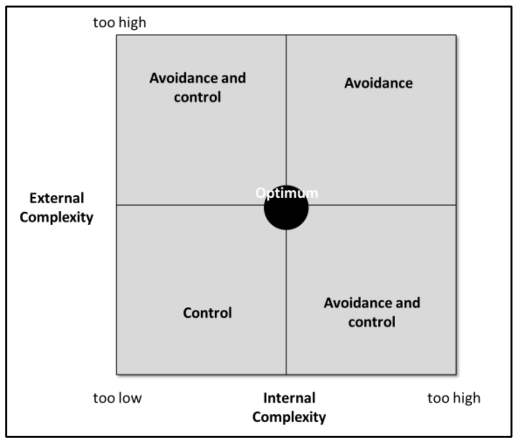


Figure 11: Appropriate situations for applying avoidance, avoidance and control, and control strategies (Kaiser, 1995, pp. 102)

Saeed and Young (1998) provide four strategies: eliminate, that is, reducing complexity; segregate, that is, modularizing products; accommodate, that is, providing the right resources to deal with complexity; and innovate, that is, developing new processes, approaches, and new products to increase customer value in order to deal with complexity.

These two sets of approaches are not contradictory; Saeed and Young's view could be integrated into Kaiser's. The difference between the two is that the Saeed and Young provide a basic strategic view, while Kaiser gives guidance on which tools to choose. Saeed and Young's approach lacks guidance when it comes to applying the strategy.

2.3.3.3. Overview of related concepts

In addition to the basic strategies, there are other concepts important to the management of complexity. According to Marti (2007), there are three major conceptual approaches to complexity management: mass customization, lean management, and optimum variety. Each of these concepts has a set of specific tools for complexity management. Figure 12 provides an overview of the most commonly used tools.

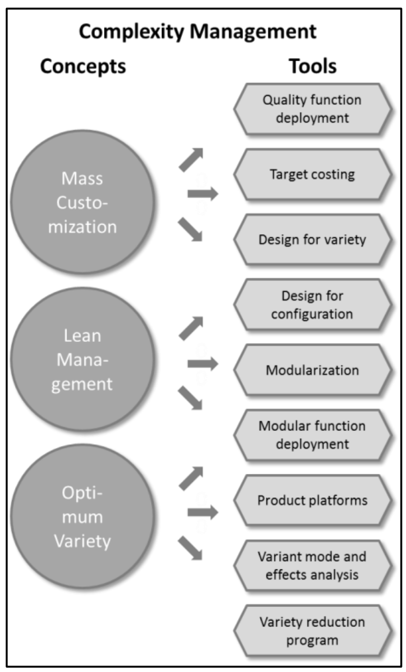


Figure 12: Complexity management tools (Marti, 2007, pp. 89)

The general concepts of these three approaches can be gleaned from the tools they use. However, it is also important to understand the philosophy behind the concepts in order to determine when the tools can be applied effectively. Later, these three approaches and their corresponding tools are described and the applicability of the concepts and the tools is assessed in the context of additive manufacturing.

2.3.3.4. Mass customization

Davis (1987) created the term *mass customization* to describe a new type of production, which combines mass production and customization. Pine (1993) and Tseng and Jiao (2001) define *mass customization* as the merger of two production models, mass and craft production. According to Pine (1993), increasingly fragmented demand, heterogeneous niches, and short product life cycles are contrary to classical mass production approaches, which are based on stability and repeatability for efficiency. Pine (1993) identifies six major events that may lead to *mass customization*: decrease in input factor stability; changing customer requirements; changes in demographic development; market saturation; general economic cycles, shocks, and uncertainties; and significant changes in technology or emerging technologies.

Table 6: Differences between mass production and mass customization (Pine, 1993, pp. 7)

	Mass Production	Mass Customization
Focus	Efficiency through stability and control	Variety and customization through flexibility and quick responsiveness
Goal	Developing, producing, marketing, and delivering goods and services at prices low enough that nearly everyone can afford them	Developing, producing, marketing, and delivering goods and services with enough variety and customization that nearly everyone finds exactly what they want
Key Features	▪ Stable demand ▪ Large, homogeneous markets ▪ Low-cost, consistent quality, standardized goods and services ▪ Long product development cycles ▪ Long product life cycles	▪ Fragmented demand ▪ Heterogeneous niches ▪ Low-cost, high quality, customized goods and services ▪ Short product development cycles ▪ Short product life cycles

Table 6 shows how Pine (1993) contrasted the two concepts of mass production and mass customization. Pine (1993) introduced five different methods for addressing different stages in the product sales and development process in mass customization. In the first approach, Pine differentiates between customizing not the product itself but the services around the product. For example, Lufthansa Airlines customizes its passenger flights by providing add-on services like fast-track boarding, seat upgrades, personal recognition of passengers, and luxury shuttle transports to the plane.

The second mass customization approach is about customizing products and services, where the standard product is manufactured such that it can adapt to the requirements of the customer (e.g., making adjustable steering wheels). In this method, the production process remains standardized.

The third method is point-of-sale (POS) customization, where customers can customize a standard product toward the end of the supply chain, that is, the POS. Depending on the amount of value added at the POS, the organization may face significant adaptability requirements within its supply chain and may lose scale effects. A typical example of POS customization is made-to-measure clothing, where a standard-sized suit is adapted according to the measurements of the customers.

The fourth mass customization method is providing a quick response throughout the value chain, which means speeding up all processes along the value chain, from product development and setup to distribution.

Finally, the fifth method focuses on the modularization of components, products, and services. According to Pine (1993), this is the most effective method of mass customization, as this allows working with standard elements, which in turn allows creating differentiated products just through different possible permutations and without losing scale effects.

A short description of additive manufacturing in the context of mass customization

Pine (1993) does not have a specific view on additive manufacturing but states that it could be used as a production and value chain management tool. Additive manufacturing can be used to support and enhance the five methods defined by Pine (1993). Apart from re-thinking how a product is produced, additive manufacturing may have limited value added in a mass customization strategy in methods one and two. A benefit in these methods could be that if product design complexity increases, additive manufacturing might be sufficient to use. In contrast, additive manufacturing may deliver a significant advantage to the third method (POS customization), the fourth method (quick response throughout the value chain), and the fifth method (modularization). Additive manufacturing may have an even higher value added in POS customization because in this type of customization, production machines are flexible and do not need specific tools. Additive manufacturing may also speed up responsiveness in the fourth method due to the minimized setup costs and the greater possibility of a decentralized production.

In the mass customization through modularization approach, additive manufacturing is still a controversial strategy, as modularization utilizes scale effects by producing standard modules, while AM allows lot-size-one production. Nevertheless, additive manufacturing may be useful to this method of customization, especially in areas where development and testing have high costs, because it allows controlled customization. If lot sizes decreases for modularized products, typically, the cost competitiveness of AM increases. The break-even point for lot sizes continues to increase, so AM could be an effective way of making modularized products more cost-competitive.

Tucker et al. (2010) claim that in rapid prototyping, additive manufacturing is considered an extreme form of customization. However, the focus of this dissertation is on the production technology itself, not on the implications on the supply chain value.

2.3.3.5. Lean management

Lean management is a management concept developed in the 1990s. It is based on a study on how Japanese automotive manufacturers have achieved a significant increase in productivity compared to Western manufacturers. A basic concept of lean management was developed by Womack and Jones (2003) based on five basic principles (Figure 13).

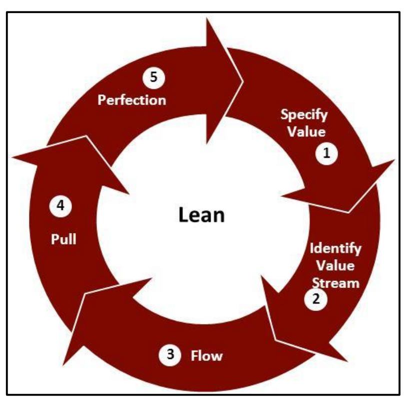


Figure 13: Lean principles (adapted from Womack and Jones, 2003, pp. 19–29)

The first principle according to Womack and Jones (2003) is *specifying value*, that is, defining the value for the corporation. In this principle, value is defined as the opposite of waste and is determined by the ultimate customer. In other words, value is everything that is valued and paid for by the customer.

The second principle is *identifying the value stream*, where value stream is defined as follows:

> "…set of all specific actions required to bring a specific product […] through the three critical management tasks […]: the problem-solving task running from concept through detailed design and engineering to production launch, the information management task running from order-taking through detailed scheduling to delivery, and the physical transforming task proceeding from raw materials to a finished product in the hand of the customer." (Womack and Jones, 2003, pp. 19)

The first step in the lean thinking process is ensuring *flow*, that is, making all the value creating steps flow (Womack and Jones, 2003). This step is based on a streamlined production line without any buffers.

The second step is *pull*, which has a strong correlation to the first step. This step attempts to forecast customer demand based on which all the required value-creating steps, from product development and production to distribution, will be determined. In contrast, in *push*, products are developed and produced even though customer demand is not known.

The final step is *perfection*, which pertains to the impeccable execution of the other steps and the continuous improvement of the performance of the organization continuously in accordance to the customers' continuously changing requirements and behaviors.

A short reflection of additive manufacturing and complexity management in the context of lean management

Lean management aims to streamline the overall value stream. Womack et al. (1994) view lean production as a new production paradigm in addition to mass and craft production.

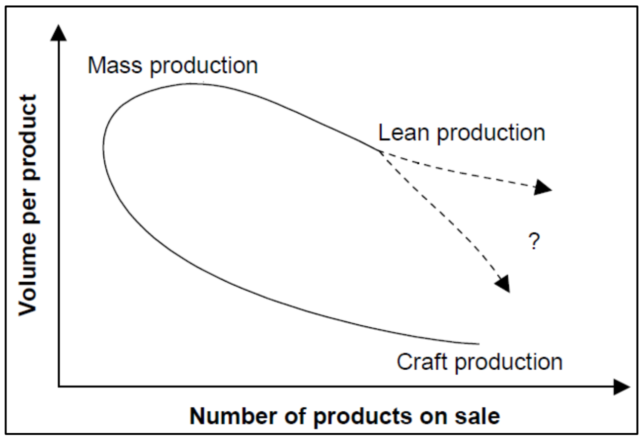


Figure 14: Production variety and volume depending on the production paradigm (Womack, Jones, and Ross, 1990, pp. 126)

As shown in Figure 14, Womack et al. (1990) see a strong correlation between production paradigms and the volume per product and the number of products on sale. They do not state which paradigm is suitable to volume per product and number of products; however, they state that additive manufacturing production can be integrated into lean management. To avoid waste, which is lean management's basic principle, additive manufacturing allows the avoidance of buffers or intermediate products following the just-in-time concept of producing a part only when it is required. In essence, additive manufacturing in this case adopts the pull step. Traditional production processes use batch production to offset setup costs and achieve economies of scale. In contrast, additive manufacturing can help to avoid such setup costs.

2.3.3.6. Optimum variety

The concept of optimum variety is based on research by Rathnow (1993), who developed a three-step approach to optimize product variance within an organization. As a first step, Rathnow proposes to optimize the product portfolio through gathering customer insights and then determining which level of variance is valued by the customers. The optimal product portfolio and the related level of product variance are defined as the product and variant mix that provides the optimal cost-benefit ratio (Figure 15). Thus, the optimum variety is a specific point (set of variety) where the marginal benefit equals the marginal cost.

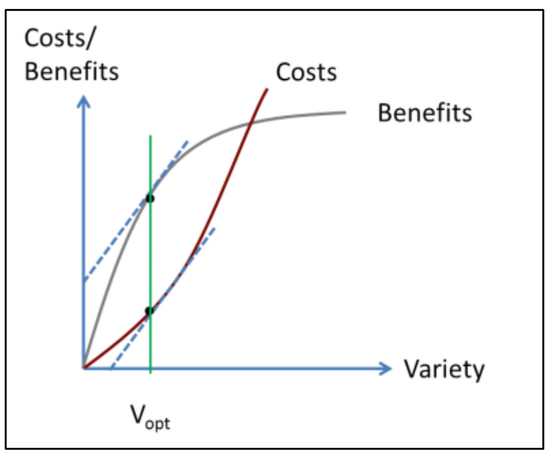


Figure 15: Optimum variety (Rathnow, 1993, pp. 42)

According to Rathnow (1993), the second step is taking a different approach by optimizing the costs for a pre-defined number of variants. The third step is bringing the independently optimized outputs from steps 1 and 2 together and then identifying their interdependence. By paying more attention to other environmental aspects (e.g., competitor behavior, governmental requirements), an optimized level of variety will be defined (Rathnow, 1993).

This conceptual framework delivers an approach to defining the optimum product portfolio; however, it has a very limited scope in supply chain complexity optimization—in fact, it reflects most supply chain issues outside the organization only by their influence on cost.

A short reflection on the optimum variant concept in the context of additive manufacturing

The major idea of the optimum variant concept is to leverage the optimum cost-benefit ratio, but Rathnow's (1993) description of the concept implies that complexity itself is fairly costly. Nevertheless, the concept seems to be right regardless of which production technology is used. However, the hypothesis that needs to be tested in this dissertation is that additive manufacturing helps to reduce the costs of complexity.

Selected Tools

2.3.3.7.Quality function deployment

Quality function deployment traces its roots to the 1960s in the Japanese ship-building industry. It is a key tool in the field of quality management and especially in the Six Sigma strategy

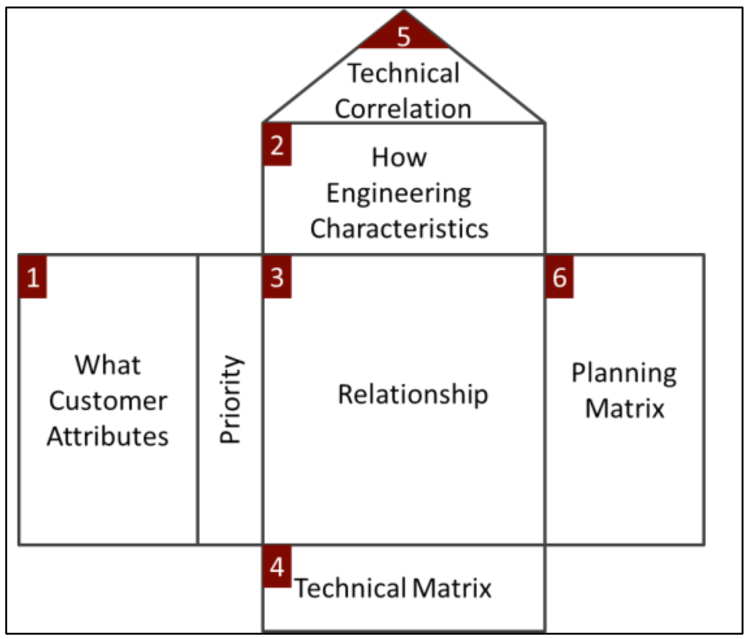


Figure 16: House of Quality (adapted from the Institute for Manufacturing, 2012)

(Rowe, 2011). QFD has been explored in depth in science. QFD is defined as “an overall concept that provides a means of translating customer requirements into the appropriate technical requirements for each stage of product development and production (i.e., marketing strategies, planning, product design and engineering, prototype evaluation, production process development, production, sales)” (Sullivan, 1986, pp. 463).

QFD is often referred as the "House of Quality," which is a matrix incorporating 10 major areas based on customer requirements that need to be incorporated in product development. The House of Quality has several variants. It has several interpretations, including one by the Institute for Manufacturing (IfM) at the University of Cambridge (which will be used in this dissertation)

Figure 16). Another interpretation is by Johnson (2003), who divided the technical assessment aspect into four different steps: technical assessment, importance, technical difficulties, and target values.

Step 1 in the House of Quality answers the question of what product to develop (Figure 16). It is the process of defining the product attributes requested by the customer, which is a process of "describing what the product must do" (IfM, 2012). It is a structured listing of all the requirements a product must provide to fulfill the customer needs determined by market research. Step 2 answers the question of how to develop the product, a process that includes gathering all the engineering characteristics to produce a product that could fulfill the customers' requirements (Figure 16).

Figure 16Step 3 is the heart of the House of Quality and involves determining the relationship between the customer and engineering characteristics and then clustering them into strong, medium, and weak relationships. For this step, there is no predefined clustering scheme or scale. It could be done with any system, such as a qualitative assessment using symbols (e.g., smiley). The relationship matrix is the basis for the cross-functional product discussions within the organization. It clarifies the dependencies between the technical and customer requirements.

Step 4 involves indicating “the technical priorities based on the relationships between customer requirements and engineering characteristics. It is also about providing quantitative design targets for each of the engineering characteristics, based on the technical priorities and competitive benchmarking” (IfM, 2012). Step 5 involves defining engineering, supporting, and contradictory technical characteristics. For example, a car with a higher speed may require a higher engine power, which may lead to higher fuel consumption. If the target is lower fuel consumption, then the higher speed would be contradictory and should be avoided. This step helps clarify all potential technical tradeoffs. Step 6, involving the planning matrix, is “providing quantitative market data for each of the customer attributes. Values can be based on user research, competitive analysis or team assessment” (IfM, (2012).

The basic idea and strength of the House of Quality is to foster a fact-based and transparent discussion of a cross-functional team to derive a consensus on how a product should look in the product development stage in a structured manner (Burn, 1990).

2.3.3.8.Target costing

According to Monden and Hamada (1991, pp. 16), "'target costing' is the system to support the cost reduction process in the developing and designing phase of an entirely new model, a full model change or a minor model change.” Target costing was first developed in the 1960s at Toyota (Tanaka, 1993). This concept changed the view on pricing from an organizational to a market one. In other words, instead of a *bottom-up* (cost-plus) calculation of a product’s price, target costing applies a *top-down* approach by defining the target prices and profit. To define the target prices, market research could be conducted as a “market-into-company” approach (Horvath, 2002; Buggert et al., 1995). Other approaches to defining a target price are “out-of-competitor,” “out-of-company,” and “out-of-standard costs” (Volkmann, 2000). However, I will not use these other approaches in this dissertation because it does not focus on where the target prices will come from.

After defining the allowable costs, management needs to define the target costs, which is in the difference between the standard costs and allowable costs of the company (Hiromoto, 1988).

The challenge in target pricing arises from the difference between the standard costs and the target price, called “drifting costs” (Buggert et al., 1995, pp. 44). To reduce drifting costs, the target price must be broken down according to either *components*, which are mainly used for existing products, or *functions*, which are mainly used for new products.

The *component* breakdown defines per-component target costs (Fröhlich, 1994).

The *functional* breakdown is similar to the component breakdown from a mathematical standpoint, but the weighting of each function is based on market research. The objective of the market research is to define how much a function is valued by a customer. Based on the outcome of the research, the importance of the function is defined (Jung, 2007). After the function and its importance are defined, the required components will be deployed. Note that the function is realized through the interaction of the different components.

Table 7 shows how functions could be assigned to components.

This function assignment method is used to define the targets for the specific development teams for each individual component. It is purely market-oriented, as it implements cost reduction efforts purely based on market requirements.

Table 7: Assignment of functions to components

		Functions				
		Function 1	Function 2	Function 3	...	Total
	Importance of function	14,4%	15,3%	9,8%		100%
	Costs contribution	30,0%	38,0%	18,0%		
Component 1	Target costs contribution	4,3%	5,8%	1,8%		14,9%
	Costs contribution	30,0%	62,0%			
Component 2	Target costs	4,3%	9,5%	0,0%		20,8%
	Target costs contribution	5,0%				
Component 3	Target costs	0,7%				
	Target costs contribution					
...	Target costs					
	Costs contribution					
Component N	Target costs contribution					

Source: Adapted from Tanaka, 1989, pp. 62–63

2.3.3.9.Design for variety

Ishii and Martin (2002) introduced the concept of "Design for Variety" to evaluate the impact of variety on a product line's cost. According to them (2002, pp. 213), "Design for variety (DFV) is a series of structured methodologies to help design teams reduce the impact of variety on the life-cycle costs for a product." In their initial research, Ishii and Martin (2002) introduced three indices for identifying and capturing the impact of variety on costs:

- the commonality index, which is "a measure of how well the design utilizes standardized parts" (Ishii and Martin, 1997, pp. 3);

- the differentiation index, which is a measure describing where differentiation occurs in the process; and
- the setup index, which is an “indirect measure of how switchover costs contribute to the overall costs of the product. […] It is meant to act as a general indicator of how substantial setups are for the product being considered” (ibid.).

To visualize variety, Ishii and Martin (1997) propose the use of a process sequence graph. This graph visualizes the process flow of the product and its differentiation points.

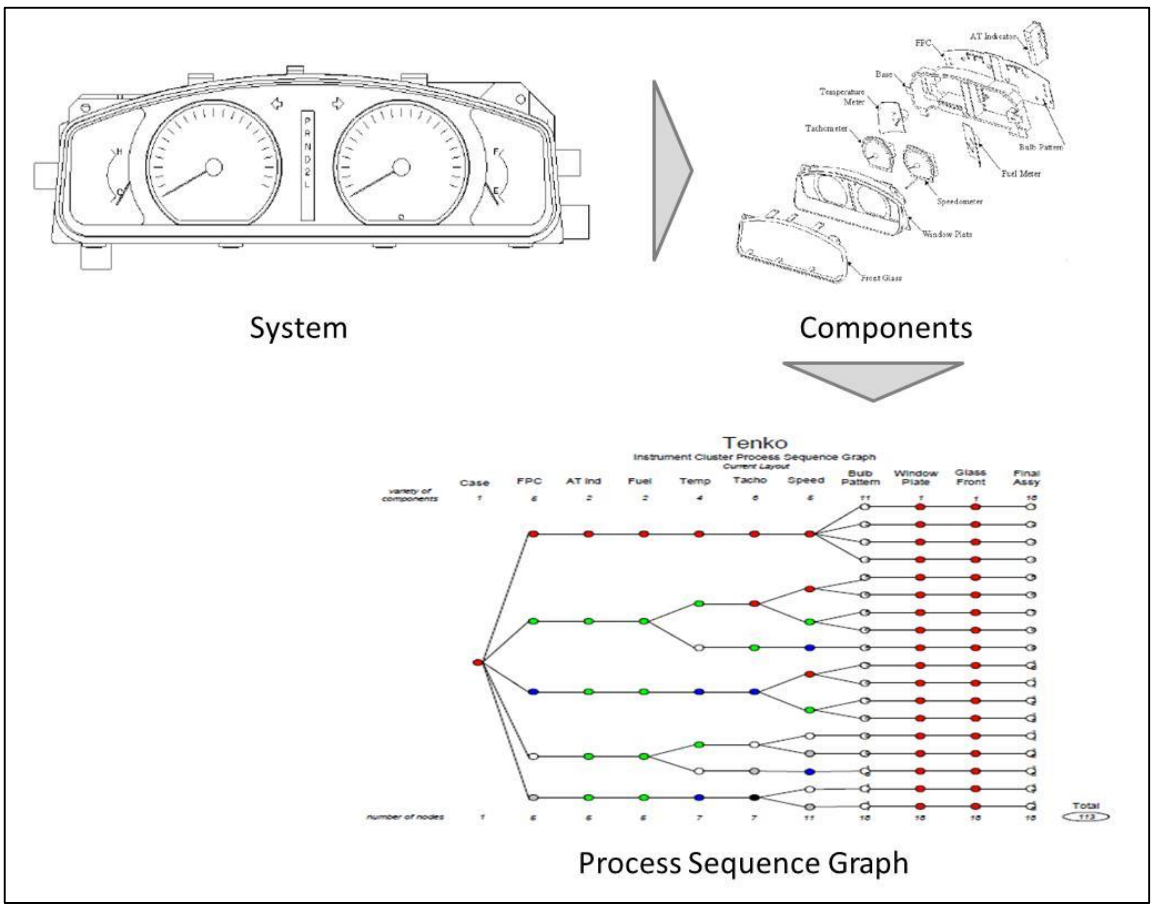


Figure 17: Development of a process sequence graph (adapted from Ishii and Martin, 1997, pp. 4–5)

Figure 17 shows the schematic development stages for a process sequence graph of a dash panel. The graphical representation shows that differentiation starts early at the second point of the process, which is the insertion of the flexible printed circuit (FBC). Ishii and Martin (1997) propose two major tools to manage complexity:

- differentiate at the latest possible stage in the process and
- reduce the overall number of differentiation points by optimizing the manufacturing and assembly sequence.

They developed an algorithm to define the optimum process sequence to gain costs benefits from reduced inventories and complexity management costs (Ishii and Martin, 1997).

2.3.3.10. Design for configuration

The Design for Configuration (DFC) methodology was developed in the late 1990s. It is based on product configuration, which has two aspects:

> *Given:* (A) a fixed, pre-defined set of components, where a component is described by a set of properties, ports for connecting it to other components, constraints at each port that describe the components that can be connected at that port, and other structural constraints; (B) some description of the desired configuration; and (C) possibly some criteria for making optimal selections.
> *Build:* one or more configurations that satisfy all the requirements, where a configuration is a set of components and a description of the connections between the components in the set, or detect inconsistencies in the requirements (Mittal and Fraymann, 1989, pp. 1396).

Based on these two aspects, DFC is a methodology for producing and managing knowledge for product configuration systems, which are an important element in mass customization (Riitahuhta and Pulkkinen, 2001). The basic idea of DFC is that products of a company should be re-engineered as configurable product families. A fixed variety of products in the assortment could be configured from a fixed set of modules, components, or add-ons, as in the case of the sales configurator in the automotive industry (Pulkkinen, 2007).

According to Pulkkinen (2007), a product configuration system has four properties. Every product variant must consist of a combination of pre-defined components or modules; the pre-defined product architecture should be designed such that it meets the range of customer requirements; the new design will not be fostered by the sales process but rather be a systematic configuration of the product variants; and finally, the architecture of all variants within one product family is the same.

DFC is a methodology with a clear focus on product architecture during the product design phase. Although it helps in determining the optimum cost in product development, it does not provide any quantifiable framework for managing product complexity (Pulkkinen et al., 1999).

2.3.3.11. Modularization

The idea behind modularization is to develop standardized modules, which could be configured in different ways to produce a final product or service. The number of permutations should provide customers the perception of having a highly customized product. In this method, scale effects should be achieved by establishing standard modules produced on a high scale. This approach is widely used in the automotive industry. Figure 18 shows how Volkswagen uses this approach by moving from using modules within a car model platform to using modules across platforms.

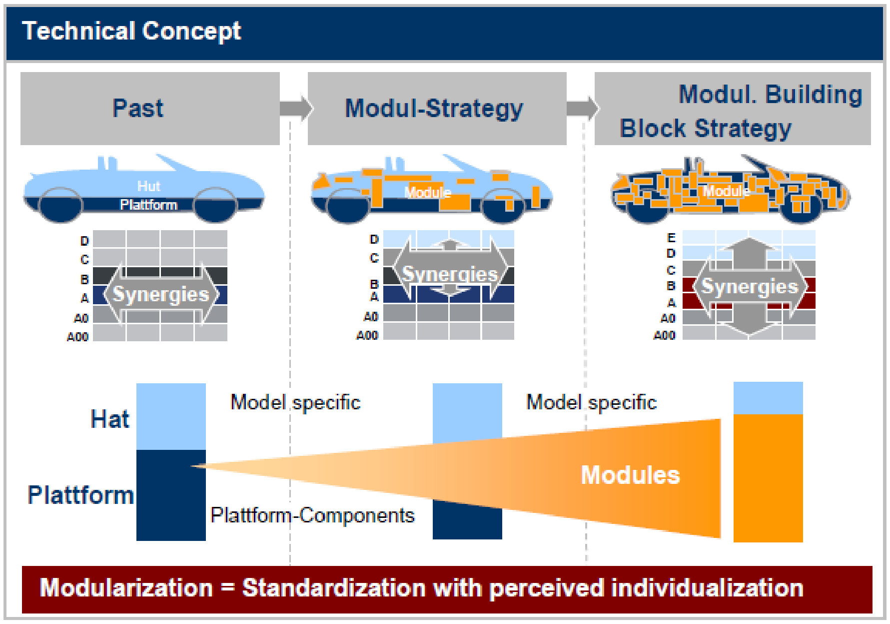


Figure 18: Modular building block concept at Volkswagen (adapted from Winterkorn, 2011, pp. 5)

Winterkorn (2011) describes Volkswagen's modularization as standardization with perceived visible individualization. Volkswagen's approach uses the "above-the-skin" concept. Scheel and Hubbart (2009) define "above-the-skin" complexity as that visible to customers and "below-the-skin" complexity as that not visible to customers, "such as component parts, raw materials or manufacturing processes" (Scheel and Hubbart, 2009, pp. 7). Volkswagen has been moving from using model-specific parts—especially the hat—to more modules, but it also uses modularization to manage "above-the-skin" complexity across model platforms.

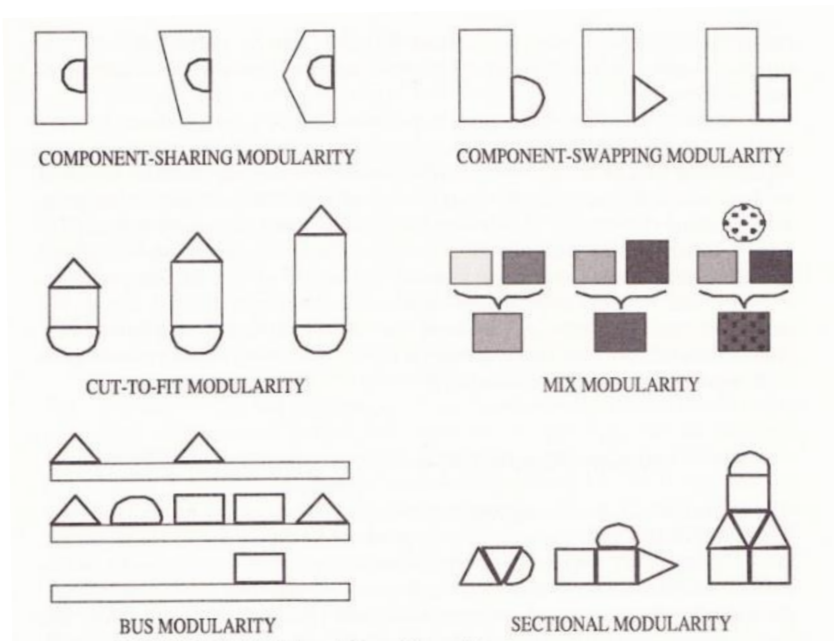


Figure 19: Six types of modularity for mass customization (Pine, 1993, pp. 201)

Pine (1993) defined six different types of modularity (Figure 19). The *component-sharing modularity* uses the same component across different products. In contrast, the *component-swapping modularity* uses different components with a basic product in order to create a number of variants. The *cut-to-fit modularity* uses a standard component that is scaled through variable components or elements and is mainly used for scaling physical dimensions. The *mix modularity* is a combination of any of the concepts above, for example, using cut-to-fit modularity for a certain set of parts and sectional modularity for other sets of parts. The *bus modularity* uses a standard structure with a pre-defined number of standard interfaces so that components could be easily added to the base structure. Finally, the *sectional modularity*, the most variable modularization type, is based on using standard interfaces between all components so they could all be combined (Pine, 1993).

2.3.3.12. Modular function deployment

Modular function deployment (MFD) is a structured five-step process first developed by Erixon in 1998 to create modular product families (Bongulielmi, 2002).

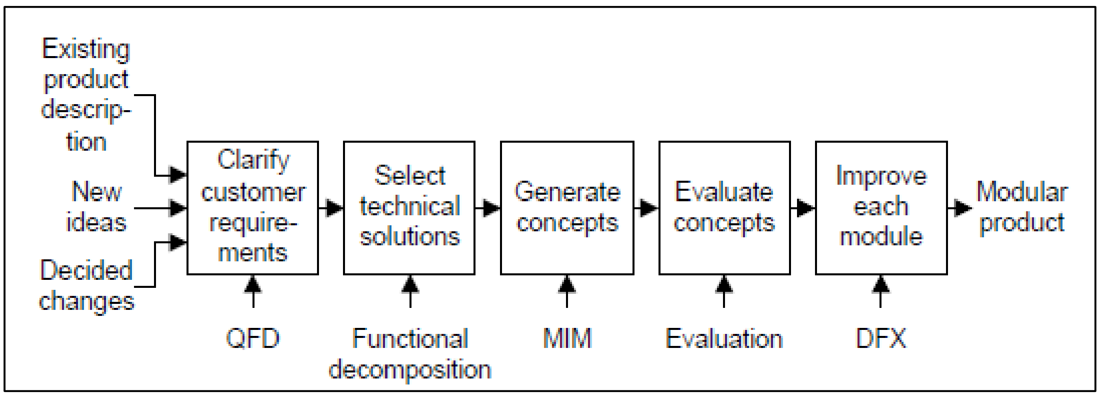


Figure 20: Modular function deployment (Erixon, 1998, pp. 66)

In the first step of MFD, the customer requirements are gathered and translated into a product. Erixon (1998) suggests QFD (see also section 2.3.3.7) as a methodology for this step. In the second step, which deals with product development, a more technology-focused approach is required; the customer requirements are decomposed into functions and sub-functions. Technological alternatives are discussed after decomposition, and thereafter, the customer requirements are translated into technical solutions. In the third step, concepts are defined and evaluated against twelve module drivers (Table 8), where additional company-specific drivers may be incorporated. In this step, each technical alternative for each sub-function is evaluated against the module drivers within the module indication matrix (MIM). The higher a sub-function is rated against the module driver, the more interesting the sub-function for modularization is.

Table 8: Module drivers

Design and development	Carry-over
	Technology push
	Product planning
Variance	Technical specification
	Styling
Manufacturing	Common units
	Process / Organization
Quality	Separate testing
Purchase	Black box engineering
After sales	Service / maintenance
	Upgrading
	Recycling
Company specific	

Source: Erixon, 1998, pp. 108

In the fourth step, the concepts are finally evaluated considering costs and assembly aspects as well as interfaces between the modules. The outcome of the overall evaluation is the final variant for production. In the fifth and last step, all modules are continuously improved or optimized by using any DFX method like *Design for Assembly* or *Design for Manufacturing* (Bongulielmi, 2002; Raap, 2010).

2.3.3.13. Product platforms

Meyer and Lehnerd (1997) define a *product platform* as a set of subsystems and interfaces building a structure as the basis for developing and manufacturing a number of products. The *product platform* concept is used to increase the number of shared parts across product variants (Meyer and Lehnerd, 1997). The concept is adopted to reduce complexity in products by dividing the product architecture into platforms, that is, into standardized and customized parts to allow the creation of a large number of distinct product variants by combining the two types of product parts. The product platform concept is used to handle the trade-off between cost savings through scale effects on the product platform parts and to create a competitive edge through differentiated, customizable product parts. According to Boutellier et al. (1997), this concept does not require the implementation of the platform across an entire product line but on individual modules.

Robertson and Ulrich (1998) proposed a three-step approach to establish a product platform process. The initial step is to develop a product plan for which models and variants should be established in the market and when. Additionally, an accompanying business plan across the life cycle of the platform can be developed.

In the second step, all product characteristics are listed and divided into common and differentiated attributes. A differentiation plan is developed, which includes all the differentiated attributes on a variant level. At this stage, a decision on the trade-off between commonality and differentiation is made. Further, the differentiation plan must have a special focus on the appropriate customer segment that needs to be targeted by the platform.

The third step is to establish the commonality plan, which includes all commonalities on a modular level. Within an iterative process, the plans may be adapted to allow the optimization of the cost vs. competitive edge trade-off (Meyer and Lehnerd, 1997).

2.3.3.14. Variant mode and effects analysis

The Variant Mode and Effect Analysis (VMEA), developed by Caesar in 1991, is a methodology inspired by the Failure Mode and Effects Analysis (FMEA), which analyzes, creates, and evaluates a product assortment across the product life cycle. The VMEA is a systematic approach that controls complexity in technical and cost issues using a four-step process. The first step, *portfolio development*, is the evaluation and creation by a cross-functional team of product functionalities based on market requirements. Pricing is fully based on the target costing concept (see section 2.3.3.8).

The second step, *product development*, optimizes product development toward product variety; the combination of functionalities is visualized and simulated with a variant tree to identify all variant drivers. The third step, *assembly*, evaluates the alternatives to realize the products technically in the assembly line and to define the assembly process step order (assembly order). The assembly order is critical because complexity should be pushed toward the latest possible step in the value chain. The different alternatives must be compared and evaluated against each other. The fourth step, *sales*, deals with complexity in the selling of a large variety of products. Due to the high number of possible product configurations, the risk that an unbuildable product configuration will be sold by the sales force is high. Thus, from a technology perspective, a pre-defined set of product configurations needs to be established, and sales channels should be created in a streamlined, simplified manner. Schuh (2005) suggests conducting business simulation games to derive to the optimum product portfolio.

2.3.3.15. *Variety reduction program*

Suzue and Kohdate developed the *Variety Reduction Program* in the 1990s as a methodology for reducing complexity costs. Instead of directly reducing complexity itself, the approach reduces the effects of complexity (as cited in Perona and Miragliotta, 2002). Suzue and Kohdate developed a threefold view on complexity costs:

- *Function*: Costs related to procuring and producing goods and materials to create a certain functionality. Costs are driven by the required functionality as well as the imminent product structure itself.
- *Variety*: Costs related to setups or equipment required by part or process varieties resulting in small lot sizes.
- *Control*: Costs related to activities for planning and controlling parts and processes.

Complexity cost drivers refer to the variety of parts, processes, and controls. To evaluate the different cost types, Suzue and Kohdate developed part, process, and control indices to estimate the effects of changes (as cited in Rapp, 2010) and developed five techniques for reducing the effects of variety without affecting the market and its requirements:

- *Fixed vs. variable*: This technique distinguishes between parts that are *fixed product components* and used for all variants of a product, and *variable parts*, which will be adapted, changed, or substituted to reflect market needs.
- *Combination*: The combination technique combines parts and components in a building block manner, so that with a limited number of parts, a high number of variants could be generated.

- *Multi-functionality and integration*: This technique reduces the total number of parts and components by integrating functionality by enhancing the design of a part or component.
- *Range*: This technique designs the specifications of a part or component (e.g., dimensions) such that the range of characteristics could be used in as many products as possible.
- *Trends*: This technique analyzes attributes and their characteristics and then tries to identify regularities across them with the objective of reducing the number of product variants.

2.4. Complexity in Supply Chains

2.4.1. Overview

As described in sections 2.2.1 and 2.3.1, the supply chain is a system itself, which consists of different interdependent and interacting elements. As described in section 2.2, the supply chain is linked to most of the business processes along the value chain as well as to all parties or partners involved.

The involvement of partners requires the harmonization of plans and value-added processes along the entire supply chain, including all business cooperation partners (Handfield and Nichols, 1999).

According to Kersten et al. (2005), there are nine different combinations of supply chain complexity as a result of multiplying three types of complexity origins by three key drivers, as shown in Table 5. Kersten et al. (2005) identify three major origins of complexity: the internal organization, supplier-customer interfaces, and customer requirements. Additionally, they identify three key driver categories: uncertainty, organizational aspects, and product or technology intricacy. This is a very generic categorization that is partially similar to the general complexity driver categorization.

Bak (2005) identified five major supply chain complexity drivers for the automotive industry:

- *Customer buying behavior*. This driver differs between target groups, especially for automotive OEMs, which usually provide a broad product portfolio to address a broad customer base. For single-product models, a customer-specific configuration is possible. This possibility produces an uncertainty in demand patterns.
- *Product configuration*. This driver results in a large number of available product variants.
- *Relationships*. This refers to the interaction between the upstream and downstream supply chain partners involved, from the supplier to the end customer.
- *Concentration of players in the market*. This driver results from an increasing consolidation and concentration of manufacturers, leading to an immobile, consolidated supplier base, which is less flexible than a widely spread supplier base. This tendency comes from the requirement of leveraging production scale effects.

- *Regulatory Power*: This driver occurs when local and regional regulatory requirements impose various standards (e.g., environmental), which require adaptation or change in production patterns.

Most researchers agree that a major driver is globalization, albeit the issue is a broad one. The increase in logistics activities required for a global-scale supply chain increases the level of complexity (Isik, 2011).

As Blecker (2005) states, there is no comprehensive list of complexity drivers for supply chains. Table 9, however, provides a general list that will be used in the dissertation. The list includes examples by Kersten et al. (2006) and Isik (2011).

Table 9: Supply chain complexity drivers

	External		Internal	
	Mass	**Change**	**Mass**	**Change**
Dynamic	Heterogeneous demands Raising product complexity General uncertainty of future developments Economic trends Decreasing accuracy of forecast Development of business environment Globalization Shortened product lifecycles	Technological innovations Changing resource requirements Technological customer demands Demand amplification(bullwhip) Parallel interactions non synchronized decisions & acting	Subjective estimations Machine breakdowns	Changing skill requirements
Static	New technologies Provisions of law Merger & acquisition activities	Non-synchronized supply chain planning & control systems Incompatible IT-Systems Different strategies non harmonized decisions & actions Supply chain bottlenecks Information gaps Non-harmonized processes Supplier & customer reliability	Lack of forecasting capabilities	Process-related deficits

Even though some examples can be categorized in more than one cluster, for simplicity, I categorize each example only in one cluster.

2.4.2. Supply chain performance measurement

To determine the effectiveness of a supply chain and the management of complexity, stringent control of the supply chain is recommended. As described in section 2.2.3, total value metrics could help derive the relevant KPIs for complexity management in terms of four major aspects, namely, quality, service, costs, and lead time (Johannsson et al., 1993, as cited in Naylor et al., 1999). Kaluza et al. (2006) suggest the following KPIs in the context of complexity management:

- *On time delivery* (OTD) $OTD(\%) =$

  $$\frac{Number\ of\ order\ lines\ delivered\ on\ or\ before\ requested\ delivery\ date}{Total\ number\ of\ order\ lines} * 100$$

  The improved supply chain performance should result in a higher OTD.

- *Inventory turnover* (ITO)

  $$ITO = \frac{Cost\ of\ sales\ (per\ period)}{Average\ cost\ of\ inventory\ (per\ period)}$$

  The improved supply chain performance should result in a higher ITO.

- *Inventory days-on-stock* (DOS)

  $$DOS = \frac{Average\ cost\ of\ inventory\ (per\ period)}{Cost\ of\ planned\ material\ demand\ (per\ period)}$$

  The improved supply chain performance should result in a lower DOS.

- *Order cycle time* (OCT)

  $$OCT = Delivery\ date\ or\ time - Order\ receipt\ date\ or\ time$$

  The improved supply chain performance should result in a lower OCT.

- *Supply chain cycle time* (SCCT)

$$SCCT = \sum_{i} (Maximum\ Lead\ Time_i)$$

where *i = Supply chain processes*

The improved performance should result in a lower SCCT.

- *Capacity utilization* (CU)

$$CU(\%) = \frac{Used\ supply\ chain\ capacity}{Total\ installed\ capacity} * 100$$

The improved supply chain performance should result in a higher CU.

- *Supply chain cost* (SCC)

$$SCC = \sum_{i} (Logistics\ cost + Production\ cost + Coordination\ cost)$$

where *i = Supply chain processes*

Logistics cost is composed of the costs for transportation, transshipment, picking and inventory. As transshipment costs are transportation costs within the production, they will be subsumed under transportation costs. Coordination costs cover the collaboration and coordination of supply chain companies and other supply chain participants. According to Kaluza et al. (2006), coordination costs include all other costs for common planning, information, and communication systems. An improved supply chain performance should result in lower SCC.

As supply chain costs are an important dimension of this dissertation, I will discuss it in further detail, building on the discussion by Kaluza et al. (2006).

I introduce the following breakdown of logistics cost (C_L) to be used in further references:

$$C_L = (C_T + C_P + C_{IH})$$

where	C_L	=	Logistics cost
	C_T	=	Transportation costs
	C_P	=	Picking Costs
	C_{IH}	=	Inventory holding costs

As the mode of transportation (e.g. ocean, air, ground, use of other material handling equipment) varies, which significantly impacts transportation costs, I will not go into a very detailed calculation of the transportation costs. The transportation costs would require an individual assessment depending on the individual design of the production network.

As Kaluza et al. (2006) only described picking costs as coming from the put-away process, the pre-process of the picking process is not considered. Thus, within a picking warehouse or a storage facility there are three major functions that need to be incorporated from a cost perspective: Put away, storing, and picking (Martin, 2009). Using the definitions of Kaluza et al. (2006), the storage function cost could be subsumed under inventory holding costs, while picking and put away costs could be subsumed under picking costs. With this definition, according to Martin (2009), the picking costs could be calculated based on time consumed for performing receiving, moving, storing goods for the put away process, as well as picking, moving, and handing over of goods. The time required—including lag times—needs to be multiplied with the cost rate for the worker and/or machine performing the task (Martin, 2009). Labor costs per hour and machine hours could be calculated analogous to the principles of machining costs for additive manufacturing as described in sections 2.1.5.2 and 2.1.5.3, respectively.

Thus, the picking costs could be reflected in the following formula:

$$C_p = \sum_i c_{ph} \, x \, t_p$$

where i = number of pick ups

c_{ph} = Hourly cost (worker/machine)

tp = Time required per picking process in hours

For the inventory costs, Slack et al. (2001) divide the costs into holding costs, which include working capital costs, storage costs, obsolescence risk costs, and order costs, which in turn, include the costs of placing an order and price discount costs. Holding costs (C_{hc}) are calculated as follows:

$$C_{HC} = C_h x \frac{Q}{2}$$

where C_h = Holding costs per unit

Q = Order quantity

Q/2 = Average inventory (assuming a constant order quantity)

Order cost (C_{oc}) is calculated as follows:

$$C_{OC} = C_o x \frac{D}{Q}$$

where C_o = Order costs per unit

D = Total demand

Q = Order quantity

Thus, the total inventory cost could be calculated as follows:

$$C_{IH} = \frac{C_h x Q}{2} + \frac{C_o x D}{Q}$$

2.4.3. Metrics for measuring the level of complexity

Kaluza et al. (2006) made a basic assumption on complexity: the more complex a supply chain is, the greater costs the supply chain will incur. To measure the level of complexity, they suggest disclosing the major source of cost reduction. For this purpose, they introduced a second set of metrics. There are several ways to measure complexity; they suggest focusing on numerousness, variety, connectivity, opacity, and dynamics, as these variables could be linked to complexity sources. These metrics are calculated as follows:

- *Numerousness metric* (NM)

$$NM_j = \sum_j Number_j$$

where j = *Elements of supply chain*

This measure gives an overview of the total number of elements in the supply chain. The more elements there are in a supply chain, the more complexity increases.

- *Variety metric* (VM)

$$VM_j(\%) = \left(1 - \frac{Number\ of\ similar\ types_j}{Total\ number\ of\ types_j}\right) * 100$$

where *j = Elements of supply chain*

The variety metric measures the diversity of the supply chain and could be derived from the ratio of similar types to total number of elements. VM_j could have values between 0 and 100—100 indicates low variety, while zero indicates high variety.

- *Connectivity metric* (CM)

$$CM_j(\%) = \frac{Number\ of\ supply\ chain\ relationships_j}{Total\ number\ of\ relationships} * 100$$

where *j = Elements of supply chain*

According to Kaluza et al. (2006), this metric provides an overview of the number of relationships between the elements in the supply chain.

- *Opacity metric*

$$KPM(\%) = \frac{Number\ of\ well-known\ supply\ chain\ processes}{Total\ number\ of\ supply\ chain\ processes} * 100$$

Kaluza et al. (2006) used two metrics to measure the opacity of a supply chain or a supply chain's elements, that is, how transparent they are. These metrics are the IT coverage metric and the *known process metric* (KPM). The former is irrelevant to the dissertation's objectives, and thus, I only use the latter. As the authors give only an indicative definition of a well-known process, it should be enhanced to be more precise and clear. I suggest defining a well-known process as a documented and trained process.

- *Dynamics metric* (DM):

  With regard to the dynamics metric, Kaluza et al. (2006) introduced a measure that covers all other parameters that might impact the supply chain and that evaluates their implications by measuring the state of the parameters at different times. The parameters could be selected by firms as they deem appropriate. In general, however, parameter selection should be based on the impact of the parameter on supply chain complexity:

$$DM_k(\%) = \frac{Parameter\ _k at\ t_1}{Parameter\ _k\ at\ t_0}$$

  where *k = Parameter of supply chain complexity*

By changing the levels of the metrics, I can determine how they impact the *supply chain complexity performance metrics* described above.

The above metrics evaluate the *elements* or *objects* of the supply chain, which are the "supply chain companies, interacting persons, inter-company business processes, employed systems, and offered products/services" (Kaluza et al., 2006, pp. 15). Through these metrics, Kaluza et al. (2006) limit the objects or elements that indicate complexity. However, the metrics do not provide any insights into whether the complexity level is beneficial and what the exact source of the complexity is. Nevertheless, these metrics provide a starting point for investigating where complexity comes from.

In addition to these fairly precise metrics, Isik (2010) proposes applying the *entropy measure*, which is based on the field of thermodynamics, to define the state of a system and the operational and structural complexity (see Appendix A). This metric provides an overall metric describing the system complexity, but it requires several heuristic observations of a system and does not identify the cause and effect of complexity. Because of these limitations, I do not use this metric in the dissertation.

2.4.4. Critical review of the metrics in the context of additive manufacturing

In reviewing the suggested performance measures vis-à-vis the total value matrix, I find that the area of services is not considered at all (Figure 21). If a complexity management strategy follows the approach of avoiding complexity, it is possible that the level of flexibility to meet customer demands increases the complexity. Thus, using additive manufacturing increases the flexibility, and consequently, the complexity itself. However, by simplifying the production process (e.g., no requirement for new tools or machines), the complexity can be manageable.

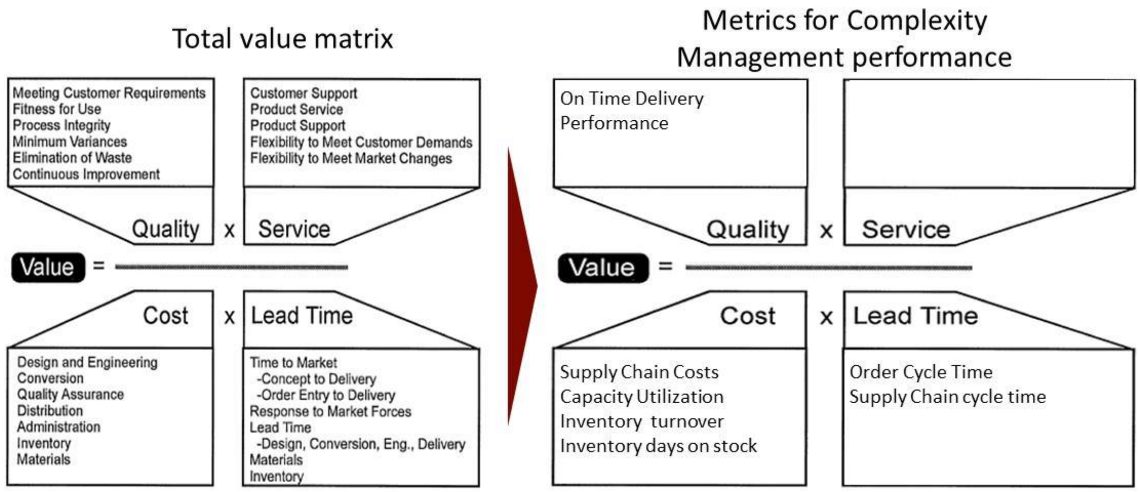


Figure 21: Metrics for complexity management performance vis-à-vis the total value matrix (using the metrics of Johannsson et al., 1993, as cited in Naylor et al., 1999, pp. 109)

Therefore, within an additive manufacturing framework, supply chain performance could be measured through KPIs of a service.

3. ADDITIVE MANUFACTURING IN SUPPLY CHAINS AND COMPLEXITY MANAGEMENT

3.1. Existing Research on Additive Manufacturing and Complexity in Supply Chains

Currently, there exists very limited research on additive manufacturing for complexity management in supply chains. As I have discussed in the previous chapter, product variants and customization requirements in mass customization are the major drivers of complexity, where mass customization is defined as "providing tailor-made solutions with near mass production efficiency" (Blecker, 2010, pp. xv) to increase customer satisfaction. From a conceptual view, mass customization uses similar strategies and approaches as complexity management. Tuck et al. (2007) combine additive manufacturing with mass or "extreme" customization, a concept that focuses on technology and the identification of customer needs. Specifically, Tuck et al. (2007) analyzed the implications of additive manufacturing on the supply chain concepts and philosophies of leanness, agility (or *leagility*), postponement, mass customization, and demand. However, they did not examine the supply chain model itself. They evaluated the supply chain principles without providing specific guidance on how to use technology.

Although mass customization has been significantly studied, the role of additive manufacturing in it has not been sufficiently explored; existing discussions within the field of additive manufacturing mainly focus on technology. To address this limitation, Tuck et al. (2010) published a handbook on mass customization. However, the focus of the handbook was defining a modus operandi for integrating customer needs into the process chain. Within scientific research, a holistic framework for managing complexity in the supply chain through additive manufacturing is not available.

3.2. Strategic Implication of Additive Manufacturing on Supply Chain Complexity Management

To evaluate the impact of additive manufacturing on complexity management, I need to determine where additive manufacturing can be positioned to address complexity. To this end, I need to revisit the complexity clusters described in section 2.3.3.2.

To position additive manufacturing in the complexity cluster frame, I also need to revisit section 2.1.1, which defines additive manufacturing as a production technology. From this definition, additive manufacturing is, on level one, an *internal* complexity cluster, as the production technology itself is the choice of the manufacturing company and is not predefined by any external factor. On level two, it is classified as *static* because the manufacturing technology is mainly installed in a fixed setup. I do not classify additive manufacturing on level three because this level depends on the attributes of individual organizations and not on the production technology itself.

In discussing complexity management, I need to revisit the complexity drivers that additive manufacturing can address. Using Lindemann's (2009) classification (Table 3), additive manufacturing is, in the first instance, a production technology that is a part of a production process, and thus, impacts the *process complexity*. However, there are dependencies and interactions (either one or two way) between the other complexity clusters. Figure 22 illustrates these interactions. I describe the four areas of complexity below.

Product complexity affects the setup of the process; the more complicated a product is, the more complicated the process setup will be. For example, the process may require different production steps and assembly efforts, causing additional buffer stocks to produce the final product. On the other hand, a technical limitation in the production process can also impact the product complexity. If an organization is not able to produce certain products with its process setup, the product may not be made available. Another example on how processes affect a product and its design is a car. A car is not a "one-piece" product—it has several parts that impact the product design and functionality.

Organizational complexity stems from complicated processes. If a process is complicated, it may require different organizational structures to manage the complexity. Thus, for example, if a product is sourced from a supplier, a buying function would be required (a function that would otherwise not be required if the product is made in-house).

Market complexity is currently considered only as coming from a two-way interaction. In this type of complexity, the availability of products is assumed to potentially impact market consumption patterns. The iPod is an example of a product that has changed market dynamics. In developing the product, Apple focused "on the user experience and interface, and the application of that to obtaining, organizing, listening to and sharing music. By leveraging digital distribution and the speed of broadband, Apple lets music lovers browse and download a song or album in a fraction of the time it had previously taken to record music onto a tape, with the convenience of portable compact storage" (Travlos, 2012). The iPod did not create a new market but extended the market size significantly.

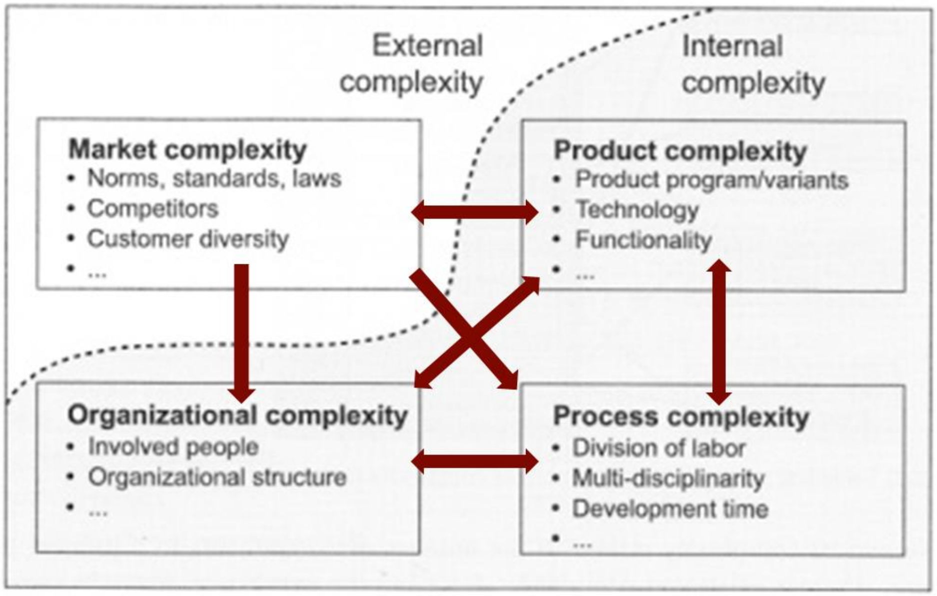


Figure 22: Four areas of complexity and their interactions (using areas identified by Lindemann et al., 2009, pp. 27)

In the other complexity areas, the impact of external complexity is assumed to be insignificant because how a company is organized might, in most cases, not affect external complexity. On the other hand, market and process complexity impacts organizational complexity.

With these complexity areas and their dependencies in mind, it is important to evaluate the implications of using additive manufacturing instead of other traditional manufacturing technologies. In some cases, additive manufacturing may be more effective than traditional technologies in handling product and market complexity. In other cases, it may be the other way around.

Additive manufacturing allows the significant re-configuration of processes and the reduction of complexity. In this dissertation's case study of a control panel production (Figure 23), the number of process steps can be reduced from 13 to 10.

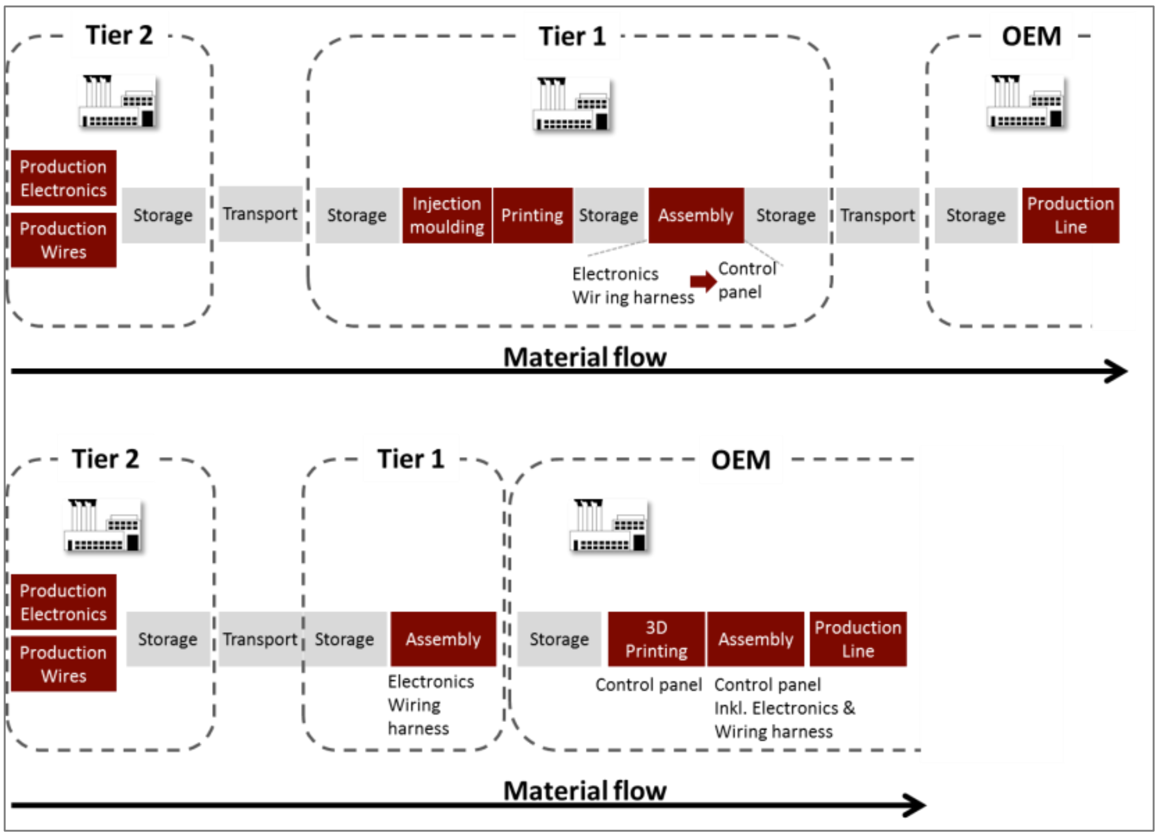


Figure 23: Case study of an initial supply chain setup and a re-configured supply chain

In the case study, additive manufacturing reduced inventory levels significantly as well as the number of transportation modes and amount of assembly work. The case study and its implications on supply chains, complexity, and technology will be discussed in a later section.

Placing additive manufacturing in a strategic context and using Kaiser's (1995) basic strategies (see section 2.3.3.2), I hypothesize that additive manufacturing can be a tool for implementing all the basic strategies (i.e., *avoidance*, *avoidance and control*, and *control*).

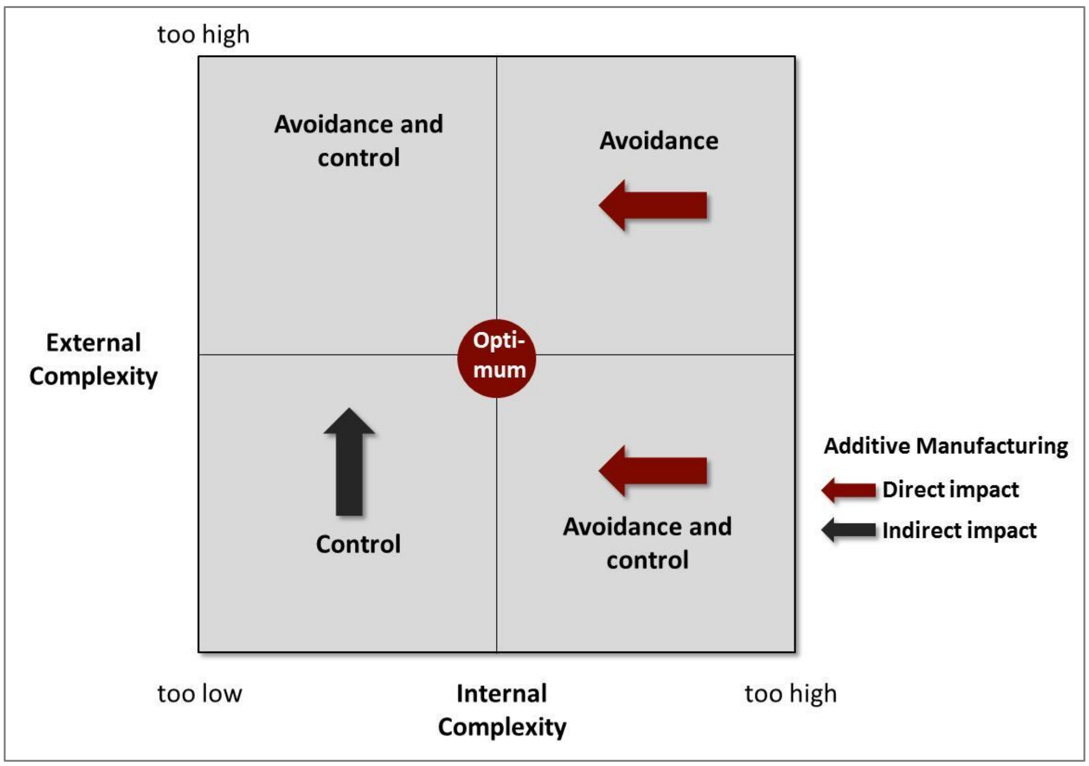


Figure 24: Additive manufacturing's impact on complexity management (adapted from Kaiser, 1995, pp. 102)

Figure 24 gives an overview of the strategic impact additive manufacturing can have on internal and external complexity drivers. I differentiate between direct and indirect impacts. As stated previously, additive manufacturing can only address internal complexity directly, albeit it can also affect external complexity. Additive manufacturing makes it easier to control complexity, but it can also be used to develop and produce new products. Additive manufacturing may enable a company to offer products in lot sizes of one, which may increase external complexity by changing demand patterns and channels for reaching customers. Additive manufacturing can also be a tool for increasing organizational capabilities for coping with complexity.

Current research does not review the implications of additive manufacturing or give a clear framework for when additive manufacturing can help manage complexity efficiently and effectively and optimize internal and external complexity.

The general strategies for complexity management and the implications additive manufacturing can have, as described above, can also be applied to supply chains because supply chains can be simplified as a defined process in an organization. With this in mind, the strategic implications of additive manufacturing could be significant for the manufacturing industry and the supply chain configuration therein.

In addition to supply chain configuration, additive manufacturing can also completely reduce internal complexity caused by production technology in manufacturing industries. Through this change, a company can move from a production company to an IT one. Firms like Apple already outsource all of their main production activities to specialized companies like Foxconn; as a next step, they can also extend the outsourcing of activities to the end customer (Rawson, 2012). An example for this case is the Wiki Weapon Project, which aims to design and sell a weapon construction plan, which anyone can download and print at a home on a 3D printer. This start-up even outsourced the design of the weapons by creating a design tender competition (Greenberg, 2012). This model follows the impact the internet has on the music, software, and publishing industries, where distribution has been completely virtualized and the end user “produces” the products on their own.

In summary, from a strategic perspective, additive manufacturing enables the avoidance of internal complexity more than any other production technology can.

4. EVALUATION APPROACH FOR ADDITIVE MANUFACTURING: IMPLICATIONS ON SUPPLY CHAIN COMPLEXITY

4.1. Overview

As stated in chapter 3, additive manufacturing in the context of complexity management ultimately is not a strategy itself; it merely enables organizations to maximize their capabilities to manage complexity, specifically that driven by production technology.

Further, as stated in the previous chapter, the choice of production technology is assumed to be mainly the choice of the organization, as regulation in the most cases does not prohibit the usage of certain production technologies but only defines standard values that are not achievable by specific technologies. Thus, the choice of the production technology can be categorized as an internal (as opposed to external) complexity driver.

To develop a generic approach for assessing when and where to apply additive manufacturing, a structured process should be defined in order to derive an evaluation framework. As a basic methodology, I chose an approach from the field of lean management to derive an assessment framework.

One common tool for process improvement is value stream mapping, which is a tool to visualize the "flow of material and information as a product makes its way through a value stream" (Rother and Schook, 1999, pp. 4). It is used to visualize and create transparency in the value-adding steps and to identify waste.

Value stream analysis consists of the steps of mapping the current state; identifying what would make the value stream lean in order to define the future improved and lean state; and finally, implementing the future state (Rother and Schook, 1999). Before performing these three major steps, it is important to define the current *as-is* status, identify the improvement potential, and define the *to-be* status. Adapting this to the dissertation's problem of assessing when and where additive manufacturing can help manage complexity in supply chains, I will perform an adapted generic value stream analysis process following five steps: 1) strategy review, 2) supply chain complexity evaluation, 3) production technology-driven complexity evaluation, 4) supply chain remodeling by using additive manufacturing, and 5) performance assessment. Steps 1 to 3 aim to capture and describe the as-is situation. Step 3 incorporates remodeling the supply chain, which is correlated to identifying the improvement potentials as well as defining the to-be process in the value stream analysis. Step 5 evaluates the effectiveness of the chosen measures, which could be mapped to the implementation stage of the value stream mapping approach, as Rother and Schook (1999) include a fairly high-level performance management in their *future state implementation* stage and suggest a value stream plan for measuring performance.

4.2.Step 1: Strategy Review

I use a simplified definition of strategy and do not attempt to fully explore the concept and its various definitions. Specifically, I use the definition of Johnson and Scholes (2002, pp. 11):

> "Strategy is the direction and scope of an organization over the long term, which achieves advantages for the organization through its configuration of resources within a changing environment, to meet the needs of markets and to fulfill stakeholder expectations."

Simply put, a corporate strategy is defined by external requirements (e.g., customers, government) and internal capabilities (e.g., resources, knowledge). This definition is based on that by Johnson and Scholes (2002). By adopting this definition, the dissertation's key question at this step is determining whether an organization chose a level of complexity because the external environment does not value a higher level of complexity or whether it did so because the available resources or internal capabilities do not allow an increase in the complexity level.

Depending on the answer to this question, the organization takes a different approach to applying additive manufacturing. If further complexity would be valued by the customer, the organization should review its processes and determine whether additive manufacturing can facilitate the organization's capabilities for managing the resulting complexity at reasonable costs. Otherwise, the organization should review its processes and determine whether additive manufacturing can help decrease the organization's cost position and improve its competitiveness.

In his approach, Rathnow (1993) does not mention this step as a strategic decision but rather suggests defining the optimum variety (compare section 2.3.3.6) to review the benefits of variety from the customer's perspective. He defines the net benefit (respectively value) as the perceived gross benefit minus the costs for acquiring and maintaining a product. Figure 25 illustrates the concept of calculating the net benefit for which Rathnow introduces benefit units that convert the benefits to monetary values.

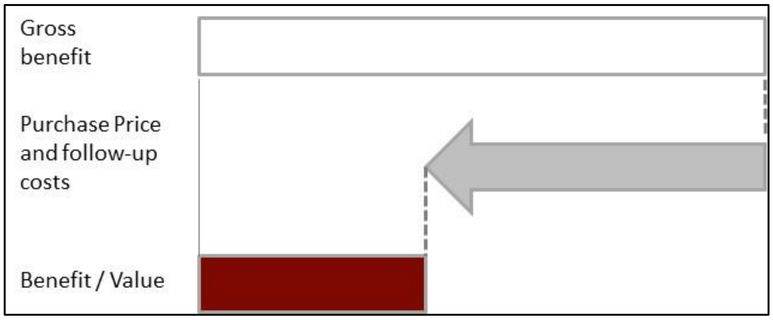


Figure 25: Concept of Customer Benefits (adapted from Rathnow, 1993, pp. 12)

Firms increase product variety either to address new customers with a different benefit perception or to increase customers' perceived net benefit. Rathnow's approach implies that variety is not an end in itself. Thus, in this step, Rathnow's approach defines the benefit curve. The basic strategic forms of the benefit curve will be discussed in further detail in section 5.2. To derive a fact-based benefit curve, Rathnow (1993) suggests using different market research tools like conjoint analysis or multidimensional scaling. I do not discuss these tools in further detail because doing so would be out of the scope of this dissertation.

The step of reviewing the strategy can be left out. However, it can help review the product, position it strategically, and identify the potential strategic implication additive manufacturing can have on the future direction of the organization.

4.3. Step 2: Supply Chain Complexity Evaluation

Because there are few supply chain complexity measures, the initial assessment should use the complexity measures defined by Kaluza et al. (2006), which were introduced in section 2.4.3: the *numerousness* metric (NM), *variety metric (VM)*, *connectivity metric (CM)*, and *opacity metric* (i.e., *known process metric or KPM*).

In this step, the dynamic metric suggested by Kaluza et al. (2006) is not considered, as it is difficult to forecast the pertinent values for the supply chain elements for a remodeled supply chain in the future. Further, the changeability of supply chain complexity is not seen as relevant, as it is assumed that additive manufacturing, compared to other traditional manufacturing methods, will not decrease the flexibility of a supply chain.

4.4. Step 3: Production Technology-Driven Complexity Evaluation

After assessing the overall complexity of a supply chain, how the choice of production technology affects the supply chain complexity should be evaluated. To this end, it is important to determine which elements or objects—Kaluza et al. use both expressions—are clearly determined by the choice of production technology. Determining the level of relationship between an element or object of the supply chain and a production technology is difficult and subjective. Table 10 provides some insight into the objects of complexity management and their possible relationships with production technology.

Table 10: Objects of complexity management and their possible relationships with production technology

Objects of Complexity Management	Possible Relationship with Production Technology
Inter- and intra-company business processes	Downstream process to production
Products	Production technology for manufacturing is exchangeable
Information	Information occurring downstream of the supply chain and information relevant to producing the product
Systems	IT system used downstream or in production; if used downstream, the system holding production-relevant information
Business partners	Partners in the downstream supply chain
Business dynamics	*Not in scope of dissertation as described above*

Source: (Objects based on Kaluza et al., 2006, pp. 6)

In this step, downstream supply chain is defined as everything prior to the final production of goods, while upstream supply chain is everything after the final production.

I propose new metrics for determining how much of the complexity is driven by the production technology. I use the metrics identified in step 2 and calculate the production technology-driven complexity as follows:

Production technology numerous metric (NM_{PT}):

$$NM_{PT}(\%) = (1 - \frac{NM_{PTj}}{NM_j}) x\ 100$$

where j = Elements of supply chain

PTj = Elements of supply chain affected by production technology

The NM_{PT} is an indicator of how production technology contributes to the overall size of the system. It could be between 0 and 100, where 0 means that a production technology does not exist, while 100 means that everything in the supply chain is affected by the production technology.

Production technology variety metric (VM_{PT})

$$VM_{PT}(\%) = \left(1 - \frac{Number\ of\ similiar\ types_{PTj}}{Total\ number\ of\ types_{PTj}}\right) x\ 100$$

The production technology variety metric is a measure of the diversity in production. The VM_{PT} could have values between 0 and 100, where 100 indicates low variety, while zero indicates high variety.

Production technology variety metric ratio (VMR_{PT}):

$$VMR_{PT} = \frac{VM_{PT}}{VMj}$$

The VMR_{PT} could have values between nil and infinite. This ratio indicates whether production technology-affected processes in the supply chain are more or less diverse than the overall supply chain. If these processes are more diverse, then production technology is one source of complexity. If VMR_{PT} is between nil and 1, production technology driven variety is more diverse than the overall supply chain, and if it is above 1, production technology driven variety is less diverse than the overall supply chain.

Production technology connectivity metric (CM_{PT})

$$CM_{PT}(\%) = \left[1 - \left(\frac{Number\ of\ relationships\ in\ supply\ chain_{PTj}}{Total\ number\ of\ relationships\ in\ supply\ chain}\right)\right] x100$$

where j *= Elements of supply chain*

PTj = Elements of supply chain affected by production technology

The CM_{PT} provides an overview of the relationships between the production technology-affected processes and elements. Further, this metric indicates how complex the process setup is, given that most elements are related with each other and each of these relationships is defined as a process or at least as an activity in a process; this was not mentioned by Kaluza et al. (2006).

Production technology known process metric (KPM_{PT})

$$KPM_{PT}(\%) = \frac{Number\ of\ well\text{-}known\ processes\ determined\ by\ production\ technology}{Total\ number\ of\ supply\ chain\ processes\ determined\ by\ production\ technology}\ x\ 100$$

This metric gives an indication of the opacity of the supply chain for production technology-determined processes. To determine whether this opacity is higher for production-related processes than for other processes in the supply chain, I introduce the following metric:

$$\Delta KPM = KPM - KPM_{PT}$$

The results for ΔKPM would indicate

< 0: the transparency for production processes is higher than for the other processes in the supply chain

0: the transparency for production-related processes equals that for the other processes in the supply chain

> 0: the transparency for production processes is lower than that for the processes in the supply chain

As stated in section 2.4.3, these metrics do not explain whether the complexity level is beneficial or what the exact source of the complexity is. Nevertheless, they give an indication of whether a change in the production technology can impact the overall supply chain's complexity. If the calculations above show that supply chain complexity is not caused by elements (objects) or processes determined by production technology, a further investigation to determine whether supply chain complexity would be improved when additive manufacturing is applied may not be reasonable.

4.5. Step 4: Supply Chain Remodeling through Additive Manufacturing

4.5.1. Overview

In the fourth step, the supply chain is remodeled by substituting traditional production technologies with additive manufacturing production technology. To this end, it is important to determine which production technology to substitute and where.

For this, a twofold approach should be taken:

- First, which production technology should be substituted is identified. This step should consider not only the focal organization but also the entire supply chain network, as mentioned in section 2.2.1 and illustrated in Figure 5.
- Second, complexity management tools are used to remodel the supply chain to reduce complexity. These tools will be discussed in detail in the following sections, but basically, they cover the following two issues. (1) Could additive

manufacturing technology consolidate production steps and reduce the overall number of manufacturing machines by incorporating different tasks into one manufacturing machine? The purpose of this step is to look at the synergies across the network because the division of labor within the network may be the result of the production technology used, which would not be required if additive manufacturing can be used instead. (2) In addition, is the point where complexity occurs at the latest possible stage?

4.5.2. Production technology selection

To answer the two questions above, whether the required materials and designs could be manufactured using additive manufacturing should be determined. Table 1 could be a good starting point for identifying the right additive manufacturing technology. The choice of the production system should include the material characteristics. At this stage, a decision needs to be made to determine if product characteristics like color, strength and surface roughness are critical and need an exact match, or if changes might be acceptable. This is critical in the selection of the right additive manufacturing technology and might stop the process and this stage.

Additionally, the application of rapid tooling should be checked. According to Pham and Dimov (2003)

> “As [rapid tooling] becomes more mature, material properties, accuracy, cost and lead-time have improved to permit it to be employed for the production of tools. Some traditional tool-making methods based on the replication of models have been adapted

> and new techniques allowing tools to be fabricated directly [by rapid tooling] have been developed." (Pham and Dimov, 2003, pp. 12).

According to Pham and Dimov (2003), there are several technologies available to produce tools for production runs of up to several thousand parts. They discuss indirect methods (e.g., metal deposition, room temperature vulcanizing, and epoxy tooling) and direct methods (e.g., Direct ACES Injection Molds, AIM, laminate tooling, and direct metal tooling). Since 2003, further processes have been developed, but they will not be discussed here in detail, as doing so would exceed the scope of the dissertation.

In summary, this step suggests also reviewing tooling processes and determining if tool manufacturing could be substituted by additive manufacturing technologies if tooling processes play a significant role in the supply chain.

4.5.3. Remodeling the supply chain with complexity management tools: Applicability and suggested usage

As a discussed in the literature review in chapter 2, there are a comprehensive set of complexity management tools available. Within this section, I will develop a set of tools to support the evaluation approach. This set will be based on two components including the suggested lever in the complexity management tool set introduced in section 2.3.3.

Review of tools

I will introduce and review tools based on the following hypotheses. Each tool focuses on a specific stage in the product life cycle (cp. section 2.2.1), that is, it will support the management of complexity within the product development, manufacturing, or marketing/utilization stage (cp. Figure 6). Thus, only a selected number of tools will be useful in the context of additive manufacturing, as it is a production technology that focuses on delivering value in the manufacturing stage, that is, it simply substitutes for another production technology. This does not mean that using additive manufacturing might not have any implications on the elements of the product life cycle (e.g., production process changes might require product development efforts). In addition, this does not consider that additive manufacturing could also be used as a technology in the sense of rapid prototyping (i.e., to produce prototypes during the development stage).

From this point, I will briefly review the complexity management tools introduced in section 2.3.3, specifically the approaches to managing complexity and where in the product life cycle they provide value. The major question in assessing each tool is if the production technology is a relevant driver for applying the tool. The findings are then used to assess if the tools are relevant in the circumstances of additive manufacturing, that is, if the results brought about by the tools are independent of the production technology used. Value in this context is assumed as the delivering of support in the additive manufacturing evaluation process as defined in chapter 4. The review of the tools will be a soft conceptual assessment.

Figure 26 provides a high-level overview of the evaluation.

Tool	Manufacturing
Quality Function Deployment	○
Target Costing	○
Design for Variety	●
Design for configuration	○
Modularization	○
Modular function deployment	○
Product platforms	○
Variant mode and effects analysis	◑
Variety reduction program	◑

Legend: ○ Not in Applicable ◑ Partially Applicable ● Fully Applicable

Figure 26: Overview of the applicability of complexity management tools for the additive manufacturing evaluation process as described in Chapter 4 (Author's own creation)

The product life cycle concept as introduced in section 2.2.1 consists of three major areas: product development, manufacturing, and marketing/utilization. The manufacturing stage is divided into the start of production and the production itself. In this stage, the physical product produced covers all production tiers as defined in chapter 2.2.

In the next paragraphs, I will review the following tools to determine whether they address the manufacturing stage or another stage in the product life cycle: quality function deployment, target costing, design for variety, design for configuration, modularization, modular function deployment, product platforms, variant mode and effects analysis, and variety reduction program.

As described in section 2.3.3.7, the objectives of quality function deployment in the context of complexity management is to define the right level of complexity by identifying the product requirements from the customer and from a technical perspective, and by evaluating interdependencies between the technical and customer requirements. Although additive manufacturing could improve or change technical aspects, its scope does not fall directly into the manufacturing stage of the product life cycle. Thus, QFD does not directly address issues in the manufacturing stage of the product life cycle.

As described in section 2.3.3.8, target costing per se focuses on the developing and designing phases of a new model, so it is applied in the product development stage. As costs also occur in the manufacturing stage, the technical opportunities provided by additive manufacturing might support the efforts for the target costing methodology, but the tool itself does not significantly support the manufacturing stage in the product life cycle, as the tool is not affected by the production technology itself.

Design for variety as described in section 2.3.3.9 also starts at the development stage and evaluates the impact of variety on the costs of a product line. Although used in the development stage, this tool could be helpful in the supply chain reconfiguration process for additive manufacturing, as it incorporates two major types of analysis: the differentiation index and the setup index.

The differentiation index helps identify where within the process complexity occurs, which in turn helps determine whether additive manufacturing could reduce the complexity in the process. On the other hand, the setup index shows how switchover costs affect total product cost. The reduction of setups is one of the major advantages of additive manufacturing, and this index helps evaluate the impact of additive manufacturing. The setup index also includes the usage of a process sequence graph, which may help visualize the areas where differentiation occurs. As described in section 2.3.3.9, two basic ways to manage complexity are to differentiate at the latest possible stage in the process and to reduce the overall number of differentiation points. These two guiding principles in the value chain reconfiguration phase may help even though additive manufacturing is technically advanced that it could allow several differentiation steps in one step.

Design for configuration, which is described in section 2.3.3.10 in detail, focuses on the product design stage, as it suggests product design components that could be configured in different setups. This approach is independent from the production technology used to produce the components or the product itself. However, this fact does not seem not to deliver a specific type of value in the context of additive manufacturing.

Modularization, as described in 2.3.3.11, also focuses on the product development stage. This approach is used to develop modules, consisting of components, which could be used across different products.

Modular function deployment (cp. section 2.3.3.12) also focuses on the product development stage but includes assembly aspects. Although it is considered as a technological alternative in step four of the evaluation process, it does not include any suggestions or tools for evaluating the production technology aspect itself, and thus, does not provide additional value in the context of the evaluation approach.

Modularization product platforms (cp. section 2.3.3.13) focus on the product development phase. Like modularization, product platforms also focus on sharing modules across platforms. However, in contrast to the modularization approach, product platforms focus on the divisibility of the platform for the construction of different products. Nevertheless, the concept is not specifically dependent on the production technology used.

Compared to the preceding method, variant mode and effects analysis (cp. section 2.3.3.14) has a much broader focus. In addition to the product development stage, it also reviews the assembly process in step 3 of the process. Specifically, it focuses on the assembly line order, and its major suggested lever is to push complexity toward the latest possible step in the value chain. Thus, this approach is one of the key elements at this stage and could be leveraged in the evaluation process for remodeling the supply chain.

As described in section 2.3.3.15, the variety reduction program provides five major techniques to help to reduce the costs of complexity. One of these techniques is the multifunctionality and integration approach. Although this approach also focuses on the product design phase, one of the major advantages over traditional production technologies of additive manufacturing is that it allows more complex product designs to be utilized. Thus, this approach of integrating functionalities by the enhanced design of a part could be utilized in the evaluation approach for remodeling the supply chain.

Several complexity management tools gather data on customer demand or customer requirements using different terms for such data, for example, customer insights (optimum variety tool), customer attributes (quality function deployment), market-into-company (target costing), customer requirements (modular function deployment), and market requirements (variant mode and effects analysis). The gathering of these pieces of data is fairly basic, and thus, will not be discussed in further detail in this dissertation. For example, in the quality function deployment method, one can simply refer to market research without going into further detail. Step 1 of the defined evaluation approach deals with the strategy, for which customer requirements are part of the external requirements (cp. section 4.2). The tools could provide guidelines on how to gather data on customer requirements but does not provide a sophisticated approach to support the evaluation process.

Application of the tools in the remodeling process

Based on the brief review of complexity management tools, in the preceding paragraphs, the major applicable levers and tools for the remodeling stage of the evaluation approach are the multifunctionality and integration approach from Suzue and Kohdate (1990), as described in section 2.3.3.15, and the consolidation of the assembly needs. Moreover, as described in the case study in section 6.5.6, these tools could help reduce overall stock levels by reducing the number of intermediates that require planning and stocking. Additionally, a change in the assembly line order would be supportive as a second iteration for remodeling, as this method—although not focusing on the advantages of additive manufacturing—could be useful, as the sequence where complexity occurs might have moved through the integration of the production steps. In this case, a process sequence graph might be a useful tool to visualize and identify complexity sources (Ishii and Martin, 1997, detailed in section 2.3.3.9). Assuming that the VMEA approach is a proven and useful tool, the guiding principle of pushing complexity sources in the assembly line toward the latest possible stage should be applied here as well.

Based on the complexity management tool evaluation in this chapter and the findings from the case study in chapter 6, the evaluation approach for additive manufacturing and its implication on supply chain complexity should incorporate complexity management tools at the remodeling process step (cp. sections 6.5.5 and 6.5.6). In this way, the process step will be enhanced by changing the assembly order stage and multifunctionality.

4.5.4. Conducting the remodeling

Having identified the stages and the production technology through the above steps, the supply chain should be remodeled. Remodeling involves the substitution of the production technology and then the assessment of its implications on other elements of the supply chain. Following the supply network concept of Saiz et al. (2006), which was introduced in section 2.2.1, the remodeling should review the implications on production units, storage points, and transportation. Thus, it should answer the following questions:

- Can stock keeping be reduced or eliminated through just-in-sequence production, in which no setups are required?
- Can assembly work be reduced or eliminated through combining productions steps in one manufacturing machine and the capability of additive manufacturing to manufacture highly complex geometries?
- Can transport be reduced or eliminated through consolidation of production processes?

Because the formats of the raw materials depend on the production technology, additive manufacturing may also have implications for elements in the supply chain related to raw materials (e.g., storage space may be reduced or eliminated as the variety of raw materials used is reduced).

There may be several feasible additive manufacturing solutions for an organization; thus, these alternatives should be compared and assessed.

4.6.Step 5: Performance Assessment

The remodeled supply chain should be assessed in terms of complexity management and improved supply chain performance.

Complexity evaluation

To evaluate the remodeled supply chain's complexity, the *numerousness metric* (NM_j), *variety metric* (VM_j), *connectivity metric (CMj)*, and *known process metric* (KPM_j) should be calculated. If NM, VM, and CM decrease and KPM increases, thus decreasing the overall supply chain complexity, the remodeling is believed to have successfully reduced complexity. Calculating these metrics is not mandatory, as they do not directly indicate whether complexity reduction helps increase supply chain performance. Thus, to calculate supply chain performance, the original supply chain should be assessed vis-à-vis the remodeled supply chain. The performance evaluation should be based on the metrics for complexity management performance transfered to the value matrix that were introduced in section 2.4.4.

Because the results of the metrics do not always indicate which supply chain is better, managers must make the final decisions using decision-making theories and tools (e.g., game theory), albeit we will introduce a general decision model in chapter 5, which will give guidance on whether additive manufacturing should be applied.

If additive manufacturing is found to be ineffective, the reason for this should be determined. This technology is very new; the parameters for assessment may change significantly over time, and more advanced technologies may yield different results. Thus, from a strategic view, it may be interesting to run the evaluation again after technological progress is made.

Supply chain performance evaluation

Table 11 gives an overview of how the assessment should proceed and which KPIs should be taken into account. The detailed calculation of the different metrics can be found in section 2.4.2.

Section 2.1.5 deals with additive manufacturing costs and section 2.4.2 deals with supply chain management costs. In the following paragraphs, I will outline the development of an overall *supply chain cost* model for additive manufacturing as this is an important part of the assessment and it is not detailed in section 2.4.2.

Table 11: Metrics for comparing supply chain complexity of original and remodeled supply chains

Area	Metrics	Characteristics	Change from traditional to additive manufacturing: value decrease favors	Change from traditional to additive manufacturing: value increase favors
Quality	On time delivery	Percentage of deliveries at promised time	TM	AM
	Performance	# of incidents where customer requirements on product is met (e.g. Strength, surface feel)	TM	AM
		# of incidents where customer requirements on delivery is met (time, quality)	TM	AM
Service	Flexibility to meet customer requirements	Weeks of product change	TM	AM
Cost	Supply Chain Costs	Total supply chain costs	AM	TM
	Capacity Utilization	Machining capacity utilization	TM	AM
	Inventory turnover	# of inventory turns per year	TM	AM
	inventory days on stock		AM	TM
Lead time	Order cycle time	days required to process an order	AM	TM
	Supply chain cylce time	days from order to delivery	AM	TM

* TM = Traditional manufacturing method
* AM = Additive manufacturing method

Additive manufacturing is one of the cost elements of the total supply chain cost. As stated in section 2.4.2, the supply chain cost is defined as

$$SCC = \sum_i (Logistics\ cost + Production\ cost + Coordination\ cost)$$

where $i = Supply\ chain\ processes$

The logistics cost is defined in section 2.4.2 as $C_L = (C_T + C_P + C_{IH})$. Thus, breaking down the overall supply chain cost function and incorporating the additive manufacturing cost function from section 2.1.5 leads to the following cost function:

$$SCC = \sum_i (C_T + C_P + C_{IH}) + [(c_{muB} * m_{uB)} + (c_{muS} * m_{uS}) - \big((I_{muB} * m_{rB}) + (I_{muS} * m_{rS})\big] + [clh * (td + ts + tpp + tpm)] + [C_{Ah} * t_A]\,) + C_K$$

where

C_L	=	Logistics costs
C_T	=	Transportation costs
C_P	=	Picking Costs
C_{IH}	=	Inventory holding costs
c_{muB}	=	Building material costs per unit (e.g., kg)
c_{muS}	=	Support material costs per unit (e.g., kg)
m_{uB}	=	Building material used in units (e.g., kg)
m_{uS}	=	Support material used in units (e.g., kg)
I_{muB}	=	Building material recycling income per unit (e.g., kg)
I_{muS}	=	Support material recycling income per unit (e.g., kg)
m_{rB}	=	Building material for recycling in units (e.g., kg)
m_{rS}	=	Support material for recycling in units (e.g., kg)
clh	=	Hourly labor cost
t_d	=	Time used for designing and converting design files
t_s	=	Time used for preparation of machining
t_{pp}	=	Time used for post-processing of parts
t_{pm}	=	Time used for post-processing of machine
t_A	=	Time in hours for setup, processing, and post-processing of machine
C_{ah}	=	Hourly machine costs
C_K	=	Coordination costs

The coordination costs could also be further broken down. Kaluza et al. (2006) summed up all costs including for systems and manpower required to manage interfaces. For simplicity, I suggest calculating coordination costs by multiplying average cost per hour with the time required:

$$C_K = c_{kh} \, x \, t_{kh}$$

where

c_{kh}	=	Coordination cost per hour
t_{kh}	=	Time required for coordination in hours

As energy costs is an increasingly important factor for production (Lewis, 2013), it must be incorporated into the cost model. The energy costs (C_E) will be calculated on a per-piece-produced basis and added into the total cost function. For simplicity, energy costs for tooling, transportation, and warehousing are assumed to be included in the according cost factor C_E. Thus, the final cost equation is as follows:

$$SCC = \sum_i (C_T + C_P + C_{IH}) + [(c_{muB} * m_{uB)} + (c_{muS} * m_{uS}) - \left((I_{muB} * m_{rB}) + (I_{muS} * m_{rS})\right] + [clh * (td + ts + tpp + tpm) + c_E] + [C_{Ah} * t_A]) + C_{Kh} * t_{kh}$$

For decision-making purposes, this model will be enhanced in section 5.3.2 to allow a direct comparison of traditional and additive manufacturing.

Product performance

Whether product performance is comparable between traditional and additive manufacturing production technologies is arguable, and thus, product performance should also be assessed. Two major measures for this assessment are *product durability* (hardness/strength), which could be measured in tensile strength, elongation, flexural strength, and modulus, as well as *surface characteristics*, which could be measured in surface accuracy and roughness. These two measures were derived from the case study in chapter 6.

5. DECISION MODEL TO DETERMINE APPLICABILITY OF ADDITIVE MANUFACTURING TO MANAGEMENT OF SUPPLY CHAIN COMPLEXITY

5.1. Introduction

The general evaluation approach as described in chapter 4 provides a structured process for applying additive manufacturing within a mass production environment to manage supply chain complexity. This chapter will discuss the prerequisites for additive manufacturing to become a primary production technology. The objective of this discussion is to provide a clear decision model for when to consider additive manufacturing as a tool to manage supply chain complexity. As additive manufacturing is a fairly young technology that is only beginning to be industrialized, clear guidance is necessary for determining which parameters improve additive manufacturing performance, and consequently, enable its application in a much broader manner.

The model provided will determine which situations additive manufacturing is suitable for. The guidance will be based on three dimensions: *strategy*, *complexity*, and *supply chain performance*. The last dimension reviews and determines the supply chain performance parameters, focusing on supply chain cost performance and product performance.

5.2. Strategy

As introduced in section 2.3.3.2 (cp. Figure 11), there are three major strategies for managing complexity: avoidance and control, avoidance, and control. These strategies are related to complexity management but do not focus on the company's broader strategy and vision. Performing a complete strategy review of the abilities of additive manufacturing and new markets is out of the scope of the dissertation, but it is nevertheless important to determine what the strategic implications of additive manufacturing are especially in supply chain complexity.

In reviewing the basic strategies and application fields of additive manufacturing determined by the level of internal and external complexity, I determine that additive manufacturing is a part of the internal complexity, and thus, the application of additive manufacturing should reduce the internal complexity by reducing interfaces and assembly efforts. In this case, the application of additive manufacturing would free up internal resources, which could be utilized for accomplishing a broader company strategy or to reduce overall costs by reducing the required internal resources. Consequently, assuming that additive manufacturing helps reduce the relative costs of complexity, the total cost function becomes more linear. An individual product might have a gentle slope as selling and coordination costs for a product portfolio increase.

Thus, to determine whether additive manufacturing has an impact on corporate strategy, I take Rathnow's (1993) concept of optimum variety into account (cp. section 2.3.3.6). If only the optimal level of variety (V_{opt}) changes, additive manufacturing should be taken into account and the business model should be reviewed. As the V_{opt} depends on two curves (i.e., the cost and benefit) in relation to the level of variety, I conceptualize the concept by introducing four different benefit curves (Figure 27).

Thus, each organization needs to review the benefit function (f_{Ben}) and its development to determine if additive manufacturing could be used as an adequate complexity management tool and for what purpose. The second panel in Figure 27 illustrates the different benefit curves.

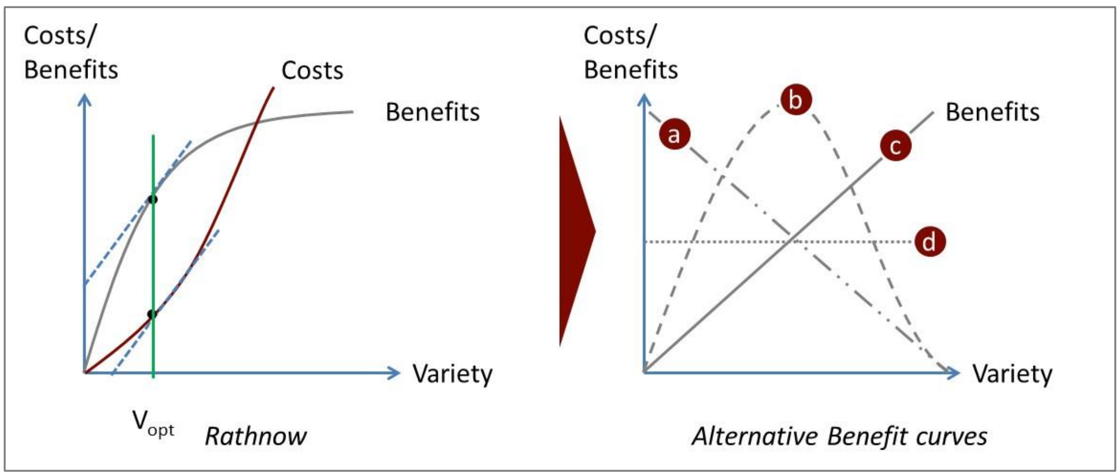
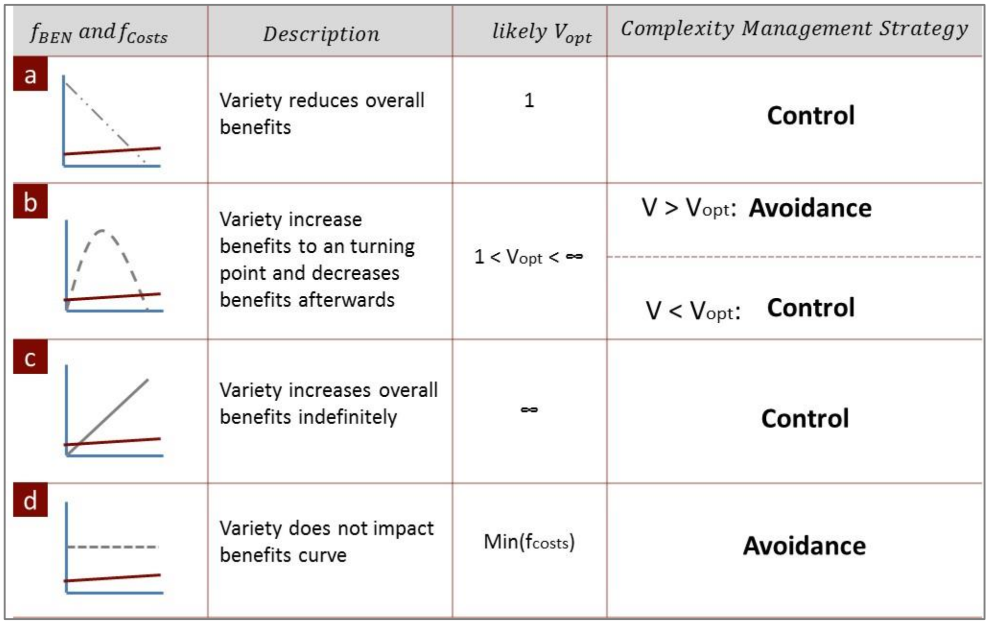


Figure 27: Rathnow's Cost /Benefit Curves (1993, pp. 11) and Alternative Benefit Curves (Author's own adaptation)

Following the definition of Rathnow (1993), the benefit could be defined as the perceived customer value including the product itself and the customer experience during the sales and other processes. Thus, a specific product is purchased based on the customer's perceived benefit from the product. Curve A is for an organization that provides a product for which additional variety would reduce customer benefits (e.g., a customer gets confused by having two differentiated products from the same company, and thus, decides to buy a competitor's product instead). In this case, the optimal variety would very likely have a value of one ($V_{opt} = 1$), and additive manufacturing should be used (if the status quo is not achieved and additive manufacturing would deliver a better cost position).

Curve B is for an organization that manufactures a product for which a certain set of variety improves customer benefits but only up to a certain point (i.e., after that point, the benefits significantly decrease). An example would be a case in which the customer loses confidence in the differentiating factors of the product, which, as Huber (2008) states, could result in either a negative buying experience or the extreme situation of avoiding purchasing the product. The optimal variety would be somewhere between 1 and infinity ($1 < V_{opt} < \infty$). Additive manufacturing should be used for the complexity management strategy of avoidance and control depending on the organization's current variety level (V)—avoidance is adopted when $V > V_{opt}$ and control when $V < V_{opt}$.

Curve C is for an organization that manufactures a product for which an indefinite number of varieties lead to an indefinite increase in customer benefits. This very unlikely case would deliver an indefinite V_{opt}, and thus, additive manufacturing should be used to control the complexity and as catalyst for increasing the number of varieties.



f_{BEN} and f_{Costs}	Description	likely V_{opt}	Complexity Management Strategy
a	Variety reduces overall benefits	1	**Control**
b	Variety increase benefits to an turning point and decreases benefits afterwards	$1 < V_{opt} < \infty$	$V > V_{opt}$: **Avoidance** $V < V_{opt}$: **Control**
c	Variety increases overall benefits indefinitely	∞	**Control**
d	Variety does not impact benefits curve	$Min(f_{costs})$	**Avoidance**

Figure 28: Complexity Management Strategies Based on Type of Benefit Curve

Curve D actually illustrates the benefit function of an organization that manufactures a product for which variety does not affect the customer benefits at all. For example, if a product is available in different colors but the customer (e.g., in a business-to-business environment) does not care about color, the variety would not affect customer benefit at all. In this case, the complexity management strategy for additive manufacturing should be to avoid complexity. Depending on the overall cost level, an organization might also use traditional manufacturing methods instead, as additive manufacturing provides benefits with increased variety. The V_{opt} would be at the minimum of the cost function. Figure 28 summarizes the appropriate complexity management strategies for the different benefits curves.

Why am I looking at benefit curves vis-à-vis complexity management strategies? I do so because I assume that additive manufacturing is, from a technology perspective, better able to produce variety than traditional manufacturing can. Thus, for benefit curve c in Figure 28, additive manufacturing would be favorable because it more easily produces variety and controls complexity. In its final evaluation, the organization should determine whether to avoid or to manage complexity.

5.3. Performance Review

5.3.1. Complexity

As addressing complexity is not an end in itself, it should be improved by applying additive manufacturing. Thus, it is important for the level of complexity to decrease. Reviewing the complexity measures or KPIs defined in sections 4.3 and 4.4 shows a reduction of the complexity levels. These metrics do not show whether complexity is good or bad, only whether the transition from the old to the new supply chain reduces complexity. Further, these can serve as benchmarks for industries with sufficient data.

In the following, I will analyze how the different measures should be evaluated in terms of how much they decrease complexity.

Numerousness metric

The numerous metrics is one of the key metrics in supply chain complexity. This metric should be reduced in applying additive manufacturing instead of traditional manufacturing.

Table 12: Interpretation of variety metric (VM)

Case	Variety Metric (VM)	Numerous Metric (NM)	Interpretation	
			Complexity Level	Explanation
A	+	+	+	Number of similar supply chain elements increased more than total number of elements.
B	–	+	–	Total number of elements increased more than number of similar elements, so diversity was reduced. This might be the case if more products were produced with the same value chain setup.
C	0	+	+	Both total number of elements and number of similar elements increased linear.
D	+	–	–/+	Total number of elements decreased more than number of similar elements, so diversity increased, albeit overall system involved fewer elements.
E	–	–	–	Number of similar elements decreased more than total number of elements.
F	0	–	–	Both total number of elements and number of similar elements decreased.
G	+	0	+	Diversity increased.
H	–	0	–	Diversity decreased.
I	0	0	0	Complexity level did not change.

Legend: + = increase level of complexity – = decrease level of complexity 0 = equal

Variety metric

The variety metric is a ratio of similar elements to total number of elements. It needs to be interpreted depending on the development of the numerousness metric (NM). Table 12 shows the different interpretations.

Based on this hypothesis, the only major benefit of additive manufacturing is its ability to consolidate production process steps. In cases A, C, and G, additive manufacturing is unfavorable because it might not utilize its full capabilities. In contrast, in cases B, D, E, F, and H, additive manufacturing is favorable because it reduces complexity.

Connectivity metric

Like the variety metric, the connectivity metric is also a ratio. However, it assumes that the total number of relationships will be reduced in the same absolute extent as the number of supply chain elements will be reduced. Thus, the connectivity metric should be reduced for additive manufacturing to be favorable for complexity management.

Opacity metric

For the opacity metric or known process metric (KPM), the total transparency should increase or stay on the same level for additive manufacturing to be favorable. This case holds only if the total number of supply chain processes decreased by the same extent. If the opacity metric decreases, traditional manufacturing methodologies would be favorable. Although by conducting the remodeling exercise I determine that this ratio should increase for traditional manufacturing also, the major benefit of additive manufacturing should be its ability to reduce the number of processes, which needs documentation and training.

For decision-making purposes, the overall number of production-related complexity measures is not relevant, as only the overall system performance matters. Thus, an interpretation only takes place at the evaluation process in Step 3 (cp. section 4.4) because this step determines whether to proceed with the process. If the complexity is not caused by the production technology, a remodeling is not considered.

Thus, to determine which of the four measures reduces the most complexity, I suggest calculating a weighted final grade for each of the four different measures. As companies might have different capabilities to manage the different drivers of the complexity, each company should define its own weighting. To derive the final grade for complexity, the company should assign each measure a zero value if it increases or maintains the overall system complexity and a value of one if it decreases the complexity. For each measure, the company will define a weighting and multiply it with the value. The weightings for all the measures should total 100%. The sum of the calculated weighted contribution would result in a positive (+) contribution if ≥ 0.5 and a negative (–) contribution if < 0.5. Table 13 provides an example of this evaluation logic. With 0.65, the overall decision model, which will be introduced in section 5.4, will derive a positive final grade. Applying this type of evaluation scheme it is important to have a common nomenclature, i.e. in the example in Table 13 a one will be awarded if it decreases the complexity, it does not mean that the value of the measure decreases or increases.

Table 13: Example of an overall complexity evaluation

Measure	Contribution to Complexity (0 = increase/maintain, 1= decrease)	Weighting	Weighted Contribution
NM	0	25%	-
VM	1	40%	0.40
CM	1	25%	0.25
KPM	0	10%	-
	Final Grading	100%	0.65 (= +)

NM = Numerousness metric, VM = variety metric, CM = Connectivity metric, and KPM = Known process metric

5.3.2. Supply chain performance

An approach similar to that for the complexity measures should be applied for the supply chain performance measures. The supply chain performance measures should be evaluated individually to derive an overall supply chain performance evaluation, as was discussed in sections 2.4.2 and 4.6. Table 14 provides an overview of the evaluation results by measure.

Table 14: Supply Chain Performance Measures and Evaluation

#	Measure	Improved Performance (1)	Reduced Performance (0)
1	*On time delivery* (OTD)	Higher	Lower
2	*Inventory turnover* (ITO)	Higher	Lower
3	*Inventory days on stock* (DOS)	Lower	Higher
4	*Order cycle time* (OCT)	Lower	Higher
5	*Supply chain cycle time* (SCCT)	Lower	Higher
6	*Capacity utilization (CU)*	Higher	Lower
7	*Supply chain cost*	Lower	Higher
8	*Product performance*	Accepted by customer	Not accepted by customer

KPIs 1 to 8 are already described in detail in section 2.4.2, but product performance and supply chain cost will be further described in the following paragraphs.

Product performance

To evaluate product performance, two KPIs outlined in section 4.6 and the case study in chapter 6 will be assessed. These measures are surface roughness and product strength. In the likely additive manufacturing case where both KPIs show decreased quality, it is critical to determine if the product performance meets customer requirements.

Supply chain cost

As already stated in section 4.6, the total supply chain cost (SCC) is a major decision criterion. The supply chain cost for additive manufacturing (SCC_{AM}) should be lower than the supply chain cost for traditional manufacturing (SCC_{TM}). As shown in the case study in chapter 6, the cost position for material costs and machine costs in traditional manufacturing is adverse (cp. Figure 45), while advantages in labor costs and tooling costs exist in additive manufacturing. This tendency is not covered in the case study but could be assumed, as it is a major characteristic of the technology described in section 2.1.2.

In the following, I will analyze the supply chain costs and the dependencies from traditional and additive manufacturing mathematically to determine when additive manufacturing is favorable or comparable to traditional manufacturing. To achieve this, I apply the following equation:

$$SCC_{AM} \leq SCC_{TM}$$

Using the more detailed representation in section 4.6, I expand the equation as follows:

$$\sum_{i}[(C_{TAM}+C_{PAM}+C_{IHAM})]+[(c_{muBAM}*m_{uBAM})+(c_{muSAM}*m_{uSAM})$$

$$-\left((I_{muBAM}*m_{rBAM})+(I_{muSAM}*m_{rSAM})\right)]$$

$$+[clh_{AM}\ *\ (td_{AM}\ +\ ts_{AM}+\ tpp_{AM}\ +\ tpm_{AM})]+[C_{AhAM}*t_{AAM}])$$

$$+c_{EAM}+C_{KAM}$$

$$\leq\sum_{i}(C_{TTM}+C_{PTM}+C_{IHTM})+[(c_{muBTM}*m_{uBTM})$$

$$+(c_{muSTM}*m_{uSTM})-\left((I_{muBTM}*m_{rBTM})+(I_{muSTM}*m_{rSTM})\right)]$$

$$+[clh_{TM}\ *\ (td_{TM}\ +\ ts_{TM}+\ tpp_{TM}\ +\ tpm_{TM})]+[C_{AhTM}*t_{ATM}])$$

$$+C_{ETM}+C_{KTM}$$

Where

i	=	# of supply chain processes
C_T	=	Transportation costs
C_P	=	Pick up costs
C_{IH}	=	Inventory holding costs
c_{muB}	=	Building material costs per unit (e.g., kg)
c_{muS}	=	Support material costs per unit (e.g., kg)
m_{uB}	=	Building material used in units (e.g., kg)
m_{uS}	=	Support material used in units (e.g., kg)
c_{lh}	=	Hourly labor cost
I_{muB}	=	Building material recycling income per unit (e.g., kg)

I_{muS} = Support material recycling income per unit (e.g., kg)

m_{rB} = Building material for recycling in units (e.g., kg)

m_{rS} = Support material for recycling in units (e.g., kg)

t_d = Time used for designing and converting design files

t_s = Time used for preparation of machining

t_{pp} = Time used for post-processing of parts

t_{pm} = Time used for post-processing of machine

t_A = Time in hours for setup, processing, and post-processing of a machine

c_E = Energy costs per piece

C_{ah} = Hourly machine cost

C_K = Coordination costs

The extensions "AM" and "TM" of each parameter stand for "additive manufacturing" and "traditional manufacturing," respectively.

To simplify the formula, I simplify its right side, as the cost function for traditional manufacturing differs from that of additive manufacturing. I assume that no support cost is required, so I set the cost (c_{muSTM}, I_{muSTM}) and mass ($m_{uSTM,}$ m_{rSTM}) elements regarding support material to nil. Additionally, I assume that the time for designing and converting design files will be equal, so that $t_{dAM} = t_{dTM}$. Therefore I take them out of the equation.

To further simplify the formula, as was also stated in section 2.1.5.3, I assume that labor rates (clh) for additive manufacturing and traditional manufacturing will be equal, so $clh_{AM} = clh_{TM} = clh$.

The cost model I have developed does not take volume, specifically lot size, into account. As traditional manufacturing costs do carry a significant share of fixed costs, a view into the effects of quantities might be interesting, to determine under which circumstances $SCC_{AM} \leq SCC_{TM.}$ Or the other way round as one major advantage of additive manufacturing is reduced fixed costs due to a tool-free production technology (cp. section 2.1.1), and thus, for example, increasing volume would favor SCC_{TM} costs per produced part. Consequently, t_s (time used for preparation of machining) and partially C_K (coordination cost) are considered to be affected by volume, as a setup is necessary for each production line, independently of the quantity to be produced. The same is valid for designing and converting design files, but as they are assumed to be equal, I will not consider them in the cost formula any further. To cover this possibility, I introduce production lot size (Q). For the preparation time I will introduce tst = ts * Q, i.e. the total time used for preparation of a machine for the quantity produced in the production run. For simplicity purposes I will not introduce the quantity for the coordination costs, as these are assumed as a minor cost driver. To compare traditional manufacturing and additive manufacturing methods, I split consolidated machining time (t_a) into the two elements: total setup and post-processing time (t_{as}), as they result in fixed costs, and processing time per produced piece (t_{ap}). Thus,

$$t_a = \frac{t_{as}}{Q} + t_{ap}.$$

The coordination costs are treated as step costs; to a certain extent one system might be sufficient to deal with a certain volume per production run but might require capacity extensions for higher production lot sizes. The same is valid for manpower. However, the suggested approach in section 4.6 to apply an hourly rate would assume an average utilization rate that might be sufficient in the first instance, as additive manufacturing intends to reduce the coordination time by reducing the overall required quantity.

For traditional manufacturing, it is also required to take tooling costs into consideration, as it is a fixed cost, and thus, drives up overall cost especially for small production lot sizes. To calculate the tooling cost per piece, the overall cost for the tool and the fixtures will be divided by the total number of parts produced (Q_T) with the tools and fixtures. For simplicity, I assume that the total tooling cost (C_W) covers all costs including purchase price, regrinding, and income like residual values, but I do not describe this assumption in further detail here. Thus, tooling cost per piece (C_{WP}) is calculated as follows:

$$C_{WP} = \frac{\sum_j C_W}{Q_T}$$

where

j	=	Number of tools required
Cwp	=	Tooling costs per piece/produced part
C_W	=	Total tooling cost
Q_T	=	Total quantity produced with tool/fixture

Thus, incorporating the preceding results in the following equation for a single piece, I get

$$\sum_i [(C_{TAM} + C_{PAM} + C_{IHAM})] + [(c_{muBAM} * m_{uBAM)} + (c_{muSAM} * m_{uSAM})$$

$$- \left((I_{muBAM} * m_{rBAM}) + (I_{muSAM} * m_{rSAM})\right)]$$

$$+ \left[clh \quad * \left(\frac{tst_{AM}}{Q} + \ tpp_{AM} \ + \ tpm_{AM}\right)\right] + \left[C_{AhAM} * (\frac{t_{asAM}}{Q} + t_{apAM})\right])$$

$$+ c_{EAM} + C_{KAM}$$

$$\leq \sum_i (C_{TTM} + C_{PTM} + C_{IHTM})$$

$$+ \left[(c_{muBTM} * m_{uBTM)} - (I_{muBTM} * m_{rBTM})\right]$$

$$+ \left[clh \quad * \left(\frac{tst_{TM}}{Q} + \ tpp_{TM} \ + \ tpm_{TM}\right)\right] + \left[C_{AhTM} * \left(\frac{t_{asTM}}{Q} + t_{apTM}\right)\right])$$

$$+ C_{ETM} + C_{KTM} + \frac{\sum_j C_W}{Q_T}$$

A limitation of this model is that it is a static cost model based on the status quo and does not provide any insights on sensitivities or future developments.

Final grading for supply chain performance

To arrive at a final decision on how to position the supply chain performance in the decision model, which will be introduced in section 5.4, a weighted grade should be calculated using the complexity measures in section 5.3.1 except for product performance, as if product performance is rated by customers as not acceptable, supply chain performance will be rated negatively (–). Table 15 illustrates the grading of supply chain performance for two cases. In case A, the product performance is accepted by the customer, while in case B, it is not.

Table 15: Two Examples of Supply Chain Performance Grading

A	*Example: Product Performance accepted by customer*			
#	**Measure**	**Supply Chain Performance (0 = decreased/maintain level, 1= increase)**	**Weighting**	**Weighted Contribution**
1	*On time delivery* (OTD)	1	10%	0,10
2	*Inventory turnover* (ITO)	0	10%	-
3	*Inventory days-on-stock* (DOS)	1	5%	0,05
4	*Order cycle time* (OCT)	1	5%	0,05
5	*Supply chain cycle time* (SCCT)	0	15%	-
6	*Capacity Utilization (CU)*	0	5%	-
7	*Supply Chain Costs*	1	50%	0,50
	Total Evaluation (1-7)		**100%**	**0,70**
8	*Product Performance*	1		
	Final Evaluation			**0,70**

B	*Example: Product Performance NOT accepted by customer*			
#	**Measure**	**Supply Chain Performance (0 = decreased/maintain level, 1= increase)**	**Weighting**	**Weighted Contribution**
1	*On time delivery* (OTD)	1	10%	0,10
2	*Inventory turnover* (ITO)	0	10%	-
3	*Inventory days-on-stock* (DOS)	1	5%	0,05
4	*Order cycle time* (OCT)	1	5%	0,05
5	*Supply chain cycle time* (SCCT)	0	15%	-
6	*Capacity Utilization (CU)*	0	5%	-
7	*Supply Chain Costs*	1	50%	0,50
	Total Evaluation (1-7)		**100%**	**0,70**
8	*Product Performance*	0		
	Final Evaluation			**0,0**

As for the complexity metrics, the weightings for measures 1 to 7 should total 100%. The sum of the calculated weighted contribution would result in a negative contribution (–) if < 0.5 and a positive contribution (+) if ≥ 0.5.

5.4. Decision Model

As already mentioned in the introduction, an easy-to-use decision model will be based on the complexity level, the supply chain performance, and the strategic benefit curve.

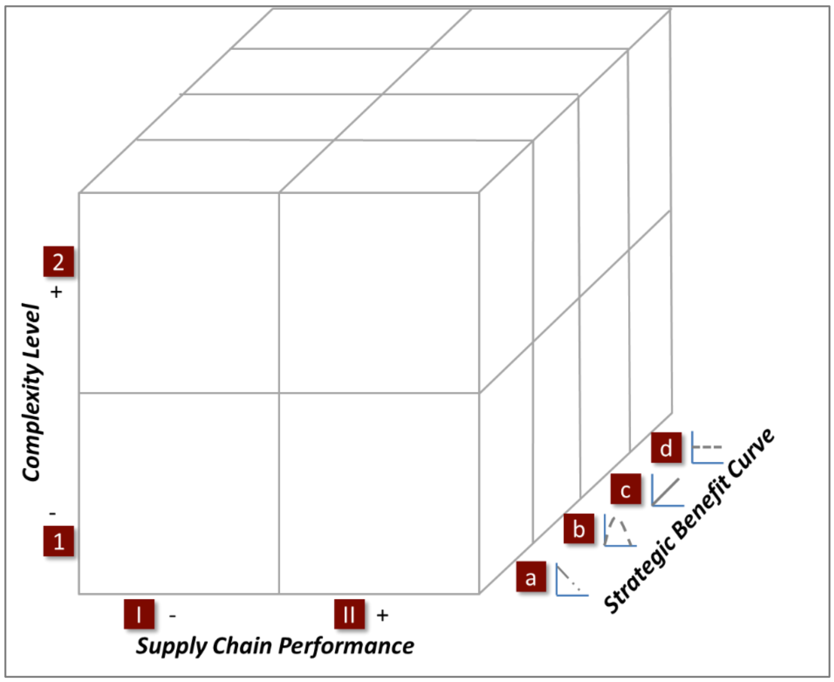


Figure 29: Decision Model

Figure 29 illustrates the decision model, which has two stages each for the complexity level (1/2) and the supply chain performance level (I/II), as well as four stages for the strategic benefit curves (a/b/c/d). I will describe the resulting 16 different situations to determine where additive manufacturing should be used to manage complexity in supply chains and for which basic complexity management strategy (cp. Section 2.3.3.2) additive manufacturing might be sufficient. This decision model should be seen as a basis for discussion for decision making.

Table 16: Decision Model Interpretation

Complexity Level	Supply Chain Performance	Strategic Benefit Curve	Application of AM	Comment
1	I	a	No	The capability of additive manufacturing to manage variety does not provide any value to the organization.
1	I	b	No	The advantage of additive manufacturing is finite, as customer value decreases if variety is too high.
1	I	c	Maybe	Additive manufacturing might be able to increase product variety and improve sales, but it does neither improve supply chain performance nor reduce complexity levels. Thus, the application should be evaluated regularly as technology improves.
1	I	d	No	The capability of additive manufacturing to manage variety does not provide any value to the organization.
1	II	a	No	The capability of additive manufacturing to manage complexity does not provide an sustainable value to the organization by increased customer value, however an organization might consider benefits from increased supply chain
1	II	b	Maybe	The advantage of additive manufacturing is finite because customer value decreases if variety is too high and it does not help to improve complexity levels. However, the application improves the overall performance of the supply chain.

Com-plexity Level	Supply Chain Per-formance	Strategic Benefit Curve	Application of AM	Comment
1	II	c	Yes (Control)	Although additive manufacturing does not reduce complexity, it improves supply chain performance and additional variety will be valued by the customer.
1	II	d	No	Supply chain performance improvements might be utilized by the organization, but the application would not be seen as mandatory.
2	I	a	No	Additive manufacturing improves the complexity level but performance of the supply chain decreases. As complexity is not an end in itself, use of additive manufacturing is not recommended especially as variety is not valued by the customer
2	I	b	Maybe (Avoid & Control)	The advantage of additive manufacturing is finite because customer value decreases if variety is too high, so additive manufacturing should only be taken into account if the organization has room to increase customer benefit with an increase in variety.
2	I	c	Yes (Control)	Additive manufacturing might increase product variety and improve sales, however supply chain performance reduces; customer acceptance of the latter needs to be evaluated.
2	I	d	No	Additive manufacturing improves the complexity level but reduces the supply chain performance of the organization. As complexity is not an end in itself and variety is not valued by the customer, use of additive manufacturing is not recommended.
Com-plexity	Supply Chain Per-	Strategic Benefit	Application of AM	Comment

Level	formance	Curve		
2	II	a	Yes (Avoid)	Additive manufacturing improves complexity levels and supply chains performance, however variety does not create customer value.
2	II	b	Yes (Avoid & Control)	Additive manufacturing should be utilized but the product variety needs to be monitored to avoid reducing customer benefits.
2	II	c	Yes (Control)	Application of additive manufacturing adds significant value to the organization.
2	II	d	Yes (Avoid)	Application of additive manufacturing adds significant value to the organization but not to customers.

AM = Additive manufacturing

Based on the evaluations in sections 5.2 (strategic benefit curve), 5.3.1 (complexity level), and 5.3.2 (supply chain performance), the appropriate quadrant will be determined. Table 16 describes each of the 16 situations or quadrants and gives an indication how additive manufacturing could be used in the context of supply chain complexity management.

6. CASE STUDY: APPLICATION POSSIBILITIES IN THE HOME APPLIANCE INDUSTRY

6.1. Introduction

The industrial applications of additive manufacturing in a mass production environment are limited based upon the current build speed of the machines. Thus, I have chosen the home appliance industry for this dissertation's case study. After describing the organization's supply chain and its complexity, the chosen approach based on chapter 4 will be discussed.

While production technology is driven by mass production, retailers and consumers seem to consistently request new product variants. In my case study, the washing machine made by a leading European home appliance manufacturer has an average lifetime of 14 months. Thus, the level of external complexity is high.

Additionally, the manufacturer follows a multi-brand strategy and runs an international production and R&D network, which results in a high level of internal complexity. The high internal and external complexities require a strict complexity management strategy. Although the manufacturer uses complexity management tools like a platform strategy, the major aspect of its complexity management is avoiding complexity.

In this case study, the application options of additive manufacturing for managing complexity are analyzed. Specifically, the supply chain and complexity of a control panel, one of the key product parts, are analyzed and remodeled by applying additive manufacturing. The objective of this case study is to explore the advantages and challenges of additive manufacturing and its ability to manage complexity in the supply chain. The case study does not attempt to find a suitable application field for additive manufacturing but rather attempts to determine what needs to be done and when to apply additive manufacturing in a series production environment to manage supply chain complexity.

In the case study, I will first introduce the technical details of the control panel and its production. Afterward, I will discuss the details of the supply chain and complexity drivers. All data are related to a leading European home appliance manufacturer and its suppliers. To ensure the confidentiality of the manufacturer and suppliers, no identifying information will be mentioned.

6.2. Washing Machine Construction

There are two major types of washing machines for residential use: top-loaders and front-loaders (Zeiger, 2002). In this case study, I focus on front-loader machines, as they are more common in Europe than top-loader machines.

A control panel is an interface that enables the user to control the functions of the washing machine, such as the temperature, water level, rotation speed, and washing duration (Zeiger, 2002). It is usually located at the upper-front of a front-loading washing machine. Figure 30 shows an example of a front-loading washing machine and the position of the control panel.

Figure 30: Example of a front-loading washing machine (Model BEKO WA 8660)

The control panel consists of different subcomponents. Table 17 provides an overview of the common subcomponents and their material costs.

Table 17: Subcomponents of a control panel

Sub-component	Material cost [€]	Comment
Plexiglas-Hood	1,75	Used only for some sales models Used for design or language differentiation No real value – could be dropped or simplified
Panel body	1,2	
Bowl handle	0,7	Inlay is an extra part used for design reasons and is not existing for the majority of standard VIBs
LED display mechanic	1,0	Only applicable if a LED display is used – LCDs are part of the electronic
Display window	0,2-0,8	Used for any display (LED and LCD)
Rotary switch	0,2-0,6	High number of variations
Keys	0,6	Average of 4 keys at 0,15 each
Electronic housing	0,4	Subject to special regulations (VDE)
Light guide	0,3	Many different shapes and prices
Language legend	0,3	Could be replaced by stickers

Source: Home appliance manufacturer, 2008

The configuration of the subcomponents depends on the sales model and platform. For example, only the high-end models have a light-emitting diode (LED) display. In general, the panel body, bowl handle, rotation switches, and other buttons and switches are made mainly of ABS. The light guides are made of polymethylmethacrylate (PMMA).

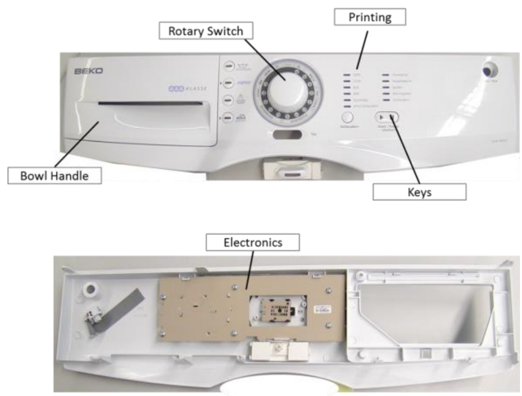


Figure 31: Control panel – Front and back (Model BEKO WA 8660)

Figure 31 shows an example of a control panel and its major elements.

A wire harness connects the control unit and all power-operated devices (Zeiger, 2002). Figure 32 shows the connections of the circuit board and the wire harness. For reference purposes, Figure 33 shows the circuit board of a different washing machine model from a different manufacturer, which has an additional liquid crystal display (LCD). Otherwise, this circuit board is identical to that in this case study's model.

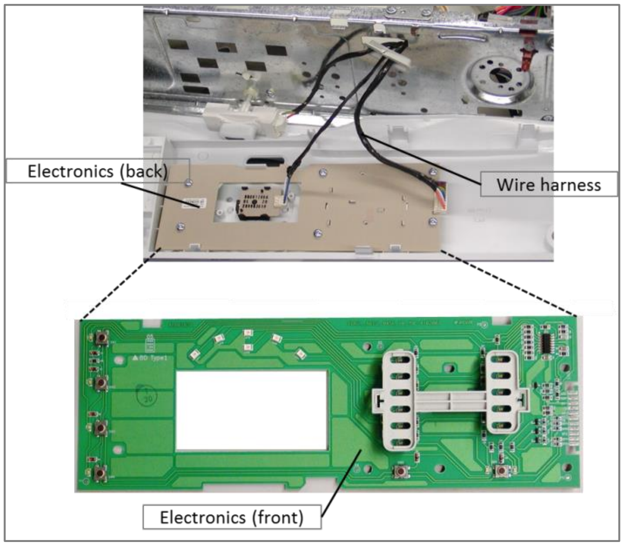


Figure 32: Control panel circuit board – Front and back (Model BEKO WA 8660)

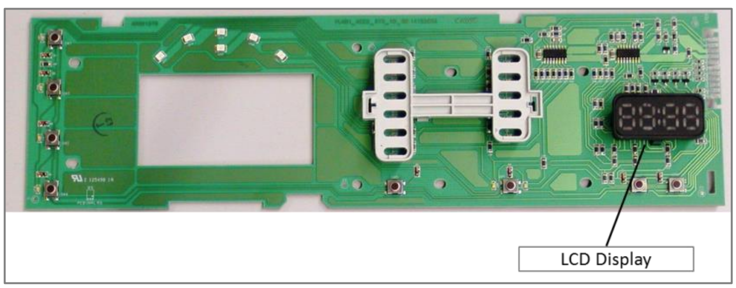


Figure 33: Control panel circuit board (Model Arcelik 3650 SJ)

There are different ways of integrating the circuit board to the control panel. Beko and Arcelic connect the board to the panel body with screws, but other manufacturers use a special housing made mainly of PMMA, which is a heat-resistant material. Figure 34 shows an example of an electronic housing construction.

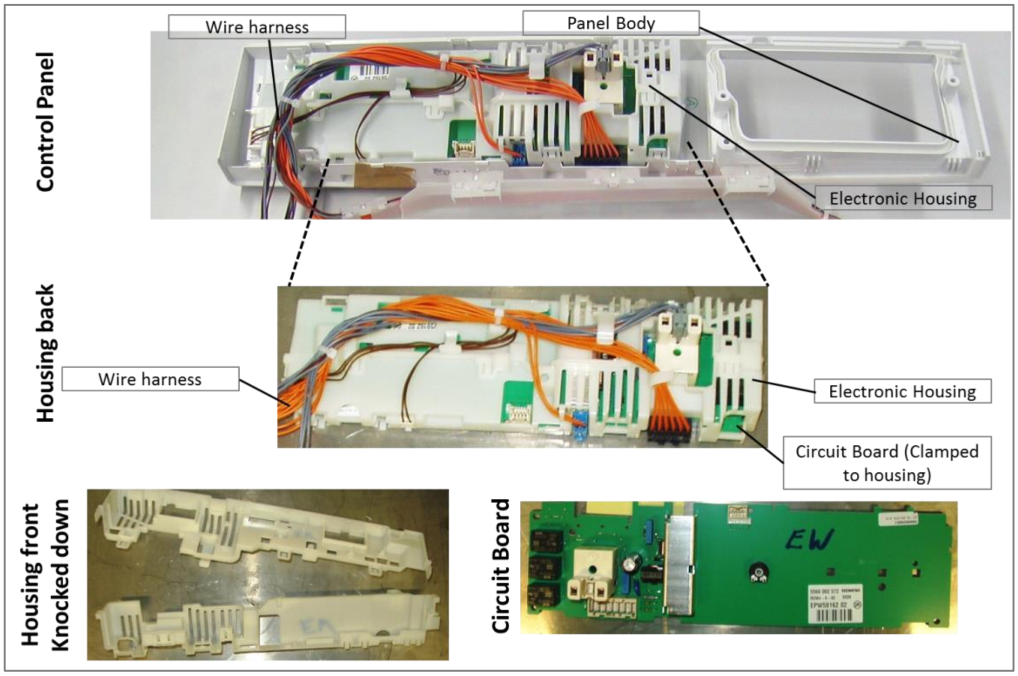


Figure 34: Electronic housing for washing machine control panel (Model: Siemens WXLM 1070EX)

6.3.Construction-Driven Complexity

In this case study, the electronic parts and the wire harness will be excluded in the initial discussion because the focus is on the direct printing of plastic materials. The electronics can be further enhanced, as demonstrated by Lopes et al. (2012) in a hybrid manufacturing methodology that combines stereolithography and direct printing to manufacture embedded electronics. However, I first focus on the following elements, which can be produced by additive manufacturing, due to their material similarities: bowl handle, control panel, rotation switch, and buttons including text and decorations for printing.

By looking at the complexity of the components, I can see that the appliance manufacturer has already initiated a modularization and platform strategy for its washing machines, dividing them into three platforms based on their product positioning: low-end, middle, and high-end platforms.

In terms of external design, these various platforms are differentiated through the parts above the appliance's skin, such as the control panel.

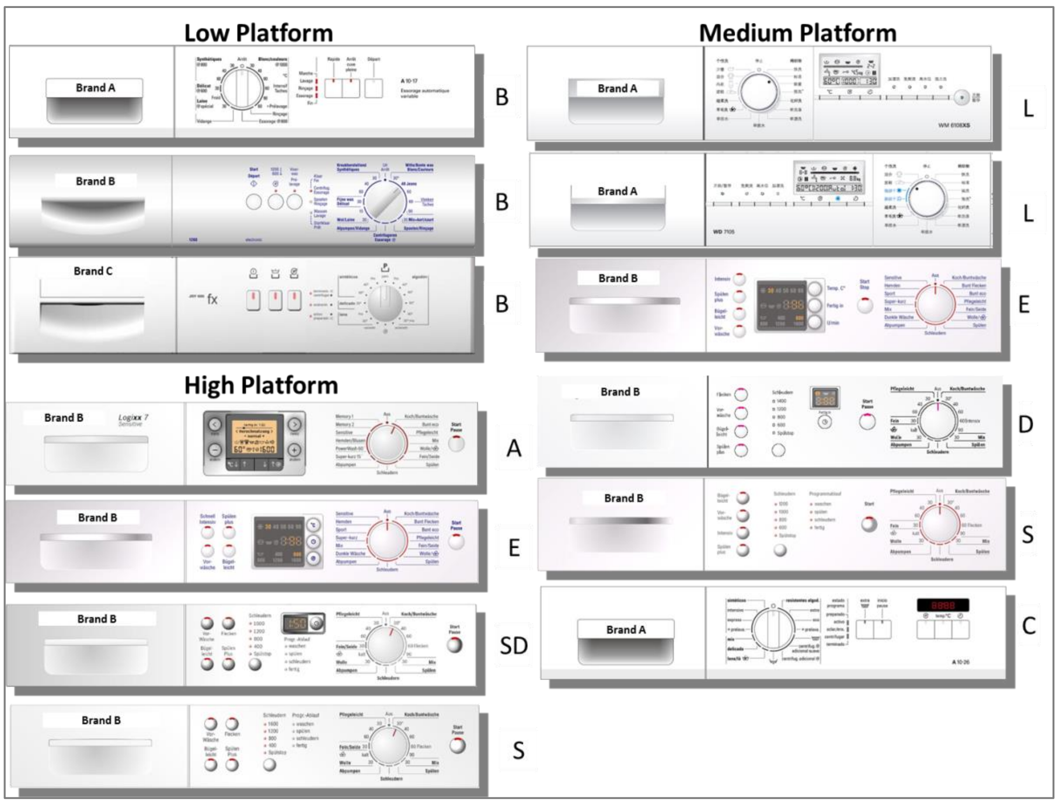


Figure 35: Control panel external designs for various platforms

Figure 35 shows examples of the external designs of the control panels of various platforms. The letters next to the control panel define which electronic control unit (operating model) is used. The operating model is divided into two major elements: the power module, which includes the washing programs, and the handling module, which contains the control buttons and rotation switches.

In this case study, I focus only on the product portfolio of one production site in the east of Germany. This production site was established initially to produce the high-end platform models. This platform has about 240 variants. Figure 36 provides an overview of the control panel complexity, using Schuh’s (2005) concept of a variant tree and the value stream analysis. The red numbers show the number of variants for each component.

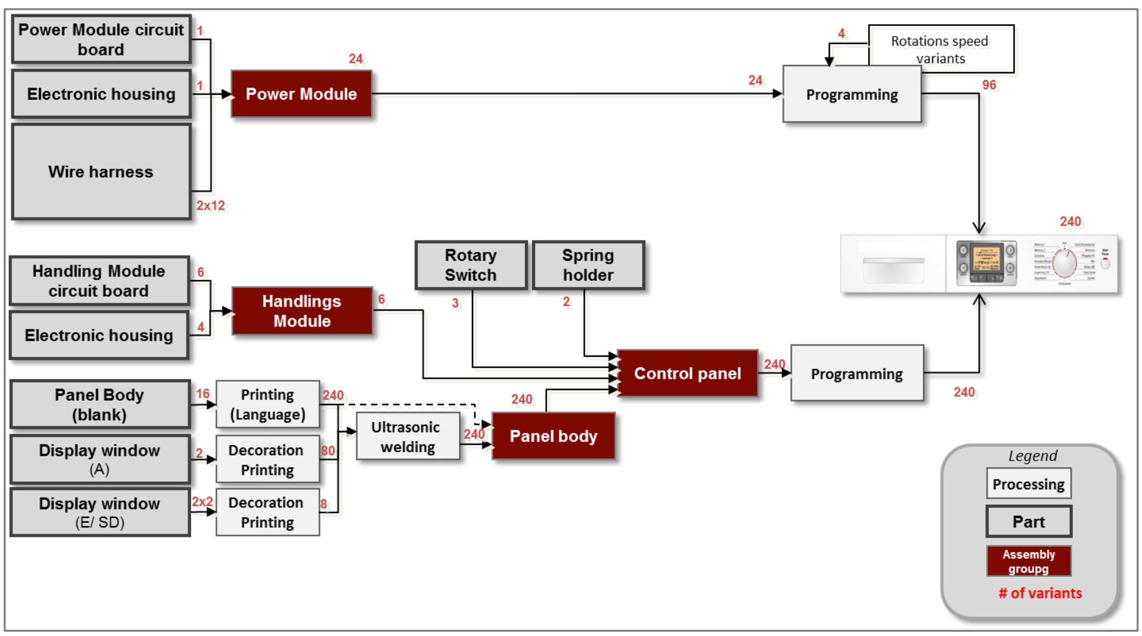


Figure 36: Variant tree of a washing machine control panel

There are 16 different base shapes for the control panel. Technically, there are only nine different platform models. However, the various control panels are used to differentiate between different brands (i.e., each brand has its own control panel design in which the major differentiator is the position of the rotary switch).

However, the major driver of complexity is the printing of the text on the control panel. All control panels have their own printed texts, which theoretically yield 240 different product variants. Additionally, most models have decorative prints (e.g., symbols, design features, logo). For simplicity, I assume these prints do not yield additional variants.

During a representative production year, the plant produces not just high-end platforms. There are 13 different models produced across all platforms, two of which are dryers (Type T9/T10). There are 27 basic panel design shapes, and thus, 27 different tools are required to produce these. Additionally, there are different printing variants per shape, resulting in 258 different shapes. Table 18 provides the details of the variant tree.

Based on the complexity clusters provided by Reiss (1993; section 2.3.2.2), I find that the complexity of the washing machine is a ‘mass complexity’ caused by the variety of products demanded by the market. Meanwhile, the major source of this mass complexity is the number of product variants (Schuh, 2005; section 2.3.2.3).

Table 18: Variant tree of the production portfolio of the home appliance manufacturer's Eastern Germany site, 2006

Site	Product	Panel Design Shape	Total Variants
Eastern German Site Portfolio	EuroTop	Brand A	12
		Brand B	11
		Brand C	1
	EuroTop Enhanced	Brand A	12
		Brand B	8
		Brand D	1
	F20-A	Brand A	27
		Brand B	31
	F20-E	Brand A	24
		Brand B	22
		Brand E	4
	S10-E	Brand A	10
		Brand B	12
	S10-S	Brand A	10
		Brand B	5
	S11-B	Brand A	8
		Brand B	1
	S11-C	Brand A	7
		Brand B	4
	Slimline	Brand A	6
		Brand B	6
	SlimLine Enhanced	Brand A	13
		Brand B	6
	SlimLine Plus	Brand A	5
		Brand B	10
	T10	Brand B	1
	T9	Brand A	1
Grand Total			258

Source: Data from Home appliance manufacturer, 2006

6.4. Current Supply Chain and Its Complexity

6.4.1. Scope

After describing the general construction-driven complexity of the washing machine's control panel, I will now focus on a specific production site of the home appliance manufacturer in Eastern Germany. Due to confidentiality issues, I use representative data only from 2006. Thus, although the supply chain described here reflects the manufacturer's current setup, the product portfolio and mix has changed. The production site has a production line setup for manufacturing washers and dryers. For simplicity and due to the broad scope of the control panel, both products are treated the same. Technically, there is no major difference between a control panel for a washer and that for a dryer; the differences are mainly in the dimensions and programming.

Table 18 gives an overview of the platforms produced at this site. The overall production capacity of the site in 2006 was approximately 520,000 machines.

6.4.2. Variants

Figure 36 in section 6.3 showed how different variants are produced within the supply chain. In the case study, the different value-adding steps in the supply chain are mapped (Figure 37). The figure gives a static view from a certain point in time; it shows that during a representative year, 258 different control panel variants exist, of which 30% account for 80% of sales.

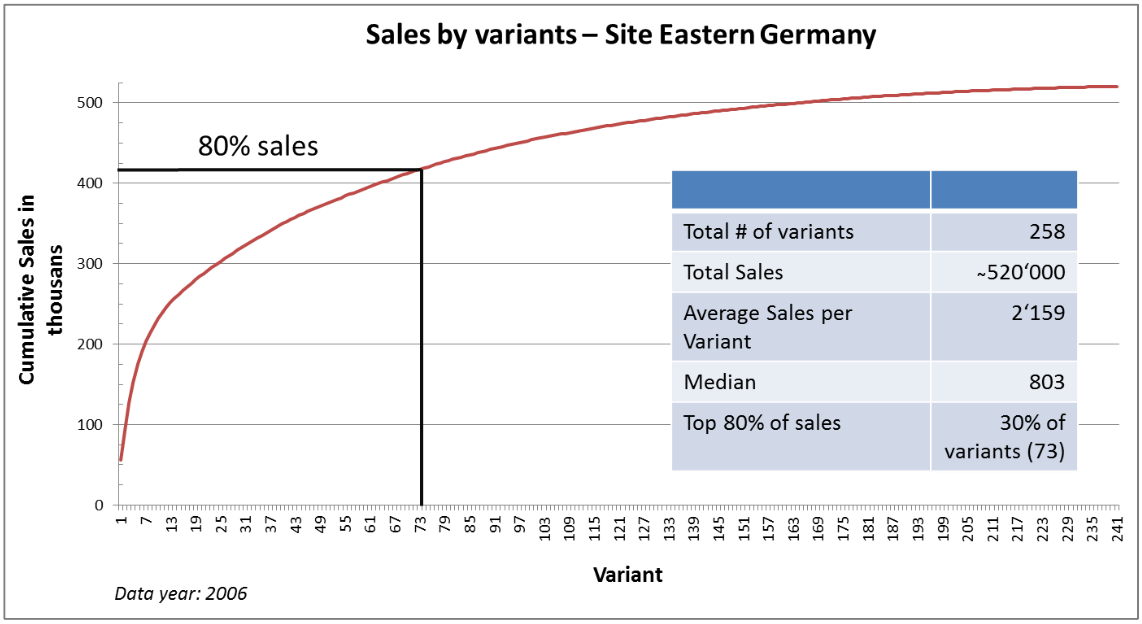


Figure 37: Sales by control panel variant (Data from Home appliance manufacturer, 2006)

Figure 37 shows that the average number of control panels sold is 2,159, while the median is 803. The low average and median values indicate a high level of complexity in the supply chain (see Appendix B: Washing machine sales by type).

6.4.3. Supply chain configuration and complexity

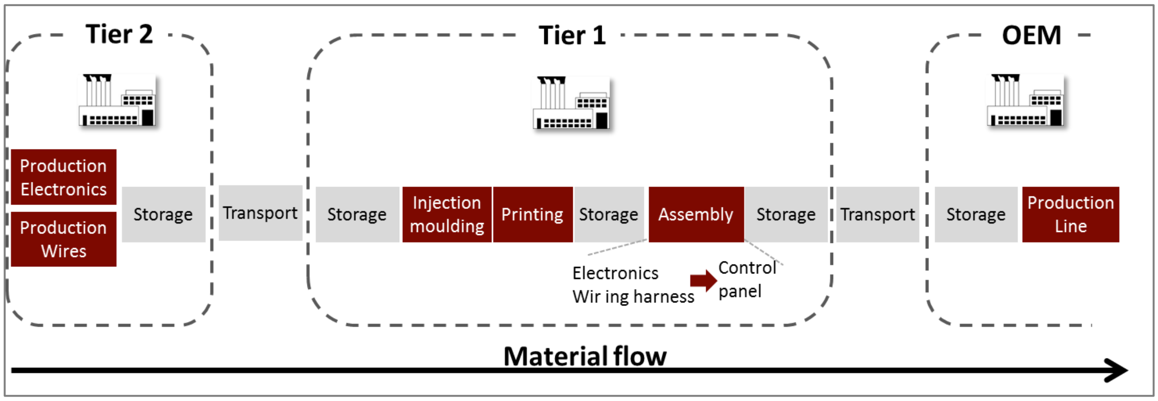


Figure 38: High-level supply chain for control panel (Based on data from Home Appliance Manufacturer, 2006)

Figure 38 gives an overview of the high-level supply chain for the control panel. Tier two suppliers provide the wires for the wire harness assembly and electronic components (e.g., power and handling module circuit boards). Tier two suppliers also store the finished products and then transport them to the tier 1 supplier upon request. Tier one suppliers add a different value in the supply chain:

- Injection molding of major plastic components (electronic housing, panel body including handle, display window)
- Printing on panel body (language and decoration)
- Storage and buffering of panel body
- Cable assembly for wiring harness and connection of electronic components to electronic modules
- Storage and buffering of electronic modules

- Assembly of electronic housing and circuit boards (clamping)
- Assembly of panel body (partially requires ultrasonic welding, e.g., for display windows) including complete electronics (i.e., circuit boards, wiring harness, and electronic housing)
- Storage and buffering of final control panel
- Sequencing of control panel
- Shipping to home appliance manufacturer (OEM)

The home appliance manufacturer buffers the final control panels and ships them to the production assembly line for the manufacture of the washing machines.

As stated in section 6.3, mass complexity is driven by the market and market requirements, and thus, it is also a dynamic complexity, based on Frizelle and Woodcock's complexity cluster (see section 2.3.2.2). The supply chain complexity is a static one mainly caused by requiring the printing at a very early stage in the process, which increases the number of variants at an early stage. This leads to additional stock requirements, which affects the ITO and SCC, as described in section 2.4.2.

6.4.4. Production processes within the supply chain

Within the supply chain for the control panel (excluding electronics), injection molding is the major production technology. The control panel consists of three different materials for its subcomponents:

- ABS for the control panel body, bowl handle, rotary switch, and buttons
- PMMA for the acrylic glass hood and window display
- Polycarbonate (PC-ABS) for the electronic housing

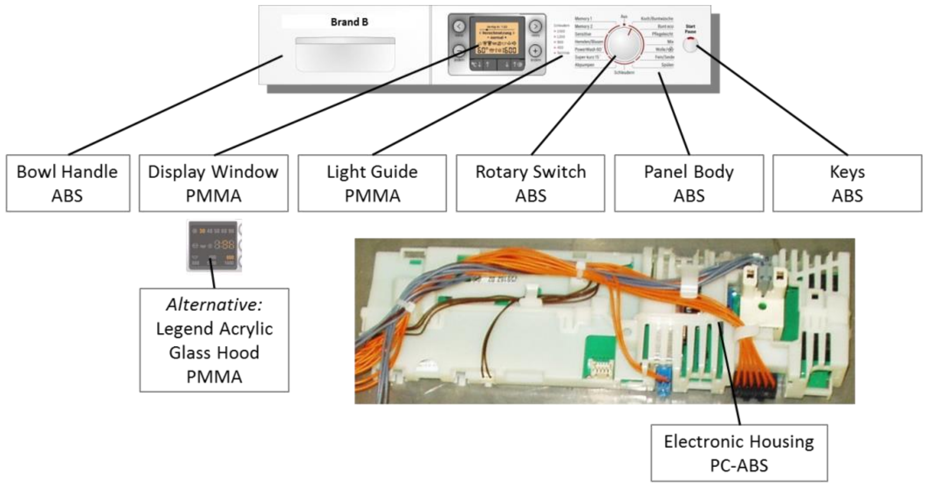


Figure 39: Overview of materials in the control panel

Figure 39 shows the different subcomponents of the control panel and the materials used. The subcomponents required for each control panel depends on the washing machine model and variant. Appendix C: Materials used per sub-component provides further details about the materials used and their weights. The usual outer dimensions of the control panel body are 595 x 110 x 45 mm (X x Y x Z); including the electronic housing and rotary switch, the width (Z dimension) increases from 45 to 85 mm.

In the following paragraphs, I will describe the control panel production. All data were collected on the home appliance manufacturer's Turkish production site. This site is slightly smaller than the German production site, but in terms of data availability is more transparent, as processes and production layouts in the latter site has changed several times recently, and thus, could not provide reliable data. To ensure the manufacturer's confidentiality, I collected data only for 2006.

This control panel supplier produced 510,129 control panels and 381,604 wire harnesses (on a second production line).

Figure 40 provides an overview of the high-level production process. The control panel production process consists of eight major steps: receiving raw materials, injection molding of parts, decoration printing, language printing (tampon printing), final assembly, packaging, storage of final goods, and shipping of final goods.

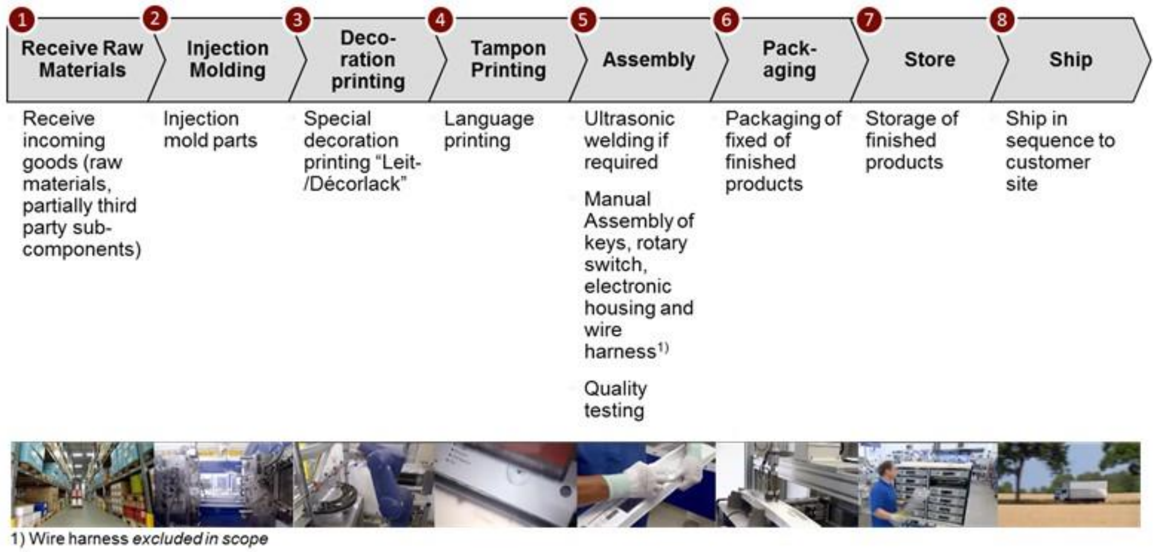


Figure 40: High-level control panel production processes (Images from PAS Deutschland GmbH, 2012; images are for illustration purposes only)

The production facility area (excluding office space) is 3,150 sqm for warehousing and wire harness production. The physical locations of the described production process steps are shown in Figure 41.

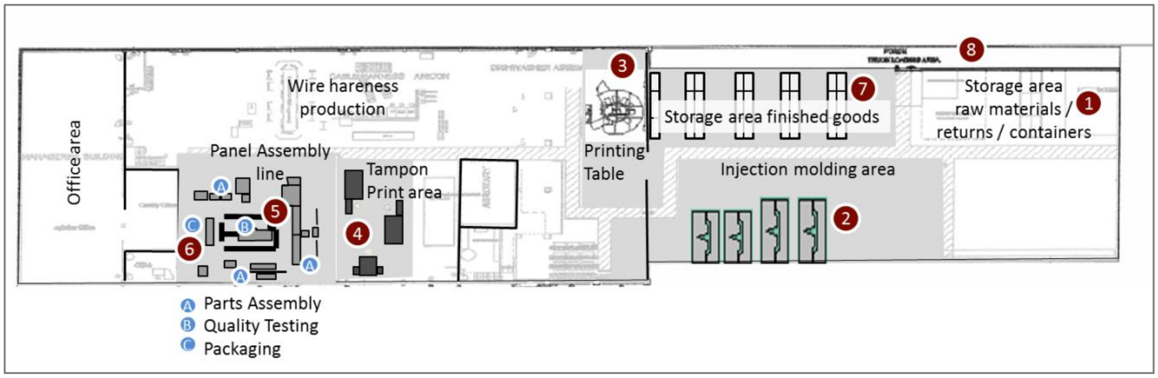


Figure 41: Location layout of control panel production (Author's own creation based on on-site assessment)

As the layout shows, injection molding, printing (two locations), assembly, and storage each have separate areas. The injection molding area has four presses (capacities: 2 x 350 tons, 1 x 250 tons, 1 x 150 tons) that operate in three shifts. The two printing areas consist of two linear pad-printing machines and a roundtable printing machine, both of which also run in three shifts. Next to the tampon printing area is a drying area that operates parallel to the printing area. Area B (quality testing) is beside a testing machine where three ultrasonic welders and three program loaders for programming the electronic components are also located. This area also operates in three shifts.

The total control panel production has 130 employees, 22 of whom are assigned in the direct production area in the wire harness production (see Appendix D: Headcount and Resource Model OF Panel Supplier). The remaining 108 employees are classified as follows: 4 managers, 12 supervisors, 10 other white collar/clerks, and 82 blue collar/production workers. A significant portion of human resources is allocated to control panel assembly (53 employees as production workers and first-line supervisors).

Table 19: Human resources and shift model of the control panel production

	Headcount				Shift model			
Official Figures	**Management**	**First line supervisor**	**Non supervisor (salaried and clerical)**	**Hourly direct work**	**Management**	**First line superviso**	**Non supervisor (salaried and clerical)**	**Hourly direct work**
Fabrication								
Injection								
Supervisor		1				Day shift		
Operators				6				Early/late/night shift
Printing								
Supervisor		1				Day shift		
Operators				7				Early/late/night shift
Prepare Klischees								Day shift
Assembly								
Supervisor		2				Day shift		
Shift supervisors		3				Early/late shift		
Assembly operators								
Assembly One								
Operator				24				Early/late shift
Packaging				4				Early/late shift
Assembly Two								
Control panel assembly								
Control surface				2				
Seal assembly				2				
Ultra sonic				4				
Display assembly				2				
Final test and preparation				6				
Packaging				4				
Shipping/recieving/material handling/stores								
Logistics management	1				Day shift			
Warehouse management		1				Day shift		
Storing				2				Early/late shift
Material handling for assembly				2				Early/late shift
Material planning/control			3					
Plant and Manufacturing Engineering		1				Day shift		
Maintenance (incl. Related projects)								
Technician mechanic/electric			2				Day shift	
Mechanic/electrician				2				Early/late shift
Injection maintence/setter				1				Day shift
Printing cliché stetter				1				Day shift
Printing Setter				3				Early/late/night shift
Quality								
Head of quality	1				Day shift			
Tech drawing		1				Day shift		
QM			1				Day shift	
Process control				3				Early/late shift
Incoming inspection				2				Day shift
Rework/Inspection				2				
Accounting/Finance	1		2		Day shift		Day shift	
Human Resources		1				Day shift		
Purchasing and Procurement			1				Day shift	
Material and Production planning/control								
Production planning/control		1				Day shift		
Material planning/control							Day shift	
IT								
Production/site mgmt	1		1		Day shift			
Other (Clean ladies/canteen)				3				Early/late shift
Totals	4	12	10	82				

Source: Author's observation/Data from Control panel supplier, 2006

Table 19 provides details of the human resource allocation. For simplicity, resources (e.g., cleaning) shared between the wire harness and control panel productions are allocated to control panel production.

6.5. Remodeling Opportunities through Additive Manufacturing

6.5.1. Overview and guiding principles

The home appliance manufacturer's supply chain is mainly defined by the production technology, namely, injection molding. In this section, the opportunities for reconfiguring the supply chain by changing the production technology to additive manufacturing will be assessed. For this purpose, I apply the five-step methodology defined in chapter 4.

This case study hypothesizes that supply chain performance—based on the metrics introduced in Figure 21—increases by reducing supply chain complexity through additive manufacturing.

The following are the assumptions and guiding principles I have chosen for the remodeling of the supply chain:

- Substitute injection molding with an additive manufacturing technology
- Fix the overall number of variants, that is, the level of product complexity will not be addressed
- Major complexity driver is the language and decoration printing
- Choice of materials should be as close to the current materials used as possible

6.5.2. Step 1: Strategy review

The strategic review will be fairly short because the focus of the case study is to evaluate additive manufacturing technology in a mass production environment. However, as stated in the case study's introduction in Chapter 6.1, the product innovation life cycle is becoming shorter in general; thus, the case study will attempt to reduce the 14-month life cycle of a washing machine variant. This shortening life cycle is driven by retailers' bargaining power, where retailers request higher discounts for older product variants, which prompts manufacturers to continuously release new variants without conducting much R&D. To this end, manufacturers utilize tools like the platform strategy. Another cause of the shortening life cycles is that retailers are increasingly requesting that specific models be sold exclusively through their outlets. This helps retailers give best-price guarantees to their customers because models are not available anywhere else. A third source of the shortening life cycles is the manufacturers' desire to differentiate themselves from competitors. Competition continues to become harsher as new manufacturers enter the market, especially those from Asia and Turkey, and manufacturers want to differentiate themselves by offering new, innovative models. Thus, management sees the ability to continuously provide new variants as strategically important to improving competiveness. The firm must improve its ability to manage the increased complexity that comes with continuously producing new variants.

The statements presented are those of the home appliance manufacturer's product management and not from any scientific research, which is beyond the scope of this dissertation.

6.5.3. Step 2: Supply chain complexity evaluation

The numerousness metric (NM), variety metric (VM), and connectivity metric (CM) will be calculated to measure the complexity of the existing supply chain. The opacity metric (known process metric or KPM) will be excluded because most of the processes in the initial analysis are on site, and thus, it is difficult to determine whether there are any unknown processes.

Numerous metric

Based on my calculation, the numerous metric is 424, which is fairly high. This metric considers the number of elements in the supply chain, including companies, interacting persons, inter-company business processes, employed systems, and offered products.

Table 20: Numerousness metric calculation

Element of Supply Chain (J)[1]	Number	Comment
Companies	5	Tier 2, Tier 1, OEM, Transports I and II
Interacting persons	136	Employees at Tier 1; assumed five full-time employees for internal transport at OEM and 1 truck driver *(Tier 2 excluded)*
Inter-company business processes	23	All high-level process steps[2] and internal production processes at Tier 1
Employed systems	2	Supplier and manufacturer ERP[3] systems
Offered products	258	Control panel variants
Numerous Metric	424	

Source: Author's assumptions and data from Home appliance manufacturer, 2006
[1] Number of supply chain elements, [2] See Figure 38, "High-level supply chain processes for control panel", [3] Enterprise resource planning

Table 20 provides details of the NM calculation. The calculation includes the entire supply chain but focuses mainly on Tier 1 suppliers and OEMs, and less on Tier 2 suppliers.

Variety metric

The VMj is calculated as follows:

$$VM_j = \left[1 - \frac{Number\ of\ simliar\ element\ types_j}{Total\ number\ of\ types_j}\right] x\ 100 = 1 - \left[\frac{36}{424}\right] x\ 100 = 91.5$$

Table 21: Number of similar product types

Element of Supply Chain (J)[1]	Number of Types	Comment
Companies	4	Transportation company II, Tier 1 suppliers, Tier 2 suppliers, OEMs
Interacting persons	7	Based on worker type[1a]; based on Tier 1 processes[2]
Inter-company business processes	23	All high-level process steps[3] and Tier 1 supplier internal production processes
Employed systems	1	Supplier and OEM ERP[4] systems
Offered products	1	Control panels
Totals	36	

Source: Author's assumptions and data from Home appliance manufacturer, 2006

[1] Number of supply chain elements, [1a] Warehousing, injection molding, decoration printing, tampon printing, assembly, packaging, transportation, [2] See Figure 40, "High-level processes in control panel production"; includes OEM warehouse, storage, and internal transportation staff, [3] See Figure 38, "High-level supply chain processes for control panel", [4] Enterprise resource planning

To determine the number of similar element types, a clustering was made within the type of elements, resulting in 36 element types. The total number of types is the same as the number of supply chain elements (J = 424). Table 21 provides details on the calculation of this metric.

There are different levels of details possible to calculate the number of similar element types. However, the level of detailsshould be the same across the entire process, as the total number of types for which the numerous metric is chosen.

Connectivity metric

The CM is not relevant in this case study's initial analysis because it focuses only on a specific part of the supply chain. Thus, I assume the CM will always be 100% because I do not incorporate the entire production network. When I reduce the supply chain complexity, the CM's numerator and denominator will decrease.

6.5.4. Step 3: Production technology-driven complexity evaluation

As described previously, different production technologies are required in control panel production, mainly in injection molding and the two types of printing (tampon and printing table). The production setup requires additional assembly work to segregate work and produce parts from different machines in order to reduce setup costs.

To assess the production technology-driven complexity, the following measures are calculated: production technology numerousness metric (NM_{PT}), production technology variety metric (VM_{PT}), and production technology variety metric ratio (VMR_{PT}).

Neither the production technology known process metric (KPM_{PT}) nor the production technology connectivity metric (CM_{PT}) is calculated because the case study does not analyze the entire process, and thus, all these metrics cannot be calculated.

Production technology numerousness metric

From my calculation, the NM_{PT} is 96.22. as follows:

$$NM_{PT}(\%) = \left(1 - \frac{16}{424}\right) x\ 100 = 96.22$$

Table 22: Production technology-related supply chain elements

Element of Supply Chain (J)[1]	Number of types	Comment
Supply chain companies	3	Tier 1 suppliers, Tier 2 suppliers, OEMs
Interacting persons	4	Based on worker type[2]; based on Tier 1 processes[3]
Inter-company business processes	9	All high-level process steps[4] and Tier 1 supplier internal production processes
Employed systems	0	Systems affected by production technology
Offered products	0	Products affected by production technology
Totals	**16**	

Source: Author's assumptions and data from home appliance manufacturer, 2006

[1] **Number of supply chain elements (e.g., warehousing, injection molding, decoration printing, tampon printing, assembly, packaging, transportation)**

[2] **See Figure 40, "High-level processes in control panel production"; includes OEM warehouse, storage, and internal transportation staff**

[3] **See Figure 38, "High-level supply chain processes for control panel"**

There are 16 production technology-related elements in the supply chain (Table 22). The total number of supply chain elements is shown in Table 21.

Production technology variety metric/production technology variety metric ratio

The number of similar production technology-driven element types (PT_j) is 16 (Table 22). To calculate the VM_{PT} and the VMR_{PT}, I need to determine the total number of production technology-related types. To this end, I assess which of the supply chain elements are related to production technology. Table 23 shows that approximately 83 elements in the supply chain are related to production technology. Thus, the VM_{PT} is 80.73, calculated as follows:

$$VM_{PT}(\%) = \left[1 - \left(\frac{16}{83}\right)\right] x\ 100 = 80.73$$

Meanwhile, the VMR_{PT} is 88.22, calculated as follows:

$$VMR_{PT} = \frac{80.73}{91.5} = 0.8822$$

Table 23: Total number of production-related elements in the supply chain

Element of Supply Chain (J)[1]	Number	Comment
Companies	3	Tier 1 suppliers, Tier 2 suppliers, OEMs
Interacting persons	71	Tier 1 supplier employees excluding non-production technology-related indirect and logistics full-time employees
Inter-company business processes	9	All high-level process steps[2] and Tier 1 supplier internal production processes
Employed systems	0	Systems affected by production technology
Offered products	0	Products affected by production technology
Total	83	

Source: Author's assumptions and data from Home appliance manufacturer, 2006

[1] Number of supply chain elements, [2] See Figure 38, "High-level supply chain processes for control panel"

6.5.5. Step 4, Part 1: Supply chain remodeling through additive manufacturing

This section first presents a short technology review and evaluation to determine which additive manufacturing technology best fits the complexity management for control panel production.

Control panel suppliers use an FDM solution from Stratasys to produce prototypes during the development stage. However, I also evaluate alternative technologies.

Because the supplier deals with three different polymeric materials (ABS, PMMA, and PC-ABS), several technologies like powder bed fusion and printing are considered. In contrast, although a large number of variants are created by decoration printing (section 6.4.2), only a limited number of technologies can print more than one color in one print job (Gibson et al., 2010).

After reviewing existing technologies for commercial usage (3Druck.com, 2012) (namely from Z Corporation (acquired by 3D Systems), Beijing TierTime Technology, Blueprinter, Stratasys/Objet (merged), EOS, Rapid Shape, Solidscape, Voxeljet, ExOne, Mcor, SLM Solutions, Optomec, Essential Dynamics, Aaroflex, Asiga, and EnvisionTEC), I find that only two systems, from Stratasys (former Objet products) and Z Corporation/3D Systems, may be able to meet the guiding principles and produce the best quality decoration printing (see Appendix E: Overview of additive manufacturing printers). Unfortunately, there is no system in the market that can work with the three different materials, print in different colors, and provide the required building area of at least 595 mm x 118 mm x 87 mm (X,Y,Z dimensions).

The technologies of Z Corporation/3D Systems and Stratasys differ significantly. Figure 42 provides a sketch of Z Corporation/3D Systems' technology. The technology uses an analogue SLS technology but does not heat-treat the material using a laser. Instead, it uses a binder material that is printed through the inkjet printer heads. The binding material is colored, which allows the printing of 390,000 different colors (e.g., the ZPrinter 850 system has five printer heads).

After printing the last layer, the part needs to dry before it could be removed. The part also requires de-powdering to remove excess powder. There are several finishing options for improving surface finish and strength using infiltrates like wax, cyanoacrylate, and epoxy. Because the process is similar to the basics of SLS, there is no support material required (Z Corporation, 2012; XPress3D, 2011).

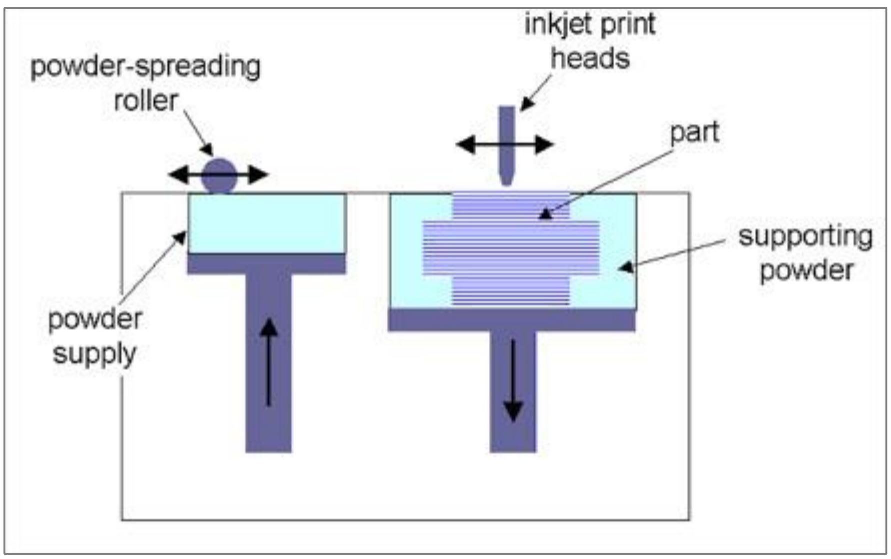


Figure 42: Z Corporation printing technology (XPress3D, 2011)

On the other hand, the Stratasys/Objet printer is based on a photopolymerization technology. As shown in Figure 43, it pushes photopolymer materials through inkjet printer-type printer heads on a building tray and then treats the materials with UV light layer by layer.

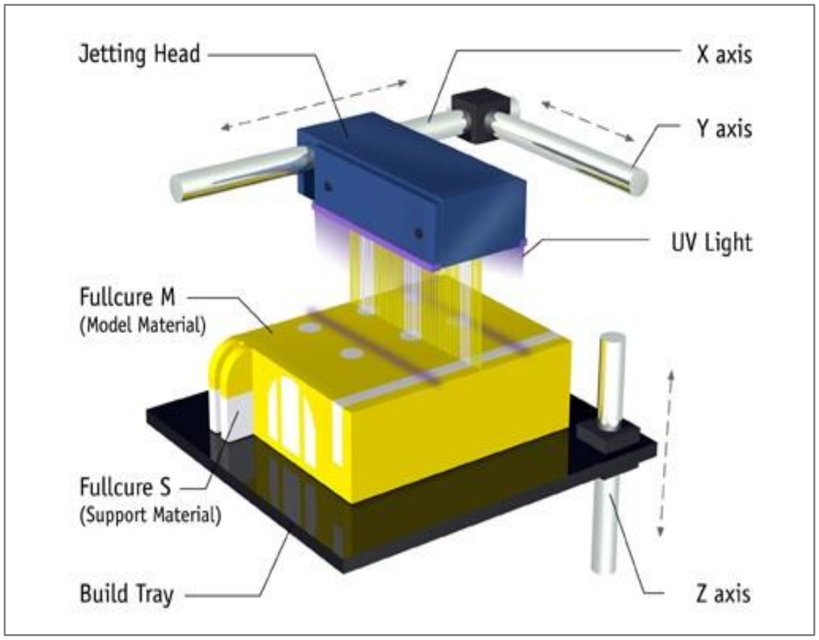


Figure 43: Objet patented printing technology (EngATech, 2012)

The Stratasys/Objet printer model Connex500 has eight printer heads, which allow the use of two different materials during one print job. The printer heads could be filled with a variety of support material, building material, and building material color. Because it is free from the building approach, it requires support material. The materials are cured directly and thus do not need any further drying; however, post-processing is required to remove the support material (Objet, 2012).

For the supply chain remodeling, the Z Corporation/3D Systems system is chosen as the basis for the calculations in the first analysis. The major reasons for choosing the Z Corporation/3D Systems system are its flexibility in printing options and ability to build materials without support materials, which reduces the materials and processing required. A major disadvantage of the system is that it can only use one material; using this technology yields major differences, as the current product is made out of several materials as previously described (e.g., ABS, PC, PMMA).

I do not review the characteristics of the material used in this section. To simplify the remodeling, I assume that the raw material used meets the strength, heat resistance, and other requirements. If only a blank control panel needs to be produced, that is, without any printing, a different technology like selective laser sintering might have been selected. However, because the complexity is driven mainly by decoration printing, a sub-optimal technology has been chosen.

In summary, in the first analysis, the remodeling is based on printing the control panels using the ZPrinter 850. Although this printer's building area is not sufficient for a control panel, I assume in my simulation of the control panel production that the building area can be extended. I make this assumption because the home appliance manufacturer knows that a tailored solution is required afterward for a series production.

6.5.6. Step 4, Part 2: Supply chain remodeling and physical material flow

As described in section 6.4.3, the major driver of supply chain complexity is the fact that the creation of variants takes place at a fairly early stage in the production process. Additionally, from the review of the supply chain performance indicators (see section 2.4.2), the two supply chain objectives are to reduce inventory and total supply chain costs.

Additive manufacturing technology allows avoiding assembly efforts by printing the material only as one piece with some predetermined breaking points, for example, for the buttons or the rotary switch, to allow full functionality. For the supply chain remodeling, I have chosen the following guiding principles:

- Create variants late in the process mainly by moving the printing processes (decoration and language printing) to a late stage of the production. This is based on Ishii and Martin's (1997) suggestion to differentiate at the latest possible stage.
- Reduce overall stock levels (specifically the stock of work-in-progress and finished goods) to reduce costs and to utilize the additive manufacturing advantage of producing theoretically a lot size of one.
- Reduce assembly efforts to reduce labor costs. This is one of the major advantages of additive manufacturing over traditional production methods in manufacturing complex structures with one production run.

This model (Figure 44) aims to move the control panel production (injection molding, printing and assembly of control panel body, electronic housing, buttons and rotary switch) from the supplier directly to the home appliance manufacturer. Consequently, suppliers will provide only the wire harness and electronics, which will be assembled after the control panel body including the electronic housing, buttons, and rotary switch is printed through an additive manufacturing process.

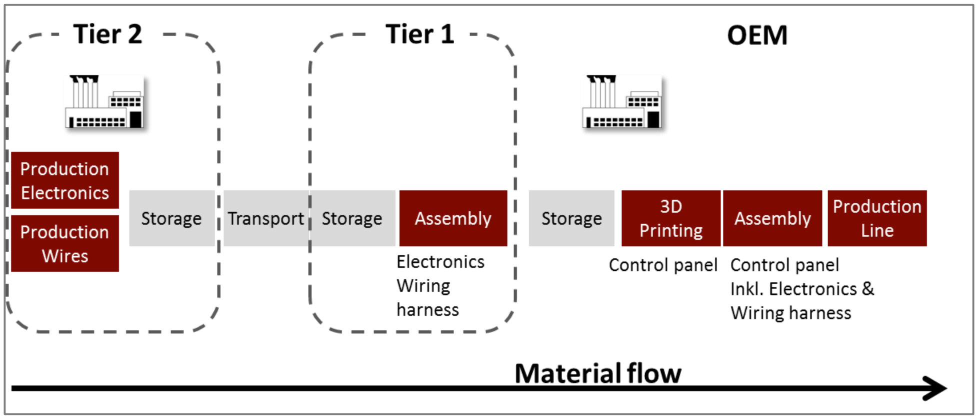


Figure 44: Remodeled supply chain

There are several other options for remodeling the supply chain that may be the optimum solution; however, the remodeled chain I have developed meets the requirements of the guiding principles and reduces the assembly efforts by enabling the printing of all printable elements at once and by moving printing (language and decoration printing) to the end of the process, which achieves full variance and reduces stock levels.

6.5.7. Step 5: Performance comparison of the two models

6.5.7.1. Overview

In this section, I compare the performance of the original and remodeled supply chain models in terms of complexity, costs, quality, service, and lead time, by using the measures identified in section 2.4.4.

6.5.7.2. Complexity measures

In steps 2 and 3, the complexity measures NM, VM, NM_{PT}, and VM_{PT} were calculated to measure the level of complexity. The basic hypothesis is that through remodeling, complexity will be reduced and the metrics will change. Thus, I will calculate the complexity measures. Table 24 provides an overview of the different complexity metrics.

Table 24: Complexity measure comparison – Before and after remodeling

Metrics	Before Remodeling	After Remodeling	Δ (absolute/relative)
NM	424	353	71 (17%)
NM_{PT}	96.2	97.2	1 (1%)
VM_j	91.5	92.9	1.4 (2%)
VM_{PT}	80.7	61.5	19.2 (23%)
VMR_{PT}	0.88	0.69	0.19 (22%)

The detailed calculations are in Appendix G: Complexity measures.

The table shows that the complexity itself decreased as the numerous metric (NM) decreased by approximately 17%. Relatively, the system maintains a high level of complexity as the variety metric increases. This is driven mainly by the number of product variances, which have not changed. The level of complexity caused by production significantly decreased as the variety metric caused by production (VM_{PT}) significantly decreased by over 23%.

The performance evaluation of complexity only helps compare the different states of a system and shows the development but does not indicate whether the achieved state or the development is beneficial. The variety metric is an example of this; however, note that the system reduced complexity significantly even when the variety metric (VM) increased, which shows that even when the complexity of the system itself increased, the overall complexity level decreased. Thus, it is important to compare the supply chain performance metrics. If the performance did not improve and if there seems to be no strategic reason behind this outcome, there is no need for remodeling, as it is not an end in itself.

6.5.7.3. Costs

I now compare the cost performance of the two models in terms of total supply chain cost (SCC) as described in section 2.4.2 as follows:

$$SCC = \sum_{i} (Logistics\ cost + Production\ cost + Coordination\ Cost)$$

The logistics cost includes all costs for storage, inventory, and transportation. The production cost includes costs of the elements described in section 2.1.5.1. I assume that in general, this cost model applies to additive manufacturing as well as to injection molding. Any cost differences for certain elements are stated explicitly. For simplicity, I assume that the coordination costs of the two models are the same because there is no reliable method for estimating the differences.

Logistics cost

Because the panel production will be moved from the supplier to the home appliance manufacturer's own production line, the logistics cost will be completely avoided when additive manufacturing is applied. This is because storage for finished goods will not be required if production is just-in-sequence, scheduled according to the washing machine production. Moreover, additional transportation from the supplier to the manufacturer will be eliminated.

Production cost

Although the variance of the products is fairly high and traditional production methods require manual labor for additional assembly, total production cost is very high for additive manufacturing compared to traditional production methods. The total production cost for a control panel manufactured using additive manufacturing is €120.92 versus €17.45 on average. The details of the calculation are provided in Table 37 of Appendix F: Cost Model Details.

As shown in Figure 45, the major cost drivers are material and machine costs. The major source of machine cost is the large number of machines. To produce one control panel by additive manufacturing, 1.7 hours are required on average, which means that 109 printers will need to be installed to produce 520,000 panels annually (assuming a 365 day-/24 hour-production and 95% availability).

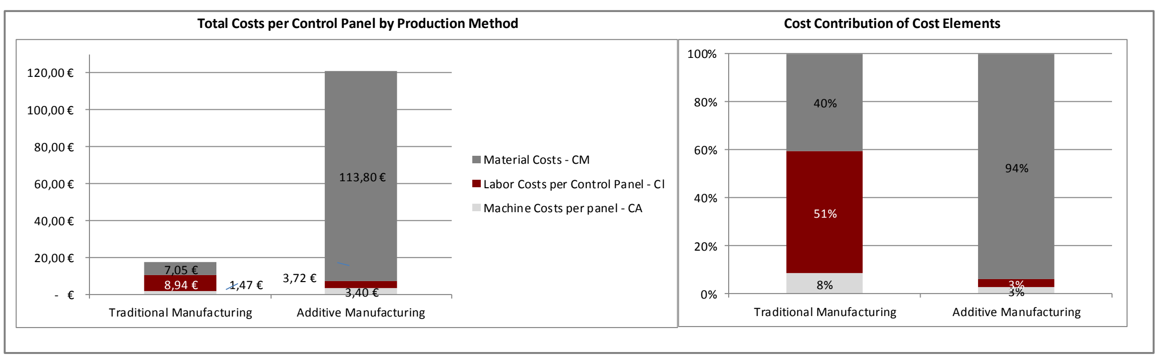


Figure 45: Production cost comparison for traditional and additive manufacturing production methods, by cost driver

By using traditional production methods, producing the control panels will require a significant amount of assembly efforts. In contrast, by using additive manufacturing technology, the manufacturer can produce all parts at once without any assembly. Consequently, the overall production costs will decrease from €8.94 to €3.72. The overall labor costs also include setup costs for the machines, which is a significant cost driver for the traditional manufacturing method. In the original supply chain, setup is required for the injection molding (tool installation) and for the printing (cliché). The overall setup costs are approximately €613 per product model or €0.41 per control panel (see Table 38: Setup costs calculation in Appendix F: Cost Model Details).

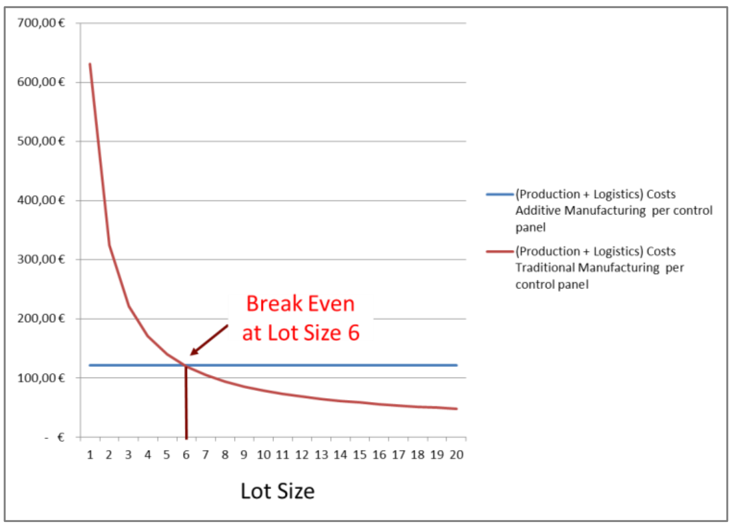


Figure 46: Comparison of breakeven points for traditional and additive manufacturing production methods (Author's calculation using data obtained from the home appliance manufacturer, 2006)

The costs for tooling and cliché do not include the costs of the tool and the clichés itself, which need to be incorporated. However, no exact figures are available for the costs of these pieces of hardware. Based on the calculations so far, additive manufacturing appears to be cost competitive for lot sizes smaller than six. However, it is still disputable if a washing machine with a control panel that costs approximately €121 can be sold.

Overall, the material costs for plastic powder, color binder material, and potential infiltration material are very high. One kg of zp150 powder is approximately €69, and a liter of the binder is approximately €448.50. Thus, the cost for the material mix for a control panel is approximately €11.24.

The case study's calculated production cost of €0.24 per ccm corresponds with those of the 3D Systems/Z Corporation (€0.15–0.35 per ccm; Z Corporation, 2012b).

The right panel in Figure 45 shows that the cost shifts significantly from labor to materials when additive manufacturing is applied. Thus, it is important to assess how material prices will change in the future. Today, the technology for traditional manufacturing methods has not yet achieved scale effects. Assuming that an increased demand would also lead to a significant reduction in material and machining costs, as already seen in other industries, additive manufacturing may be used effectively for high-scale productions. Because additive manufacturing is still a new technology, relevant material costs are significantly higher than comparable plastic material costs; however, there is no reason that material costs for additive manufacturing should be significantly higher if they are produced in a comparable scale as plastic materials are. Thus, assuming similar material costs, the overall costs for a control panel would be €14.17 by using additive manufacturing and €17.56 by using traditional production (basis: lot size of 1,483). In short, additive manufacturing costs would be approximately 19% lower than traditional production costs when similar material costs are assumed.

Additionally, new breakthrough technologies may emerge in the future, delivering even more significant increases in production efficiency or decreases in machining costs.

Nevertheless, this scenario is hypothetical because technological developments in the market are still unknown. However, it is important to note that the AM production technology is fairly young and its full potential has not yet been clarified.

6.5.1.1.Quality

I compare the quality of the two models in terms of two aspects: *supply chain performance (on time delivery)* and *product performance*. However, I first determine if the performance of the products manufactured by using the two processes is comparable.

Supply chain performance

Only a theoretical evaluation of supply chain performance is possible. On time delivery appears to have improved with additive manufacturing, as the production time of the control panel is reduced to 1.7 hours compared to the four-day average lead time for the Turkish control panel supplier. However, this is not a like-for-like comparison because it is still possible to move the assembly of the control panel to an early stage in the traditional production process. Nevertheless, shipping the finished control panel to a distance of 45 km alone would take approximately 45 min. Although production and assembly are possible in less than an hour, all the required parts must already be produced. Even if only one part is missing, the average setup time will be 27.5 hours. Thus, if only one part is produced within this production run, the cost for that one part would be a minimum of €613.24 for the setup.

In summary, the injection molding technology can match additive manufacturing's on time delivery performance if the buffers of finished products are already available.

Further, additive manufacturing provides very high flexibility and agility in terms of reaction times to changes in demand, and thus, has a better OTD performance than injection molding does.

Product performance

Two important aspects of product performance are *strength* and *surface properties* such as *accuracy* and *roughness*. Due to the different production methodologies, there is a significant variance in surface roughness. With the injection molding technology, a roughness of 2–4 microinches can be achieved (Wikipedia, “Injection Molding,” 2012). With additive manufacturing, there are still limitations in terms of surface roughness. Due to additive manufacturing’s layer-by-layer production methodology of bonding of multiple cross section, there is always a so-called stair-stepping surface that is visible and tangible (Hague et al., 2003). Two strategies can be used for mitigating this issue: reducing the layer thickness and post-processing of the building model. However, both of these strategies, but especially the former, have the disadvantage of increasing building time and effort (Hague et al., 2003).Further, the post-processing option would require additional materials and time. For this strategy, the use of infiltrants is one option (Figure 47).

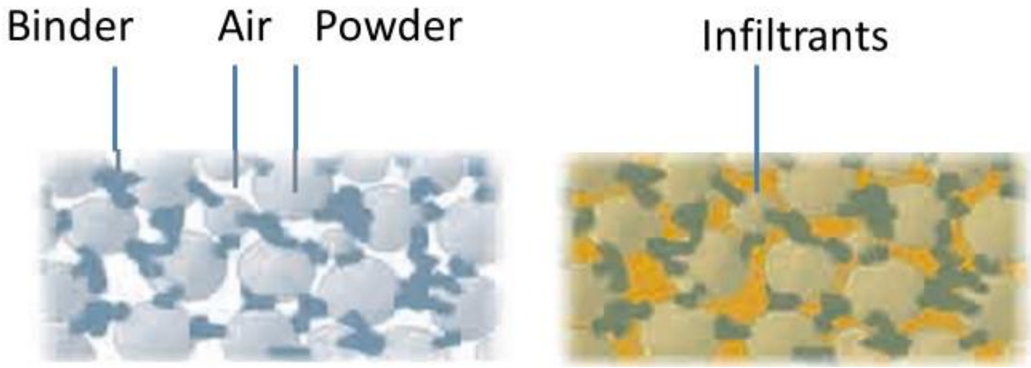


Figure 47: Application of infiltrants (adapted from Z Corporation, 2012b, pp. 10)

After the model is printed, an infiltration solution is sprayed or brushed on it. The solution removes the air and closes all micro holes in the model. This solution can simply be water- or salt-water-based, which can be a disadvantage because it does not significantly improve the strength of the model. To overcome this limitation, the manufacturer may use infiltrates based on epoxy resins (Z Corporation, 2012b).

Using additive manufacturing technology always involves a tradeoff because although it can improve surface roughness by reducing the amount of the powder used, doing so will require more layers and thus, reduce the printing speed. Using additive manufacturing technology in the traditional production method in this case study will have significant consequences. In the traditional production, a layer is approximately 0.1 mm high, which is nearly 1,000 times higher than the roughness accuracy of 4 microinches of additive manufacturing. Thus, attempting to overcome such a difference would result in a significant increase in production time.

There are also options available to improve product strength.

Table 25 provides a comparison of the strength characteristics of the zp150 powder used with Z-Max glue and a general purpose ABS. It is evident from the table that the two materials differ significantly in terms of tensile and flexural strength. The ABS used in the injection molding process is significantly stronger than the printed material.

Table 25: Comparison of strength for zp150 and ABS[1]

	ZP 150 with Z-Max	ABS General Purpose
Tensile Strength	26 MPa	60MPa
Tensile Elongation	0.2%	60%
Flexural Strength	44 MPa	75MPa
Flexural Modulus	10.680 MPa	2.5MPa

Source: Z Corporation, 2012 and MatWeb, 2012

[1] Acrylonitrile butadiene styrene

The above comparison is not a like-for-like one because the general purpose ABS has no extra enhancements like fiberglass to improve strength, while zp150 is already post-processed using epoxy glue (Z-Max). Several options are available for infiltrations; for example, the part can be infiltrated with cyanoacrylate or Z-Max epoxy, which makes the part stronger (Xpress3D, 2011).

Table 26: Material strength of zp150 with different post-processing options

	zp 150 Water Cure	zp 150 Z-Bond	zp 150 Z-Max
Tensile Strength		14 MPa	26 MPa
Tensile Elongation		0.2%	0.2%
Flexural Strength	13.1 MPa	31 MPa	44 MPa
Flexural Modulus	6,355 MPa	7,160 MPa	10,680 MPa

Source: Z Corporation, 2012

Table 26 provides examples of post-processing options and their implications on material strength. As can be seen from the tables, post-processing with Z-Bond, an infiltrant that works well as glue, or Z-Max, improves the strength of the material.

In summary, the traditional process of injection molding yields significantly different results from additive manufacturing. The performance of the part is not driven by the basic material used, but rather by the glue used during the printing and post-processing. In the future, material characteristics can potentially be improved by using different tools. For instance, in the future, gluing (during printing or post-processing) or thermal polymerization of the base material resin (e.g., through the baking process to further achieve thermal polymerization) may be used instead of chemical-driven polymerization. By using the current technology, it is difficult to provide similar product strength characteristics with additive manufacturing. However, it might be worthwhile to determine if traditionally produced parts are over-engineered and require high strength values (e.g., for a part like the control panel, which is not subject to high-strain conditions). In terms of on time delivery, I can only assume that the performance will be the same. The major cost drivers for quality are materials.

6.5.1.2. Lead time

I expect that the supply chain lead time will improve with additive manufacturing. The supplier has a one-week lead time from receiving the order to on-site delivery. The major cost driver of the lead time is optimizing the production schedule to reduce potential setups. There are two major reasons additive manufacturing may be better for lead time optimization. First, it requires less setup, so scheduling can be made ad hoc. Second, through additive manufacturing, production will be integrated on-site and physical road transportation will be eliminated, reducing lead time by 45–60 minutes. Therefore, theoretically, assuming that one panel requires approximately 3.5 hours to be printed and providing an allowance of 20% for safety, administration, or machine availability reasons, the lead time can be reduced from one week to 4.2 h.

6.5.1.3. Service

In terms of the service KPIs shown in Figure 21, especially “flexibility to meet customer demands” and “flexibility to meet market changes,” additive manufacturing has a significant advantage in that it can adapt to changes very quickly and at a lower cost compared to the traditional process of injection molding. Additive manufacturing does not require change in tooling; thus, it is more flexible. It can adapt to change faster and at a lower cost because it only needs to make a change in the computer-aided design (CAD) drawing. In contrast, the traditional process requires either a new tool or at least a tool adaptation for each change.

As mentioned at the beginning of this chapter, the home appliance manufacturer operates an international production network. Through additive manufacturing, the manufacturer will not require tools for production, will be able to optimize production capacity utilization, and will be able to adapt to local customer needs much faster. This is because additive manufacturing only requires an electronic transfer of data and does not need to physically transport materials around, which altogether saves time and money.

6.6. Case Study Conclusion

This case study provides an overview of how additive manufacturing can significantly affect complexity management in a mass production environment. The analyses show that applying this technology improves the supply chain's performance in terms of lead time, service, and quality. The case study shows that the technology can be a step change in complexity management. The technology can change the strategy from complexity avoidance to complexity control to address external complexity. The technology also helps reduce internal complexity significantly by combining several process steps, making the supply chain much more streamlined. However, additive manufacturing has two major disadvantages:

- Cost: The cost associated with the technology, especially material costs, is not competitive for this application. This may change in the future when additive manufacturing becomes more widely used.

  The same applies to machining costs. In the case study simulation, a large number of machines were required to produce the control panels, making the production time relatively long.

- Quality: The product quality in terms of strength and surface roughness is much better in injection molding than in additive manufacturing. However, the question of whether a high quality is really required remains unresolved.

From the results of my simulation, I find that an application of additive manufacturing in the mass production of washing machine control panels is not economically feasible, but it is possible to further simplify this technology and make it more adaptable to production.

7. CASE STUDY: APPLICATION POSSIBILITIES IN THE DENTAL INDUSTRY

7.1. Introduction and Approach

The home appliance case study in chapter 6 shows that challenges still exist in the application of additive manufacturing. In this chapter, I introduce a second case, which shows how additive manufacturing is applied. In this case study, I will analyze the consequences of additive manufacturing on the supply chain and its complexity.

This case study is based on Align Technology, a manufacturer of dental aligners. There are currently no attempts to change the supply chain in dental aligner manufacturing, and thus, I will compare two competing technologies also used by competitors of Align Technology. Additionally, this case study does not aim to determine the best technology available in the market, but rather assumes that the chosen additive manufacturing technology is the most appropriate. The case study will be based mainly on publicly available information and less action decision research based on the previous case study. Further this case study aims to demonstrate the application of the basic methodology discussed in chapter 4.

7.2. Current Supply Chain and Its Complexity

7.2.1. Company overview

According to Align Technology, Inc.'s (hereafter *Align Tech*) Securities and Exchange Commission (SEC) Form 10-K for 2012 (pp. 4), it "designs, manufactures and markets a system of clear aligner therapy, intra-oral scanners and CAD/CAM (computer-aided design and computer-aided manufacturing) digital services used in dentistry, orthodontics, and dental records storage. Align Technology was founded in March 1997 and incorporated in Delaware in April 1997." It sells a vast majority of its products directly to orthodontists and dentists and offers its services across the globe directly and in some non-strategic countries via distributors.

The firm has two operating segments, the clear aligner segment, which markets the Invisalign systems, and the scanner and CAD/CAM service segment, which markets the iTero, iOC, and OrthoCAD systems. In 2011, the former segment accounted for 94 percent of the revenue, while the latter segment accounted for the remaining 6 percent. According to the 2012 Form 10-K (p. 4), the "Invisalign system is a proprietary method for treating malocclusion based on a series of doctor-prescribed, custom manufactured, clear plastic removable orthodontic aligners. The Invisalign system offers a range of treatment options, specialized services, and proprietary software for treatment visualization." Meanwhile, the scanner and CAD/CAM service segment provides intra-oral handheld scanning technology that creates 3D images of patients' teeth. The technology is based on a laser and optical scanning process called parallel confocal imaging, which captures the contours of the "dentition, gingival structures and the bite

[…] capturing 100,000 points of laser light" (ibit, p.5). The systems consist of a "mobile computer unit, display screen, a control foot pedal and scanning wand to scan and capture a patient's dentition (full or partial dental arch). System software features include occlusal map, eraser tool, edge trim tool, real-time modeling and an option to submit scans for Invisalign treatment," (ibit, p.5) as well as generating digital export files. This case study will focus on the clear aligner segment and its technology utilizing stereolithography technology for aligner mold production.

7.2.1.1. Value Chains Overview

There are two different basic methods for treating misaligned teeth: serial aligner technology and step-wise gradual fabrication (Madaan and Khatri, 2012). The serial aligner technology changes the teeth model and produces aligners from produced molds, while in step-wise gradual fabrication one mold will be manufactured, an aligner will be produced and then the aligner itself will be manipulated to achieve the desired treatment. I describe both value chains in the following sections. Align Tech's technology is characterized as serial aligner manufacturing. I will also introduce a competing method, the clear aligner methodology (by the Clear Aligner company), which also utilizes step-wise gradual fabrication. While Align Tech manufactures a new mold for each step, Clear Aligner manipulates the mold into a setup model to build different aligners.

I will introduce the step-wise gradual fabrication process to give an overview of how aligners were used prior to the market entry of Align Tech. Align Tech's and Clear Aligner's approaches differ significantly, as Align Tech produces molds for the different stages the teeth undergo during treatment, while the Essix technology makes adjustments to the aligner itself to get the desired teeth alignment. I will not compare the two different treatment methodologies. Rather, I will briefly describe how to build molds without having the full image of the future state of dentition for which a mainly manual process is required to build setup models out of plasters. This method could be seen as an alternative mold production technology to SLA technology.

7.2.1.2.Serial aligner manufacturing

7.2.1.3. Align Tech value chain

A dental professional sends all relevant patient treatment data to Align Tech, including the prescription form, a polyvinyl siloxane (PVS) impression, and photographs and x-rays or intra-oral scans of the patient's teeth. The PVS impression, photographs, and x-rays could also be substituted by a 3D intra-oral scan, which helps reduce physical shipping. If no 3D intra-oral scan is available, Align Tech uses the provided data to prepare and construct a 3D computer model of the original dentition using a CT scan of the PVS impression. For information purposes only, in 2011, there were 2,100 users of Align Tech's scanning solution (SEC, 2012).

The company prepares the patient data in its data processing branch in San Jose, Costa Rica (SEC, 2012). Based on the patient's current malocclusion, a treatment plan will be developed, which consists of a simulation of tooth movements in a series of two-week sequences using the aligner (using software called ClinCheck). The treatment plan comprises detailed timing and placement attachments that are used to increase the force on each specific tooth to foster the desired movements. Usually, the treatment plan consists of 24 steps, providing the patient with a total of 48 aligners (24 each for the upper and lower arch) (Coyne, 2012). This treatment plan will be made available to the dental professional via an internet portal. The dental professional has the ability to project and amend tooth movements, and thus, has control of the patient's treatment. Invisalign treatments are done across the globe. In 2012, Align Tech had 31,300 selling points/distributors (SEC, 2012) and sold 365,500 cases, each of which consists of 48 aligners (SEC, 2013a).

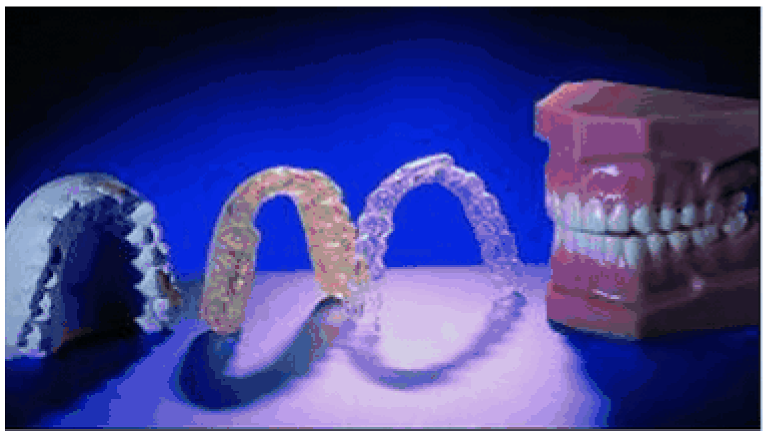


Figure 48: Tooth SLA Model, Aligner pattern, Study model from Align Tech (Source: 3D Systems, 2008, pp. 25)

After the dental professional approves the molds for each step of the treatment, they will be produced via the additive manufacturing technology stereolithography (SLA). Align Tech uses the SLA 7000 and the iPro 8000 systems from 3D Systems (Coyne, 2012). It also purchases resins from 3D Systems exclusively (SEC, 2008; 3D Systems, 2002). The resins for the dental models are assumed to be purchased from Rock Hill 3D Systems facility in South Carolina, USA, where 3D Systems headquarters is located (SEC, 2013b). Align Tech also operates a manufacturing facility in Juarez, Mexico (SEC, 2012, pp. 8), which uses the rapid tooling process briefly described in section 4.5.2. This facility produces the aligners from these molds using a Biostar pressure molding machine, and then ships the aligners via UPS air freight to the dental professional customers (SEC, 2012). The polymer for the production of the aligners is purchased from a sole supplier (SEC, 2008).

During productions, the aligners are trimmed automatically by a five-axis milling machine and marked with the patient initials, case and aligner number, and arch type by laser. Afterward, they are disinfected, packaged, and shipped to the dental professional via parcel service UPS (Madaan and Khatri, 2012; SEC, 2012). The aligner is made of EX30 and EX40 polyurethane material with the following characteristics (Madaan and Khatri, 2012):

Specific gravity:	1.215
Mold shrinkage:	0.005 in/i8n
Tensile strength at yield:	9,140 psi
Tensile strength at break:	9,150 psi
Tensile modulus:	309,000 psi
Flexural modulus:	286,000 psi

The thickness of an aligner is approximately 0.75 mm (Engeln, 2010).

According to McNamara and Brudon (2001), aligners are made from a thin proprietary plastic material comparable to polycarbonate, which in turn is comparable to the 1 mm-thick biocryl plastics used for other aligner technologies.

Clear Aligner technology

The Clear Aligner technology was originally developed by Dr. Tae Weon Kim in 1998. The treatment is described as follows (Kim and Stückrad, 2010). The treatment has several steps. In the first step, an impression is taken from the patient out of which a model will be built. The model will be made of plaster, as it will be described in section 7.2.1.4. As the model is just a projection of the current dentition, it needs to be modified to achieve the appropriate pressure for the teeth to adjust. To simulate the desired outcome of a dental treatment, the so called setup model will be used (Haidan, 2002). The setup model will be manually manufactured based on the original cast model. The required movements will be modeled by sawing parts out of the model and positioning the teeth in the correct location. The model will be fixed with a special type of wax, as shown in Figure 49. Additionally areas could be blocked out by a special photo-polymeric material called Blue Blokker.

With a Biostar vacuum molding system, the setup model will be used to produce three types of aligners: soft with a .5 mm thickness, medium with a .62 mm thickness, and hard with a .75mm thickness. To this end, a special foil (foils from brand names ISOFOLAN or Clear Aligner) will also be used to produce Essix or other aligners. In the Clear Aligner methodology, the aligners are produced not in specialist laboratories but in the local dental practice itself. The produced aligners will be sequentially worn by the patient: in the first week, the patient wears the soft aligner; in the second week, the medium aligner; and in third week, the hard aligner. Figure 50 shows the three different aligners produced from a setup model. After the first three weeks, a new image will be taken and three new aligners will be produced based on a new setup model. The steps will be repeated until the desired correction is achieved. The models will be manufactured either by the dental professional or by a local dental laboratory.

Figure 49: Fixing of a setup model with wax for Clear Aligners (Source: Kim and Stückrad (2010), Figure 3)

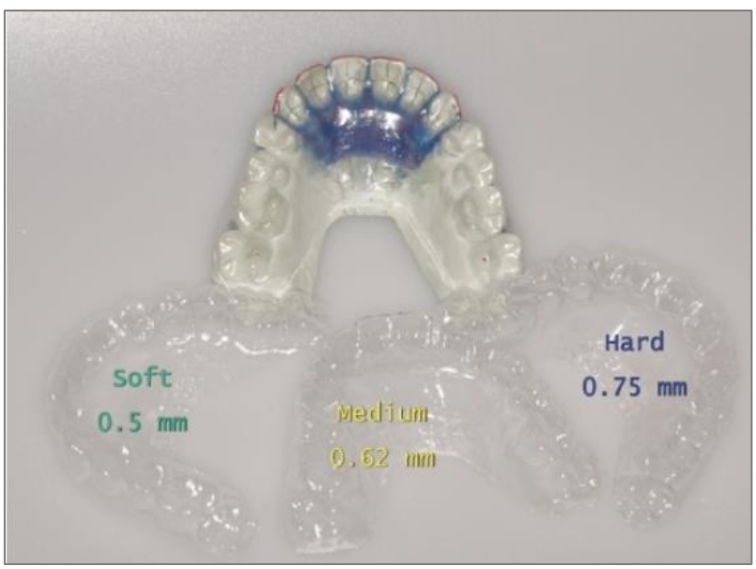


Figure 50: Clear Aligners (Source: Kim and Stückrad (2010), Figure 1)

7.2.1.4.Step-wise gradual fabrication

I will describe the Essix methodology, which was developed by Dr. John J. Sheridan in 1993 (Madsen, n.d.), as a step-wise gradual fabrication method for an alternative, established value chain.

In contrast to Align Tech's methodology, the Essix methodology is a more localized, decentralized approach of producing aligners. Madaan and Khatri (2012) describe the process as follows. In the first step, the dental professional will make an impression of the patient's teeth (e.g., using PVS). This impression is a negative of the teeth. In the second step, the dental professional will either prepare the cast mold in an internal laboratory or send the impression to an orthodontic laboratory where a cast mold will be prepared. The cast will have an approximately 2 cm-high base. The casting is critical, as this process is substituted by stereolithography in Align Tech's methodology. There are several options for building a 3D model of a denture. A very common approach is to build a cast model. For malocclusion treatment, there are two types of cast materials used: improved dental stone and SuperStone. The casting itself will be conducted on a vibrating table where the plaster will be filled into the negative impression. Finally, supported by a special forming tool, the base will be formed. After curing the negative impression, the form will be immediately separated (Heraeus, 2008).

After the cast is ready, the aligner will be produced via plastic thermoforming machines that either work with pressure or with vacuum. The pressure thermoforming machine, which is also used to create Align Tech's aligners, presses the heated plastic over a cast with positive pressure within a heat chamber. On the other hand, the vacuum thermoforming machine uses negative pressure. According to Madaan and Khatri (2012, pp. 59), “The vacuum machine adapts softened plastic to the cast by negative pressure, concentrating the vacuum by reducing the surface area to which it is applied, which amplifies the force and improves the adaptation of the plastic to the cast.” The material used for aligners are typically poly-methyl-methacrylate (PMMA), poly-vinyl-chloride (PVC), polysulfone (PS), or polyethylene (PE). The various Essix materials are called Essix C+, Essix A+, Essix Embrace, and Essix U-C-ME. The Essix C+ typically uses a layer thickness of 1 mm, the Essix A+ 0.5–3.0 mm, the Essix Embrace 0.75–1.0 mm, and the Essix U-C-ME 1 mm (Madaan and Khatri, 2012). Any excess plastic will be removed using Mayo scissors and bladed instruments.

As the aligner currently only represents a model of the status quo, it needs to be treated in order to be able to move the teeth to the desired position. To this end, space and force are required. Figure 51 gives an overview of the major steps in Essix retainer preparation. There are three different methodologies for creating space within the aligner. One method is to use thermoplastic pliers to put pressure on the targeted tooth. A second methodology is to block out the areas on the cast with acrylic, stone, or light-cured composite prior to thermal casting, which creates a bubble in the thermoformed aligner (Figure 51, panels 7–9). The third alternative is to cut a window for the targeted tooth to move into with a trimming bur and scalpel or knife (Figure 51, panels 2–5). Meanwhile, there are two methods for creating the appropriate force in Essix aligners: Hilliard thermoforming pliers and mounding. The former alters the structure of the aligner, similar to the space-creating methodology, while the latter uses composite on the tooth surface.

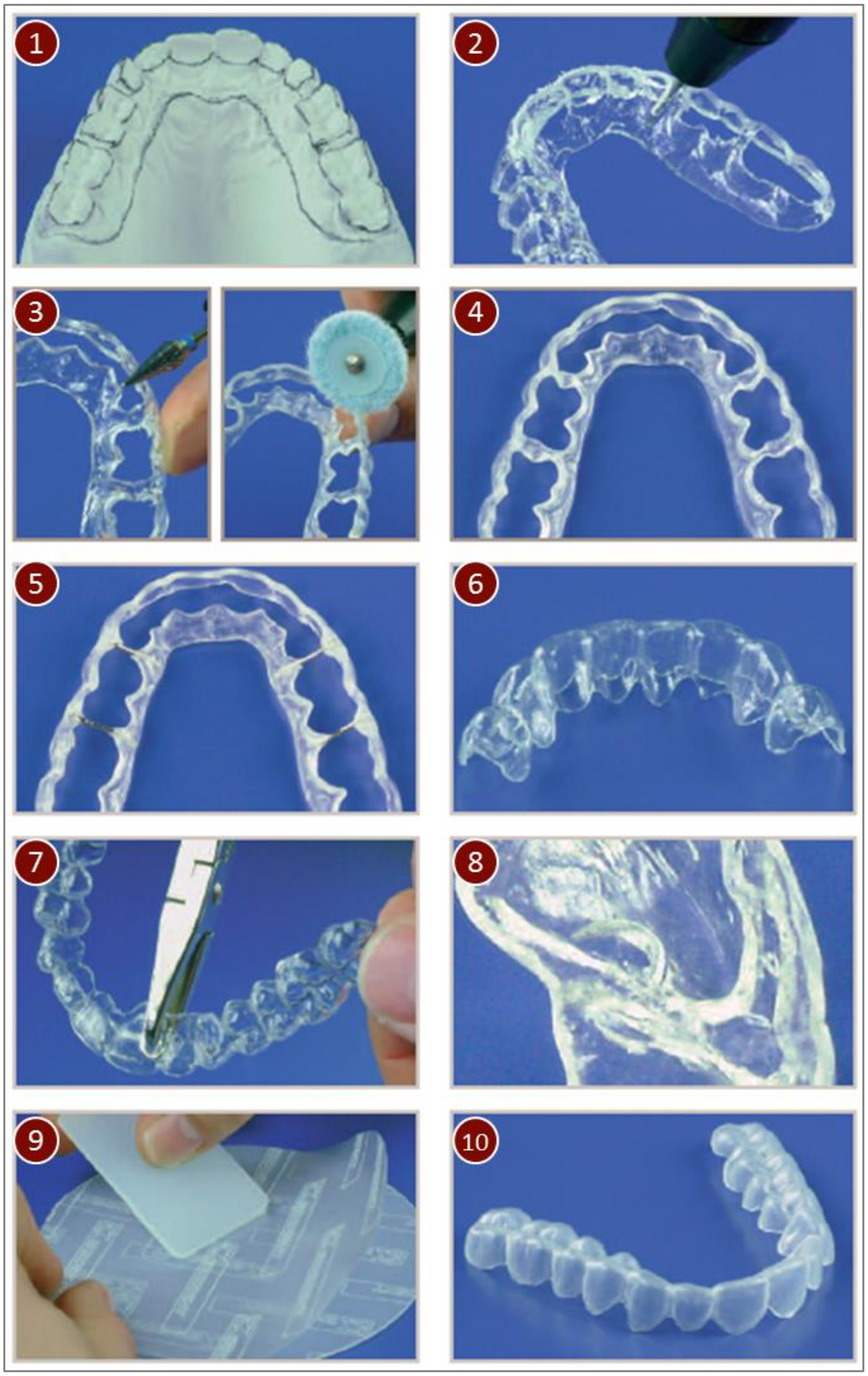


Figure 51: Essix Retainer Preparation (Source: Erkodent, (2013))

The chosen force-creating method will be iterated until the desired tooth position is achieved and will always involve manual rework. The Essix aligner could be worn for up to 6 months (Essix A+), over 16 months (Essix Embrace), and 2 years (Essix C+ and U-C-ME) (Madaan and Khatri, 2012).

7.3. Remodeling Aligners Supply Chain

7.3.1. Introduction

In the following sections, I will evaluate and remodel the aligner supply chain complexity. Using the evaluation approach described in chapter 4 and desk research, I will remodel the supply chain and evaluate how the supply chain complexity evolved by using additive manufacturing. Instead of substituting a traditional manufacturing technology with an additive manufacturing one, I will substitute stereolithography-based production with the traditional production methodology described in section 7.2.1.4. However, this comparison is somewhat artificial, as Align Tech has completely changed the method of treating patients by making it more economical through using additive manufacturing technology. Thus, it is arguable if anybody would have built up a centralized production of aligners in the same manner but utilizing a traditional production method.

In the following sections, I discuss the five steps of the evaluation approach.

7.3.2. Strategy review

In the strategy review, I will not perform a detailed analysis to derive a fact-based approach benefit curve as suggested by Rathnow (see section 4.2), as a full customization of the product is required to ensure a successful medical treatment. Thus, the benefit curve will be like curve c as described in section 5.2 or shown in Figure 52.

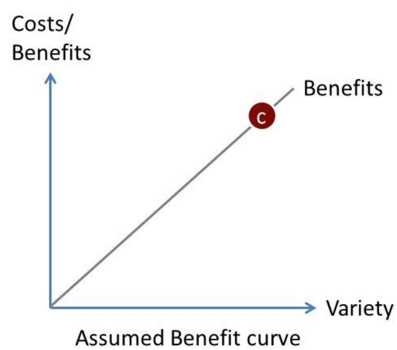


Figure 52: Assumed benefit curve for Align Tech's methodology

As the aligners are custom-made, a new variant is created for a new customer. Thus, variety is not created to increase customer benefit but to target new customers. Based on the lean manufacturing principles described in section 2.3.3.5, this follows a pull, not push, principle, that is, producing a new variant without a specific demand will not result in additional sales, as no customer would benefit from an aligner that does not fit.

7.3.3. Supply chain complexity evaluation

To calculate the level of supply chain complexity, I will discuss the supply chain described in section 7.2.1.2 further, and illustrate it as shown in Figure 53.

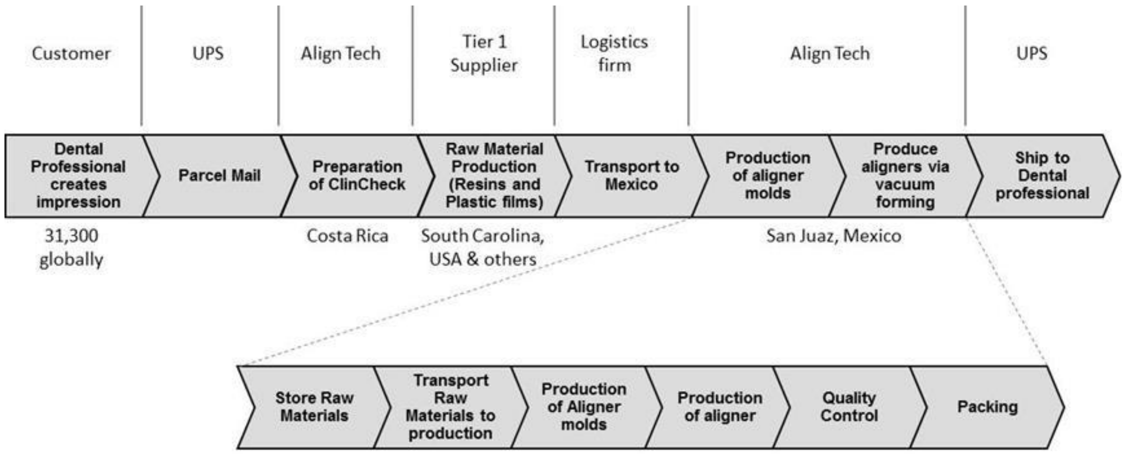


Figure 53: High-level value chain for Align Tech

I calculated the current supply chain and complexity **measures** as in Table 27.

Table 27: Numerousness metric for Align Tech

		Count	Comment
Companies	Number of customers	31,300[1]	Dental professionals around the world
	Aligner Tech	1	
	Transportation firm	1	UPS
	Suppliers	2	Simplified (Aligner foil/3D Systems)
	Production facilities	2	San Jose, Costa Rica/San Juarez, Mexico
Interacting persons	Number of employees	3,176[2]	
Inter-company business processes	Number of main processes	12	cp. Figure 53
Offered products	Total number of products	11,280,000	235,000[3] cases with, on average, 48 different aligners (24 sets each for upper and lower jaws); each aligner is worn for two weeks
Employed systems	Systems	1	ClinCheck (simplified)
		11,314,495	

[1] SEC (2012), pp. 9, [2] SEC (2013), pp. 12, [3] SEC (2013), Excel Table 31

From Table 27, we see that the major driver of complexity is the number of aligners produced and the number of customers. I calculated the variety metrics as in Table 28.

Table 28: Variety metric for Align Tech

		Similar	Total	Comment
Companies	Number of customers	1	31,300 [1]	Dental professionals
	Aligner Tech	1	1	
	Transportation firm	1	1	UPS
	Suppliers	2	2	Simplified (Aligner foil/3D Systems)
	Production facilities	2	2	San Jose, Costa Rica / San Juarez, Mexico
Interacting persons	Number of employees	4	3,176 [2]	High level[2]: - Manufacturing and operations - Marketing and sales - R&D - General and administrative functions
Inter-company	Number of main processes	11	12	Consolidation of parcel/ship to dental professional
Offered products	Total number of products	1	11,280,000	Only aligners as a product
Employed systems	Systems	1	1	ClinCheck (simplified)
	Total	**24**	**11,314,495**	
$Variety\ Metric: VM_j(\%)$		99.999787		$\left(1-\frac{Number\ of\ similar\ types_j}{Total\ number\ of\ types_j}\right)*100$

[1] SEC (2012), pp. 9, [2] SEC (2013), pp. 12, [3] SEC (2013), Excel Table 31

The CM cannot be calculated accurately in this context, as complete details are currently available only for the supply chain and only limited information is available for the overall company processes. Thus, I assume the CM will always be 100% because I do not incorporate the entire production network and company processes. When I reduce the supply chain complexity, both the CM's numerator and denominator will decrease.

Meanwhile, I also assume the known process matrix as 100%, which indicates that all processes relevant for the production are taught to the employees, documented, and known.

7.3.4. Production technology-driven complexity evaluation

Table 29: Production technology-driven supply chain elements

Supply Chain Element		Count	Comment
Companies	Number of customers	0	Not production technology-driven
	Aligner Tech	0	
	Transportation firm	0	Not production technology-driven
	Suppliers	2	Production technology-driven
	Production facilities	2	San Jose, Costa Rica/San Juarez, Mexico
Interacting persons	Number of employees	2,086[1]	Manufacturing and operations employees
Inter-company business processes	Number of main processes	6	cp. Figure 53
Offered products	Total number of products	11,280,000	235,000[3] cases with, on average, 48 different aligners (24 sets each for upper and lower jaws); each aligner is worn for two weeks
Employed systems	Systems	1	ClinCheck (simplified)
NM_{PTj}		**11,282,096**	

[1] SEC (2013), pp. 12, [2] SEC (2013), Excel Table 31

To determine the level at which production technology affects the supply chain complexity, I calculate NM_{PT}, VM_{PT}, and KPM_{PT} as in section 7.3.3.

The NM_{PT} is calculated by identifying the total number of supply chain elements as shown in Table 29.

Thus, NM_{PT} is calculated as follows:

$$NM_{PT}(\%) = \left(1 - \frac{\mathbf{11,282,096}}{\mathbf{11,314,495}}\right) x\ 100 = 0.28$$

The NM_{PT} is fairly low, which indicates that most of the complexity in this context is driven by the production technology. However, the number of products also has a significant influence, and thus, it may also be production technology driven. What this indicates for Essix aligner production (cp. section 7.2.1.4) and traditional retainer production is that if it is very complex to produce the high number of setup models, alternative treatments are applied.

The variety metric caused by production technology is calculated as follows using VM_{PT} and VMR_{PT}:

$$VM_{PT} = \left[1 - \left(\frac{Number\ of\ similiar\ types_{PTj}}{Total\ number\ of\ types_{PTj}}\right)\right] x\ 100 = \left[1 - \left(\frac{14}{\mathbf{11,282,096}}\right)\right] x\ 100$$

$$VM_{PT} = 99.999875$$

where the number of similar types is defined as in Table 30.

Table 30: Similar types – PTj

Supply Chain Element		Number of Similar Types	Comment
Companies	Number of customers	0	Not production technology-driven
	Aligner Tech	0	
	Transportation firm	0	Not production technology-driven
	Suppliers	2	Production technology-driven
	Production facilities	2	San Jose, Costa Rica/San Juarez, Mexico
Interacting persons	Number of Employees	2	Simplified two types of workers: manufacturing and operations employees
Inter-company business processes	Number of main processes	6	cp. Figure 53
Offered products	Total number of products	1	One type of product (upper and lower aligners)
Employed systems	Systems	1	ClinCheck (simplified)
Total number of similar types		**14**	

Thus, VMR_{PT} is calculated as follows:

$$VMR_{PT} = \left(\frac{99.999875}{99.999787}\right) = 1.000001$$

VMR_{PT} indicates that the level of diversity affected by the production technology used with a value of approximately 1 is similar to the level of diversity for the overall supply chain. Thus, a change in the production technology might affect the overall complexity level of the supply chain. The diverse product base is a major source of complexity. On the other hand, VM_{PT} indicates that the overall diversity is fairly limited, so the system is not very complex.

As the KPM is 100, the KPM_{PT} must be 100 as well, as it is a subset of the overall processes.

Thus, the review of the complexity measures suggests not remodeling the supply chain, as the overall supply chain is not very complex and the production technology is not a significant driver of complexity, as the VM_{PT} indicates that the current setup matches the complexity level of the overall supply chain with the complexity level of the production technology-affected processes. However, I will proceed with the remodeling stage of this case study to demonstrate that the current set up is an optimized solution.

7.3.5. Supply chain remodeling

As I already mentioned, I will adopt an artificial remodeling approach to demonstrate how additive manufacturing evolved the dental health industry and how it affects the industry's complexity. As described in sections 7.2.1.2 and 7.2.1.4, there are two competing methodologies and correlated supply chains currently available: the Clear Aligner and the Essix approaches. However, I will examine the Clear Aligner approach because it allows a feasible comparison (i.e., a like-for-like comparison) of supply chains. This is because the Essix methodology focuses on manipulating the aligner itself, while the Clear Aligner approach works with molds to produce aligners.

The Clear Aligner value chain will look as described in section 7.2.1.2 and illustrated in Figure 54.

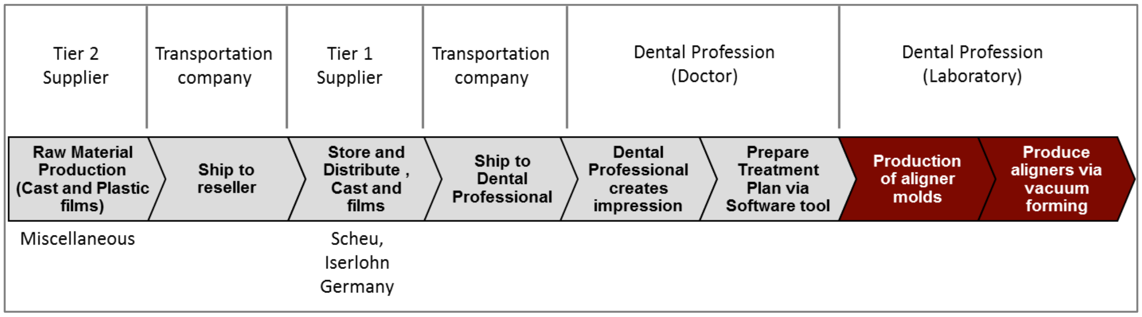


Figure 54: Supply chain of Clear Aligner production

The process outlined in Figure 54 needs to be repeated several times, as not all aligners will be produced in one production run. The production of aligner molds and of the aligners are highly manual processes, which will be further described below.

Figure 55 illustrates the different process steps in setup model (mold) production. (1A) A master model will be castand trimmed. (1B,C) With a special thermoforming film (e.g., 3 mm Bioplast), an imprint of the denture will be manufactured. (2A) Manually, the position of each tooth will be plotted on the model so that each tooth will be marked individually. (3B, C) Afterward, the model will be trimmed so that only the tooth ring is left. Then, with a saw, each tooth will be separated. To allow an exact positioning, the snags will be grounded and cut to create space for movement. (4A) The teeth will be positioned in the plastic imprint according to the treatment plan. (4B) The plastic imprint will then be filled with hot wax to fix the teeth position.

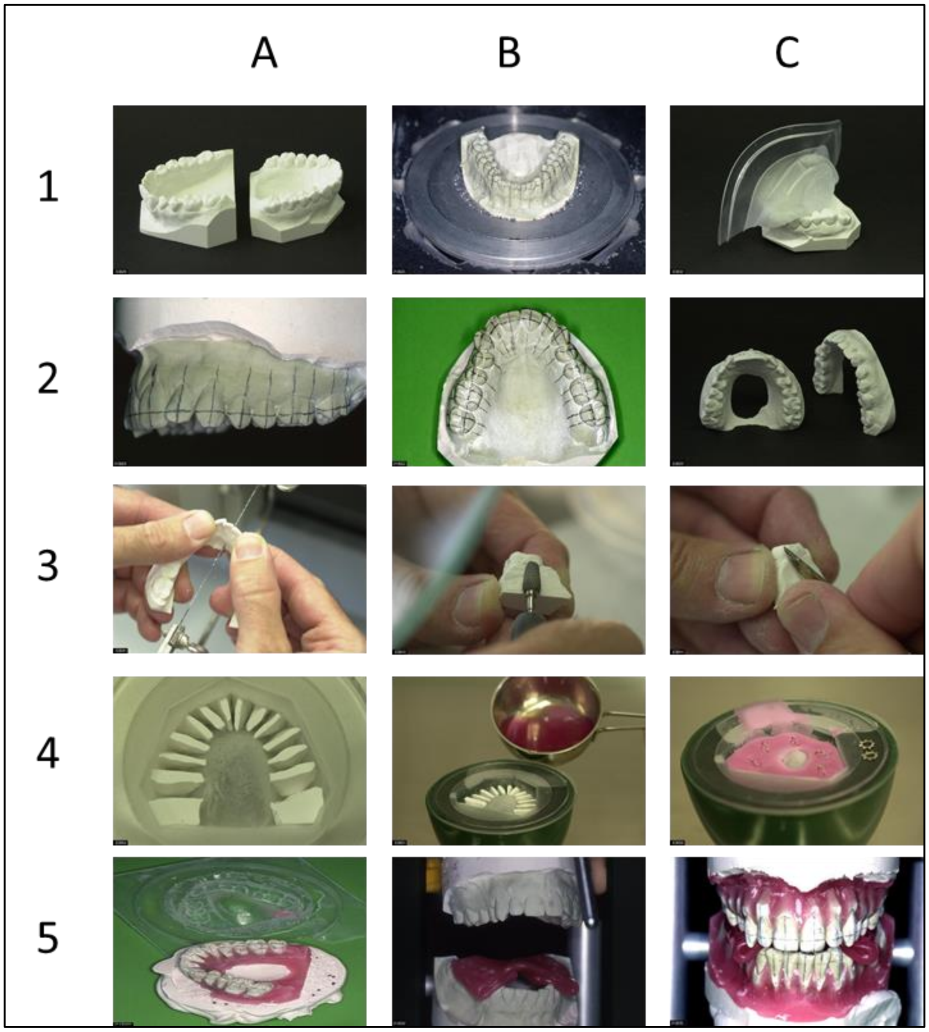


Figure 55: Setup model production (Mold production) (Author's Own creation, using images from Hertrich, (2012))

(4C) Prior to their complete cool down, the retentions will be positioned to help to fix the wax afterward onto a cast baseplate. (5A) After the retention cools down, the model will be fixed onto a baseplate, with the cast and the imprint foil removed. (5B, 5C) To check the positioning of the lower and upper jaws, the model will be positioned in an articulator.

In reviewing the remodeling approach as outlined in chapter 4.5, I find that the complexity is moved to a later stage in the process, that is, complexity occurs at the point of sale as after which the production takes place. The technology substituted is stereolithography by using handcraft work instead of producing the tool, so the remodeling addresses the tooling process mainly. Whether this remodeling is favorable will be discussed in the performance assessment section below.

7.3.6. Performance assessment

7.3.6.1.Overview

In the following, I will compare the performance between the original and the remodeled supply chains. The comparison will be based on specified assumptions and covers product performance, supply chain performance, and complexity level according to section 4.6.

7.3.6.2.Product performance

For this case study, there is no detailed information available on surface roughness and strength regarding the setup model preparation or the mold aligner production. However, because both Invisalign and Clear Aligner are established products with high accuracy necessary for a successful medical treatment, it could be assumed that both products have a comparable degree of surface finish. The requirements for product strength does not seem to be very high, as the molds (setup models) for the Clear Aligner methodology are used only three times (for producing three aligners with different thicknesses) and are made partially with wax, which is not a very strong material. It is assumed that the molds produced via SLA do have better strength characteristics; although their strength is not measured, they are only used once, and thus, strength is not very important. As the Clear Aligner production process is a highly manual process, the repeatability and the accuracy might be sources of flaws.

In looking at the final product (the aligner), both technologies deliver a product quality that meet the requirements of the medical treatment.

7.3.6.3.Supply chain performance

For measuring supply chain performance, the supply chain performance KPIs of quality, service, cost, and lead time as described in section 4.6 will be discussed and compared in detail in the following paragraphs.

Total supply chain costs

To evaluate cost performance, I will make some assumptions based on Align Tech's cost basis and the industry KPIs for dental laboratories in Germany. This approach might not be as accurate as I would like, but at the very least, it allows some evaluation. Due to the limited information available, I will not follow the cost model outlined in chapter 4.

To calculate the costs for Align Tech for comparison, the cost per case of US$304.26[1] is used. This does not include expenditures for research and development, marketing, sales, and administration. As a case consists of 48 aligners or 24 aligner sets (for the upper and lower jaws), the cost per aligner set is approximately US$12.68.

[1] Calculation based on cost of 110.6 million USD, which includes the salaries for employees involved in the production process, material cost, packaging and shipping costs, depreciation on capital equipment used in the production process, training costs, and stock-based compensation expense production costs (SEC, 2013, Excel Table 32), divided by the total number of cases sold in 2012 of 363,500 (SEC, 2013, Excel Table 30).

Calculating the costs for the Clear Aligner supply chain will be somewhat imprecise, as the value chain is completely decentralized. To collect the necessary cost information, I took the following approach. I take the compensation defined by German law for the setup model and define its real costs based on German industry benchmarks for dental laboratories. This cost comparison contains some inaccuracies, as it focuses on a German cost basis and is not specific to a comparable (like-for–like) supply chain. However, this calculation should be sufficient to derive to reliable conclusions here. Thus, I determine that the cost of an aligner set (for the upper and lower jaws) is approximately US$91. The details of this calculation are in Appendix H: Clear Aligner supply chain costs calculation.

Thus, SLA manufacturing delivers a benefit of approximately US$78 per aligner.

On time delivery

On time delivery could not be evaluated precisely, as there is no measured information available. However, as production and point of sale for the Align Tech supply chain are different and sometimes involve intercontinental transport, the likelihood of delays is higher than at the alternative supply chain, where the aligners are produced after the point of sale.

Customer requirements met

Whether *customer requirements are met* could also not be evaluated precisely, as there is no measured information available. However, a major advantage of the Clear Aligner methodology for dental professionals is that they have full control over the treatment, as the aligners are produced in a four-week interval, not produced upfront for a year as in the Align Tech methodology, so the dental professionals can adapt the treatment more easily (Gaugel and Gedigk, 2010). However, while this aspect makes the Clear Aligner supply chain more advantageous, the Clear Aligner production process is highly manual, and thus, has higher chances for flaws than additive manufacturing.

Weeks to change a product

Since in both supply chains, all products are individually customized, their performance levels should be equal. If corrections in the treatment plan are required, the Clear Aligner supply chain is advantageous, as it allows adaptation directly at the point of sale.

As I mentioned earlier, *on time delivery* could not be evaluated precisely, as there is no measured information available. However, as production and point of sale for the Align Tech supply chain is different and sometimes involves intercontinental transport, the likelihood of delays is higher than at the alternative supply chain, where the aligners are produced after the point of sale.

Number of inventory turns and inventory days on stock

For the finished products, performance level should be similar, as all aligners are built-to-order and shipped to the customer. Due to partially longer shipment times for the Align Tech value chain, the stock in transit might be higher. As Align Tech performs an annual production of the products, inventory levels at the customer are higher (only two weeks for Clear Aligner vs. six month for Invisalign on average). Further, as production is centralized, the overall inventory level for raw materials might be lower at Align Tech (Liberatore, 2007).

Order cycle time/Supply chain cycle time

The overall supply chain/order cycle time for Align Tech is estimated to be 17 days.[2] On the other hand, in the remodeled process, the aligners could be produced theoretically in one day. Thus, the remodeled process is more favorable.

Machining capacity utilization

The clear aligner technology is also more favorable in terms of machine capacity utilization, as it bundles all demands from across the world into one production facility, while the remodeled supply chain fulfills demand using cheap but specialized machines at the dental practice offices, and thus, does not likely have full utilization.

Overall supply chain performance evaluation

Table 31: Summary of overall supply chain performance evaluation

KPI	Align Tech	Remodeled supply chain
Total supply chain cost	US$12.68	US$91
On time delivery		Favorable
Weeks of product chance		Favorable
Customer requirements met	Partially favorable	
Order cycle time/Supply chain cycle time		Favorable
Number of inventory turns and inventory days on stock	Favorable	
Machining capacity utilization	Favorable	

[2] The cycle time consists of shipping the impression and parcel to Costa Rica (1 week), conducting the ClinCheck (2 days), producing the aligners (1 day), and shipping the aligners from Mexico to the dental professional (1 week).

Table 31 provides an overview of the supply chain performance assessment. At first, the overall KPIs seem to favor the remodeled supply chain. However, additive manufacturing is more favorable in terms of cost, so a qualitative minor performance of the molds produced with an additive manufacturing technology might be acceptable.

7.3.6.4. Supply chain complexity

In the following paragraphs, I will evaluate the complexity measures for the remodeled supply (i.e., Clear Aligner supply chain). As the general treatment practice differs between the supply chains, I will make some assumptions to allow a reliable comparison.

Numerousness metric (NM) and *variety metric (VM)*

For the numerous metrics the same production volume for Align Tech as outlined in section 7.3.3 is assumed. Table 32 provides an overview of how the numerous and the variety metrics have been calculated.

Connectivity metric (CM)

As the connectivity metric was not measured for Align Tech, a direct comparison is not possible. However, as there are only eight main process steps, the connectivity for the remodeled supply chain should be less complex, even though the production process consists of 15 steps. Note that all these steps are conducted by one person consecutively, and thus, do not add complexity toward connectivity.

Table 32: Numerousness and variety metrics for the remodeled supply chain

Supply Chain Element		Similar	Total Elements	Comment
Companies	Number of dental professionals	1	31,300	Assumed professionals would use Clear Aligner instead of Invisalign
	Transportation firm	1	1	Parcel service used by Scheu Dental (assumed based on German setup)
	Suppliers	1	1	Simplified (used retailer Scheu based on German setup)
	Production facilities	1	31,300	Dental professionals
Interacting persons	Number of employees	1	31,300	High level: Dental professionals
Inter-company business processes	Number of main processes	22	(8 + 14) x 24 = 528	Compare description in section 7.3.5, Figure 54 (8 major process steps), and Figure 55 (15 sub-process), i.e., 22 steps overall that needs to be repeated 24 times (as a case consists of 24 pairs of aligners)
Offered products	Total number of products	1	11,280,000	Only aligners
Employed systems	Systems	1	1	CA Software
	Total	**29**	**11,374,431**	
Numerous Metric: NM_j		*11,374,431*		
$Variety\ Metric: VM_j(\%)$		99.9999974504		$\left(1 - \frac{Number\ of\ similar\ types_j}{Total\ number\ of\ types_j}\right) * 100$

Known process metric (KPM)

To evaluate the KPM I assume a lower value, as the decentralized production and the mainly manual production makes it more difficult to standardize and train each professional in the same manner as in the centralized production environment of Align Tech.

Overall complexity performance evaluation

Table 33: Summary of complexity performance evaluation

Complexity Metrics	Align Tech	Remodeled Supply Chain
Numerous Metric	11,314,495	11,374,431
Variety Metric	99.999787	99.999997
Connectivity Metric	Favorable (12 main processes)	Favorable (8 main processes)
Known Process Metric	100% favorable	< 100%

Thus, except for the connectivity metric, which could not be evaluated precisely, the supply chain using additive manufacturing is less complex, as it involves fewer people in the aligner production. This supply chain is still diverse and complex because it is driven by the total number of produced aligners, but it has lower diversity, as indicated by the lower variety metric, and a lower numerous metric.

7.3.7. Conclusion of the case study

The case study above used the evaluation process developed in chapter 4 successfully, albeit the process was intended to be used to analyze the application of additive manufacturing for complexity management. The case study also demonstrated that the current supply chain using SLA as an additive manufacturing production process for tool production, that is, rapid tooling for aligner molds, reduced supply chain complexity, improved supply chain performance, and lowered supply chain costs.

8. CONCLUSION

8.1.Overview

The focus of this dissertation is on supply chain complexity management through additive manufacturing. As this topic has not yet been fully researched, I developed a practical process and decision model, which gives a framework for arriving at a fact-based decision on whether additive manufacturing should be utilized to manage complexity in a supply chain network. In short, the model gives professionals clear guidance on when and how to apply additive manufacturing in the context of a production environment. It also overcomes the problem of not having strict, fact-based theorems of managing complexity by implementing fact-based metrics and incorporating these into the context of supply chain management performance (including for costs), as complexity management and utilizing additive manufacturing are not ends in themselves.

8.2. Contribution to the Body of Knowledge

The dissertation has contributed to the existing body of knowledge by adding a structured, five-step process for managing supply chain complexity through additive manufacturing. To this end, it identified and improved upon clear metrics for supply chain complexity and performance including a comprehensive cost model for a supply chain utilizing additive manufacturing as production technology.

Additionally, the dissertation also developed a decision model that provides clear guidance on when to apply additive manufacturing to manage complexity in supply chains. This decision model is based on strategy, supply chain performance, and supply chain complexity levels. The dissertation improved upon relevant metrics for supply chain performance and complexity and developed a detailed supply chain cost model for additive manufacturing. In addition, it compared this cost model with a newly developed cost model for traditional manufacturing to allow a direct comparison of overall supply chain cost performance.

In terms of strategy, the dissertation expanded the concept of customer benefit curves, providing a new strategic decision variable to determine the complexity management strategy in supply chains. Finally, the two case studies demonstrated the functionality of the methodology.

8.3. Areas for Future Research

This dissertation opened an avenue in the topic of supply chain complexity management. As additive manufacturing is a fairly young technology that is only beginning to be industrialized, clear guidance is necessary for determining which parameters improve additive manufacturing performance, and consequently, enable its application in a much broader manner. As different additive manufacturing technologies are currently in different development and industrialization stages, further analyses on which technology might be most appropriate for specific industries might help managers determine when they can apply additive manufacturing in their industry.

Another area for future research that might be of interest is the optimization and scenario technique. The current evaluation methodology is static, so optimization and scenario techniques can be applied and incorporated into the methodology to evaluate under which circumstances a technology review might be needed. Additionally, the optimization and scenario techniques might be used to develop the optimal model, which the current methodology does not fulfill.

A third proposed research area is the implication of additive manufacturing on supply chain risk. Researchers can investigate which risks additive manufacturing ads and how additive manufacturing helps manage supply chain risks.

REFERENCES

3Druck.com (2012) Das Magazin für 3D Drucktechnologien, “3D- Druckerliste,” URL: http://3druck.com/3d-drucker-liste/, Visited: August 30, 2012

3D Systems, Press Release (2002), “3D Systems and Align Technology Renew Agreement,” Released May 14th, 2002

3D Systems (2008), “Investor Meeting RAPID Show Orlando,” URL: http://google.brand.edgar-online.com/EFX_dll/EDGARpro.dll?FetchFilingHtmlSection1?SectionID=5952079-5875-43925&SessionID=47aiWHH8YxwBeA7, Visited: July 2, 2013

ASTM International (2011), “F2792-10 Standard Terminology for Additive Manufacturing Technologies,” URL: http://www.astm.org/Standards/F2792.htm, Visited: August 9, 2011

ASTM International (2012), “F2792-12a Standard Terminology for Additive Manufacturing Technologies,” ASTM International, West Conshohocken, Pennsylvania

Bak, O. (2005), “Complexity and Impact of Internet Technologies: A Study on Supply Chain Management,” in Blecker, T., Kersten, W. “Complexity Management in Supply Chains,” pp. 265–284, Berlin

Battaglia, G. (1991), “Strategic Information Planning: A Corporate Necessity,” Journal of Systems Management, February, pp. 23–26.

Binner, H., (2002), “Unternehmensübergreifendes Logistikmanagement,” Munich.

Blaustein, B. T., McCollum, C. D., Rosenthal, A., Smith, K. P., and Notargiacomo, L. (1995), “Autonomy and Confidentiality: Secure Federated Data Management,” Proceedings of the 2nd International Workshop on Next Generation Information Technologies and Systems, pp. 40–70, JAI Press, Reston, Virginia.

Blecker, T., Friedrich, G. (2010), Foreword, in “Mass Customization: Challenges and Solutions,” Springer, New York.

Blecker, T., Kersten, W., Meyer, C. (2005), “Development of an Approach for Analyzing Supply Chain Complexity,” in: Blecker, T., Friedrich, G. (Eds.), “Mass Customization: Concepts-Tools-Realization,” Proceedings of the International Mass Customization Meeting 2005, pp. 47–59, June 2–3, 2005, Klagenfurt/Austria, Berlin.

BME (2012), “BME-Preisspiegel Frachten Q3/2012,” Frankfurt.

Bongulielmi, L. (2002), “Die Konfigurations & Verträglichkeitsmatrix als Beitrag zur Darstellung konfigurationsrelevanter Aspekte im Produktentstehungsprozess,” Zurich.

Boutellier, R., Dinger, H., Lee, H. (1997), "Plattformen – Ein Erfolgsfaktor im Wettbewerbsdruck," Technische Rundschau, 89 (37–38), 58–61.

Buggert, W., Wielpütz, A. (1995) "Target Costing," Munich.

Burn, G. R. (1990), "Quality Function Deployment" in Dale B. G., Plunkett, J. J. (Eds.), "Managing Quality," pp. 66–88, Philip Allan, London.

Bützer, P. (2009), "Zementhärtung," URL: http://www.isitech.com/fileadmin/pb/pdf-Dateien/Zementhaertung.pdf, Visited: August 10, 2010, St. Gallen.

BZEAK – Bundeszahnärztekammer (2012), "Gebührenordnung für Zahnärzte (GOZ)," URL: http://www.bzaek.de/fileadmin/PDFs/goz/gebuehrenordnung_fuer_zahnaerzte_2012.pdf, Visited: July 25, 2013.

Chan, L. K., Wu, M. L. (2001), "Quality Function Deployment: A Literature Review," European Journal of Operational Research, 143, pp. 463–497.

Childerhouse, P., Deakins, E., Böhme, T., Towill D. R., Disney, S. M., Banomyong, R. (2011), "Supply Chain Integration: An International Comparison of Maturity," Asia Pacific Journal of Marketing and Logistics, 23 (4), pp. 531–552.

Chopra, S., Meindl, P. (2007), "Supply Chain Management: Strategy, Planning, & Operation," 3rd Ed., Pearson Education, Upper Saddle River, New Jersey.

Chua, C., Leong, K., Lim, C. (2010), "Rapid Prototyping: Principles and Applications," 3rd Ed., World Scientific, Singapore.

Chu, C., Graf, G., Rosen, D. (2008), "Design for Additive Manufacturing of Cellular Structures," URL: http://www.cadanda.com/CAD_5_5__686-696.pdf, Visited: August 9, 2010.

Cormier, D. R., Harrysson, O. L. A. (2002), "Mass Customization via Rapid Manufacturing," International Electronics Recycling Congress 2002, May 19–21, 2002, Orlando, Florida.

Council of Supply Chain Management Professionals, "Supply Chain Management," URL: http://cscmp.org/aboutcscmp/definitions.asp, Visited: October 21, 2011.

Coyne, K. (2012), "Testing Product design to the Max," URL: http://www.prw.com/subscriber/headlines2.html?id=296, Visited: July 2, 2013.

Jankowksi, P., (2012), "Dentallabore – Branchenreport 2012 – WZ-Code 32.50.3," Deutscher Sparkassen- und Giroverband, Stuttgart.

Domschke, W., Scholl, A., Voß, S. (1997), "Produktionsplanung," Berlin.

EngATech, "Objet 3D Printing Technology," URL: http://www.engatech.com/Objet-3D-Printing-Technology.asp, Visited August 30, 2012

Engeln, J. (2010), “Kieferorthopädische Behandlungen mit transparenten Schienenapparaturen: Therapeutische Möglichkeiten am Beispiel des Invisalign-Systems,” Krems, Austria.

Entsorgung Punkt DE GmbH,“Schrottpreise,” URL: http://www.schrott.de/schrott/preise, Visited: February 2, 2012.

Erkodent, (2013), “Korrekturschienen und Retainer, URL: http://www.erkodent.de/dental/anleit/KorrektRetain.pdf,” Visited: July 3, 2013

Erixon, G. (1998), “Modular Function Deployment: A Method for Product Modularisation,” Royal Institute of Technology, Department of Manufacturing Systems, Assembly Systems Division, Stockholm.

Frazelle, E. (2002). “World-Class Warehousing and Material Handling,” McGraw-Hill, New York.

Fritz, H., Schulze, G. (1998), “Fertigungstechnik,” 4th Ed., Berlin.

Frizelle, G., Woodcock, E. (1995), “Measuring Complexity as an Aid to Developing Operational Strategy,” International Journal of Operations & Production Management, 15 (5), pp. 26–39.

Fröhling, O. (1994), “Strategische Produktkostenermittlung am Beispiel der Automobilindustrie” in KRP, No. 2.

Gaugel, H., Gedigk, M. (2010), “Aktuelle Marktübersicht für Aligner & Schienensysteme in der KFO (I)” in J. Compr. Dentof. Orthod. + Orthop. (COO) (Umf. Dentof. Orthod. u. Kieferorthop. (UOO), No. 3/4 2010, pp. 63–67

Greenberg, A. (2012), “‘Wiki Weapon Project’ Aims to Create a Gun Anyone Can 3D-Print at Home,” URL: http://www.forbes.com/sites/andygreenberg/2012/08/23/wiki-weapon-project-aims-to-create-a-gun-anyone-can-3d-print-at-home/, Visited: October 7, 2012.

Grüning, M. (2001), “Performance-Measurement-Systeme,” Dissertation, Wiesbaden.

Hague, R., Campbell, I., Dickens, P. (2003), “Implications on Design of Rapid Manufacturing,” Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 217 (1), pp. 25–30.

Haidan, S. (2002), “Zahnmedizinisches Setup – Datenerfassung,” Karlsruhe, URL: http://wwwiaim.ira.uka.de/Teaching/ProseminarBildverarbeitung/Ausarbeitungen/03_Zahnmedizin.pdf, Visited: July 5, 2013

Handfield, R., Nichols, E. (1999), “Introduction into Supply Chain Management,” Prentice-Hall, Upper Saddle River, New Jersey.

Heraeus (2008), “Alginate – Leitfaden für die Perfekte Situationsabformung,” URL: http://static.zahniportal.de/fileadmin/mediensammlung/partner/heraeus/Alginat%20Leitfaden.pdf, Visited: July 3, 2013.

Hertrich, K. (2012), “Kieferorthopädisches Set-up im Artikulator: Herstellung,” Universitätsklinikum Erlangen, URL: www.kieferorthopaedie.uk-erlangen.de%2Fe394%2Fe407%2Fe1355%2F inhalt1356%2FHerstellungsetupPrsentation.ppt&ei2sTvUfTLMYLPtAbksIGYCQ&usg=AFQjCNHwJvVdMIGod7LAoDneXqsgLjIZsg&bvm=bv.49641647,d.Yms, Visited: June 12, 2013.

Hiromoto, T. (1988), “Another Hidden Edge—Japanese Management Accounting,” Harvard Business Review, July/August, pp. 22–26.

Horvath, P. (2002), “Strategieorientiertes Kostenmanagement in der Produktentwicklung,” Url: Http://Www.Sfb374.Uni-Stuttgart.De/Forforum2002_Vortraege/3_Sfb_270202_Horvath.Pdf, Visited: February 13, 2012.

Hopkinson, N., Dickens, P. (2001), “Rapid Prototyping for Direct Manufacture,” Rapid Prototyping Journal, 7 (4), pp. 197–202

Hopkinson, N., Dickens, P. (2003), “Analysis of Rapid Manufacturing—Using Layer Manufacturing Processes for Production,” Proceedings of the Institute of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 217 (1), pp. 31–39.

Hronec, S. M. (1993), “Vital Signs: Using Quality, Time, and Cost Performance Measurements to Chart Your Company’s Future,” Arthur Andersen & Co., Chicago.

Huber, F. (2008), “Viel - Aber Nicht Zu Viel,” URL: http://www.marketing-i.bwl.uni-mainz.de/Dateien/PM_Nachkaufempfinden.pdf, Visited: June, 13, 2013.

Institute for Manufacturing, University of Cambridge (2012), “Quality Function Deployment—QFD, URL: http://www2.ifm.eng.cam.ac.uk/dmg/tools/definition/qfd.html, Visited: February 13, 2012.

Ishii, K., Martin, M. V. (1997), “Design for Variety: Development of Complexity Indices and Design Charts,” The 1997 ASME Design Engineering Technical Conference, September 14–17, Sacramento, URL: http://www.gsb.stanford.edu/scforum/login/pdfs/0103MA.pdf, Visited: February 13, 2012.

Ishii, K., Martin, M. V. (2002), “Design for Variety: Developing Standardized and Modularized Product Platform Architectures,” Research in Engineering Design, 13 (4), pp. 213–235

Isik, F. (2011). “Complexity in Supply Chains: A New Approach to Quantitative Measurement of the Supply-Chain-Complexity in Supply Chain Management,” Li, P. (Ed.), URL: http://www.intechopen.com/articles/show/title/complexity-in-supply-chains-a-new-approachto-quantitative-measurement-of-the-supply-chain-complexity, Visited: October 22, 2011.

IRapid, URL: http://www.irapid.de/epages/63283565.sf/de_DE/?objectPath =/Shops/63283565/Categories/ABS_Kunststoffdraht, Visited: February 10, 2012.

Jahnke, U., Lindemann, C. (2012), "Costing Analysis for Additive Manufacturing during Product Lifecycle" In Schmid, H.-J. (2012), "Direct Manufacturing Research Center Annual Report," pp. 16–18, Url: Https://Mb.Uni-Paderborn.De/Fileadmin/Dmrc/Research/ Publications/Dmrc_Report_2012.Pdf, Visited: July 23, 2013.Johansson, H., McHugh, P., Pendlebury, A., Wheeler, P. (1993), "Business Process Reengineering: Breakpoint Strategies for Market Dominance," John Wiley & Sons, Chichester, England.

Johnson, C. N. (2003), "QFD Explained," Quality Progress, 36 (3), pp. 104.

Johnson, G., Scholes, K. (2002), "Exploring Corporate Strategy," 6th Ed., Pearson Education, Essex, England.

Jung, H. (2007), "Controlling," 2nd Ed., Munich.

Kaiser, A. (1995), "Integriertes Variantenmanagement mit Hilfe der Prozesskostenrechnung," Dissertation no. 1742, University of St. Gallen, St. Gallen, Switzerland.

Kaluza, B., Bliem, H., Winkler, H. (2006), "Strategies and Metrics for Complexity Management in Supply Chains," in Blecker, T., Kersten, W. (Eds.), "Complexity Management in Supply Chains," pp. 3–19, Erich Schmidt Verlag GmbH, Berlin.

Kaplan, D., Norton, P. (1992), "The Balanced Scorecard - Measures that Drive Performance," Harvard Business Review, January/February, pp. 71–79.

Kaseva, M. E., Gupta, S. K. (1996), "Recycling—An Environmentally Friendly and Income Generating Activity towards Sustainable Solid Waste Management. Case Study—Dar es Salaam City, Tanzania," Resources, Conservation and Recycling, 17 (4), pp. 299–309.

Kersten, W., Rall, K., Meyer, C., Dalhöfer, J. (2006), "Complexity Management in Logistics and ETO-Supply Chains," in Blecker, T., Kersten, W. (Eds.), "Complexity Management in Supply Chains," pp. 325–347, Erich Schmidt Verlag GmbH, Berlin.

Kim, T., Stückrad, P. (2010), "Das CLEAR-ALIGNER-Konzept nach Dr. Kim," URL: http://www.zwp-online.info/de/fachgebiete/kieferorthopaedie/aesthetik/das-clear-aligner-konzept-nach-dr-kim, Visited: July 8, 2013.

Klaus, P. (2005), "Die Frage der optimalen Komplexität in Supply Chains und Supply-Netzwerken," in Essig, M. (Ed.), "Perspektiven des Supply Management, Konzepte und Anwendungen, " pp. 360–375, Heidelberg.

Kotzab, H. (2005), "The Role and Importance of Survey Research in the Field of Supply Chain Management," in Kotzab, H., Seuring, S., Müller, M., Reiner, G.," "Research Methodologies in Supply Chain Management," pp. 125–137.

Lewis, M. (2013), “4 Ways Manufacturers Can Cope With Rising Energy Prices,” URL: http://www.manufacturing.net/articles/2013/06/4-ways-manufacturers-can-cope-with-rising-energy-prices, Visited: July 29, 2013.

Liberatore, M. (2007), “Chapter 7: Distribution Strategies CMB 8050,” Villanova, URL: http://www.google.de/url?sa=t&rct=j&q=&esrc=s&source=web&cd=5&ved=0CFAQFjAE&url=http%3A%2F%2Fwww70.homepage.villanova.edu%2Fmatthew.liberatore%2FCMB8050%2FSKS007.ppt&ei=ZUPyUZigCMm0PMOVgbAJ&usg=AFQjCNHRzC7oOYYGdhApnmAIqoRSV6uOrw&bvm=bv.49784469,d.ZWU, Visited: July 26, 2013.

Lindemann, C., Jahnke, U., Moi, M., Koch, R.,(2012), “Analyzing Product Lifecycle Costs for a Better Understanding of Cost Drivers in Additive Manufacturing,” 23rd Annual International Solid Freeform Fabrication Symposium - An Addictive Manufacturing Conference, Austin, Texas, August 6–8, 2012

Lindemann, U., Maurer, M., Braun, T. (2009), “Structural Complexity Management: An Approach for the Field of Product design,” Springer, Berlin.

Lopes, A., MacDonald, E., Wicker, R. (2012), “Integrating Stereolithography and Direct Print Technologies for 3D Structural Electronics Fabrication,” Rapid Prototyping Journal, 18 (2), pp. 129–143.

Madaan, J., Khatri, J. (2012), “Invisible Aligners in Orthodontics - Straighten Teeth without braces,” Saarbrücken.

Madsen, H. (n.d.) “ESSIX nach J. Sheridan,” URL: http://aligner-info.de/aligner-varianten/essix-nach-j-sheridan-us-seit-19931996/, Visited: June 25, 2013.

Malik, F. (2003), “Strategie des Managements Komplexer Systeme,” Bern.

Mansour, S., Hague, R. (2003), “Impact of Rapid Manufacturing on Design for Manufacture for Injection Moulding,” Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 217 (4), pp. 453–461.

Marti, M. (2007), “Complexity Management: Optimizing Product Architecture of Industrial Products,” Dissertation, University of St. Gallen, St. Gallen, Switzerland.

Martin, H. (2009), “Transport und Lagerlogistik,“ 7th Edition, Wiesbaden.

MatWeb (2012), “Flexural Strength Testing of Plastics,” URL: http://www.matweb.com/reference/flexuralstrength.aspx, Visited: November 12, 2012.

Meyer, M.H., Lehnerd, A. P. (1997), “The Power of Product Platforms: Building Value and Cost Leadership,” The Free Press, New York.

McKinsey & Company (2010), “The Challenges Ahead for Supply Chains: McKinsey Global Survey Results,” McKinsey & Company, San Francisco.

McNamara, J., Brudon, W.L. (2001), “Orthodontics and Dentofacial Orthopedics,” Needham Press, Ann Arbor, Michigan.

Mittal, S., Fraymann, F. (1989), “Towards a Generic Model of Configuration Tasks,” in Proceedings of the 11th International Joint Conference on Artificial Intelligence, August 20–26, 1989, Detroit, Michigan.

Müller, M. (2005), “Action Research in Supply Chain Management – An Introduction,” in Kotzab, H., Seuring, S., Müller, M., Reiner, G., “Research Methodologies in Supply Chain Management,” pp. 350–364.

Müller-Dauppert, B. (2005) (Ed). “Logistik-Outsourcing,” pp. 14–18, Munich.

Monden, Y., Hamada, K. (1991), “Target Costing and Kaizen Costing in Japanese Automobile Companies,” Journal of Management Accounting Research, Fall 1991, pp. 16–34.

Naylor, J., Naim, M., Berry, D. (1999), “Leagility: Integrating the Lean and Agile Manufacturing Paradigms in the Total Supply Chain,” International Journal of Production Economics, 62 (1–2), pp. 107–118.

Objet (2012), “Connex500,” URL: http://oldsite.objet.com/Portals/0/docs/German/NewNov08/Connex_A4_Grm_low.pdf, Visited: August 30, 2012.

Olfert, K. (1987) “Kostenrechnung,” 7th Ed., Ludwigshafen (Rhein) http://www.rz.fh-ulm.de/projects/lars/Projstud/Fallbsp/Kostenrechnung/MSSR.htm

PAS Deutschland GmbH (2012), URL: http://www.pas-net.biz/index.php?article_id=36&clang=0, Visited: August 23, 2012.

Pavlinek, P., Janek, L. (2007), “Region Restructuring of the Skoda Auto Supplier Network in the Czech Republic,” European Urban and Regional Studies, 14(2), pp. 133–155.

Perona, M., Miragliottab, G. (2002), “Complexity Management and Supply Chain Performance Assessment: A Field Study and a Conceptual Framework,” International Journal of Production Economics, 90 (1) pp., 103–115.

Petrovic, V. Haro, J., Jordá, O., Delgado, J., Blasco J., Portolés, L. (2009): “Additive Layer Manufacturing: State of the Art in Industrial Applications through Case Studies,” in International Journal of Production Research, (Review Status: Doc ID:TRPS-2009-IJPR-0575.R1).

Pinepham, B. J. (1993), “Mass Customization: The New Frontier in Business Competition,” Harvard College, Boston.

Pfeiffer, H. (2004), “Einführung in die Kunststofftechnik - Kompendium zur Vorlesung ‘Kunststofftechnik’ für: WIng, WOT,” URL: ftp://ftp.hof-university.de/lehre/hpeiffer/ftp-Kunststofftechnik-Vorlesungsskript/Microsoft%20Word%20-%20Vorlesungsskript-KT-an%20Studenten%20verteilt.doc.pdf, Visited: November 12, 2012.

Pham, D., Dimov, S., (2003) “Rapid Prototyping and Rapid Tooling—The Key Enablers for Rapid Manufacturing” in Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 217 (1), pp. 1–23.

Pham, D., Gault, R. (1998) “A Comparison of Rapid Prototyping Technologies,” International Journal of Machine Tools and Manufacture, 38 (10–11): pp. 1257–1287.Pires, S., Aravechia, C. (2001), “Measuring Supply Chain Performance,” Proceedings of the Twelfth Annual Conference of the Production and Operations Management Society, March 30–April 2, 2001, Orlando, Florida.

PKV Verband der Privaten Krankenversicherungen e.V. (2009), “Allgemeine Versicherungsbedingungen 2009 für den Standardtarif,” Cologne.

Pulkkinen, A. (2007), “Product Configuration in Projecting Company: The Meeting of Configurable Product Families and Sales Delivery Process,” Dissertation, University of Tampere, Tampere, Finland.

Pulkkinen, A., Lehtonen, T., Riitahuhta, A. (1999), “Design for Configuration – Methodology for Product Family Development,” in Lindemann, U., Birkhofer, H., Meerkamm, H., Vajna, S. (Eds.), Proceedings of the 12th International Conference on Engineering Design, pp. 1495–1500, August 24–26, 1999, Munich, Germany.

Raap, T. (2010), “Produktstrukturierung: Komplexitätsmanagement durch modulare Produktstrukturen und – plattformen,” Munich.

Rathnow, P. (1993), “Integriertes Variantenmanagement: Bestimmung, Realisierung und Sicherung der optimalen Produktvielfalt,” Goettingen.

Rawson, C. (2012), “Why Apple’s Products Are ‘Designed in California’ but ‘Assembled in China’,” URL: http://www.tuaw.com/2012/01/22/why-apples-products-are-designed-in-california-but-assembled/, Visited: October 7, 2012.

Reeves, A. (2008), “Manufacturing a Low Carbon Footprint: Zero Emission Enterprise Feasibility Study,” 2nd International Conference on Additive Technologies (iCAT), September 17–19, Maribo/Slovenia.

Reiner, G. (2005), „Supply Chain Management Research Methodology Using Quantitative Models Based on Empirical Data“ in Kotzan, H., Seuring, S., Müller, M., Reiner, G., „Research Methodologies in Supply Chain Management“, (2005), Heidelberg

Reiss, M. (1993a), “Komplexitätsmanagment I,” WISU, 1, pp. 54–59, 1993.

Reiss, M. (1993b), “Komplexitätsmanagment II,” WISU, 2, pp. 132–137, 1993a.

Reiss, M. (2001), “Komplexitätsmanagement als Grundlage wandlungsfähiger Produktionssysteme,” Industrie Management, 3, S.77–81.

Riitahuhta, A., Pulkkinen, A. (2001), “Design for Configuration: A Debate Based on the 5th WDK Workshop on Product Structuring,” Springer, Heidelberg, Germany.

Robertson, D., Ulrich, K. (1998), “Planning for Product Platforms” Sloan Management Review, 39 (4) pp. 19–31.

Rother, M., Shook, J. (1999), "Learning to See - Value Stream Mapping to Create Value and Eliminate Muda," Brookline, Massachusetts.

Rowe, P. (2011), "Quality Function Deployment: What's the Problem?" URL: http://6sigmaindia.in/Documents/R4%20Quality%20Function%20Deployment.pdf, Visited: February 13, 2012.

Ruffo, M., Tuck, C., Hague, R. (2005), "Cost Estimation for Rapid Manufacturing – Laser Sintering Production for Low to Medium Volumes," Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 220 (9), pp. 1417–1427.

Russell, S. (1997), "Supply Chain Management: More than Integrated Logistics," Air Force Journal of Logistics, 31 (2), pp. 56.

Saeed, B., Young, D. (1998), "Managing the Hidden Costs of Complexity," Boston Consulting Group Whitepaper, URL: www.bostonconsulting.com.au/documents/file13304.pdf, Visited: October 15, 2011.

Saiz. E., Castellano, E., (2006), "Global and Flexible Supply Chain Networks Modelling and Simulation," in Blecker, T., Kersten, W. (Eds.), "Complexity Management in Supply Chains," pp. 161–189, Erich Schmidt Verlag GmbH, Berlin.

Seuring, S. (2005), "Case Study Research in Supply Chains – An Outline and Three Examples," in Kotzab, H., Seuring, S., Müller, M., Reiner, G., "Research Methodologies in Supply Chain Management," pp. 1–15, Heidelberg.

Seuring, S., Müller, M., Reiner, G., Kotzab, H. (2005), "Is There a Right Research Design for Your Supply Chain Study?," in Kotzab, H., Seuring, S., Müller, M., Reiner, G., "Research Methodologies in Supply Chain Management," pp. 236–255.

Shishko, R., Aster, R. (1995), "NASA Systems Engineering Handbook," URL: http://articles.adsabs.harvard.edu//full/1995NASSP6105.....S/0000003.000.html, Visited: February 10, 2012.

Sullivan, L. P. (1986), "Quality function deployment," Quality Progress, 19 (6), pp. 39–50, as cited in Chan, L. K., Wu, M. L. (2002), "Quality Function Deployment: A Literature Review," European Journal of Operational Research, 143, pp. 463–497.

Scheel, O., Hubbart, J. (2009), "Innovation and Complexity Management," in Engel, K., Hubbart, J. (Eds.), "Innovation, Sustainability and Complexity," pp. 6–8, Dusseldorf.

Schuh, G. (2005), "Produktkomplexität managen, Strategien - Methoden – Tools," Munich.

Securities and Exchange Commission (2005), "Annual Report Pursuant to Section 13 or 15(d) of the Securities Exchange Act of 1934 for the Fiscal Year Ended December 31, 2004," Commission file number: 0-32259 for Align Technology, Inc., URL: http://investor.aligntech.com/sec.cfm?DocType=&Year=&FormatFilter=, Visited: July 1, 2013.

Securities and Exchange Commission (2006), "Annual Report Pursuant to Section 13 or 15(d) of the Securities Exchange Act of 1934 for the Fiscal Year Ended December 31, 2005," Commission file number: 0-32259 for Align Technology, Inc., URL: http://investor.aligntech.com/sec.cfm?DocType=&Year=&FormatFilter=; visited: July 1, 2013.

Securities and Exchange Commission (2007), "Annual Report Pursuant to Section 13 or 15(d) of the Securities Exchange Act of 1934 for the Fiscal Year Ended December 31, 2006," Commission file number: 0-32259 for Align Technology, Inc., URL: http://investor.aligntech.com/sec.cfm?DocType=&Year=&FormatFilter=, Visited: July 1, 2013.

Securities and Exchange Commission (2008), "Annual Report Pursuant to Section 13 or 15(d) of the Securities Exchange Act of 1934 for the Fiscal Year Ended December 31, 2007," Commission file number: 0-32259 for Align Technology, Inc., URL: http://investor.aligntech.com/sec.cfm?DocType=&Year=&FormatFilter=, Visited: July 1, 2013.

Securities and Exchange Commission (2009), "Annual Report Pursuant to Section 13 or 15(d) of the Securities Exchange Act of 1934 for the Fiscal Year Ended December 31, 2008," Commission file number: 0-32259 for Align Technology, Inc., URL: http://investor.aligntech.com/sec.cfm?DocType=&Year=&FormatFilter=, Visited: July 1, 2013.

Securities and Exchange Commission (2010), "Annual Report Pursuant to Section 13 or 15(d) of the Securities Exchange Act of 1934 for the Fiscal Year Ended December 31, 2009," Commission file number: 0-32259 for Align Technology, Inc., URL: http://investor.aligntech.com/sec.cfm?DocType=&Year=&FormatFilter=, Visited: July 1, 2013.

Securities and Exchange Commission (2011), "Annual Report Pursuant to Section 13 or 15(d) of the Securities Exchange Act of 1934 for the Fiscal Year Ended December 31, 2010," Commission file number: 0-32259 for Align Technology, Inc., URL: http://investor.aligntech.com/sec.cfm?DocType=&Year=&FormatFilter=, Visited: July 1, 2013.

Securities and Exchange Commission (2012), "Annual Report Pursuant to Section 13 or 15(d) of the Securities Exchange Act of 1934 for the Fiscal Year Ended December 31, 2011," Commission file number: 0-32259 for Align Technology, Inc., URL: http://investor.aligntech.com/sec.cfm?DocType=&Year=&FormatFilter=, Visited: July 1, 2013.

Securities and Exchange Commission (2013a), "Annual Report Pursuant to Section 13 or 15(d) of the Securities Exchange Act of 1934 for the Fiscal Year Ended December 31, 2012," Commission file number: 0-32259 for Align Technology, Inc., URL: http://investor.aligntech.com/sec.cfm?DocType=&Year=&FormatFilter=, Visited: July 1, 2013.

Securities and Exchange Commission (2013b), “Annual Report Pursuant to Section 13 or 15(d) of the Securities Exchange Act of 1934 for the Fiscal Year Ended December 31, 2004,” Commission file number: 0-32259 for 3D Systems Corporation, URL: http://www.3dsystems.com/files/downloads/DDD-2012-Form-10-K.pdf, Visited: July 5, 2013.

Seuring, S., Goldbach, M., Koplin, J. (2004), “Managing Time and Complexity in Supply Chains: Two Cases from the Textile Industry,” International Journal of Integrated Supply Management, 1 (2), pp. 180–198.

Slack, N., Chambers, S., Johnston, R. (2001), “Operations Management,” 3rd Ed., Financial Times Management, Essex, England.

Smirnov, A., Shilov, N., Kashevnik, A. (2006), “Analysing Supply Chain Complexity via Agent-Based Negotiation,” in Blecker, T., Kersten, W. (Eds.), “Complexity Management in Supply Chains,” pp. 51–65, Erich Schmidt Verlag GmbH, Berlin.

Stevens, G. C. (1989), “Integrating the Supply Chain,” International Journal of Physical Distribution and Materials Management, 19 (8), pp. 3–8.

Stock, J., Lambert, D. (2001), “Strategic Logistics Management,” McGraw-Hill/Irwin, Boston.

Stucker, B., Gibson, I., Rosen, L., (2010), “Additive Manufacturing Technologies,” Springer, New York.

Sprauer, J., Z Corporation (2009), “Product Launch zp150 Material System,” URL: http://www.rapidconcepts.com.au/PDF/ZP%20150%20Material%20System.pdf, Visited: September 1, 2012.

Suzue, T., Kohdate, A. (1990) “Variety Reduction Program – A Production Strategy for Product Diversification,” Productivity Press, Cambridge, Massachusetts.

Tanaka, M. (1989), “Cost Planning and Control Systems in the Design Phase of a New Product,” in Monden, Y., Sakurai, M. (Eds.), “Japanese Management Accounting: A World Class Approach to Profit Management,” pp. 49–71, Productivity Press, Portland.

Tanaka, T. (1993), “Target Costing at Toyota,” Journal of Cost Management, 7 (1), pp. 4–11.

Thaler, K. (2001), “Supply Chain Management: Prozessoptimierung in der Logistischen Kette,” 3rd Ed., Cologne.

Travlos, D., (2012), “The iPad will Mirror the iPod’s Market Dominance: Here’s Why and Why It Matters,” URL: http://www.forbes.com/sites/darcytravlos/2012/07/13/the-ipad-will-mirror-the-ipods-market-dominance-heres-why-and-why-it-matters/, Visited: August 3, 2012.

Tseng, M, Jiao, J. (2001), “Mass Customization,” in Salvendy, G. (Ed.), “Handbook of Industrial Engineering - Technology and Operations Management,” 3rd Ed., pp. 684–709, John Wiley & Sons, New York.

Tuck, C., Hague, R. J. M., Burns, N. D. (2007), “Rapid Manufacturing – Impact on Supply Chain Methodologies and Practice,” International Journal of Services and Operations Management, 3 (1), pp. 1–22.

Tuck, C., Ong, M., Wagner, H., Hague, R. (2010,) “Extreme Customization: Rapid Manufacturing Products that Enhance the Consumer,” in Piller, F. T., Tseng, M. M. (Eds.), “Handbook of Research in Mass Customization and Personalization Vol. 1,” pp. 535–581, World Scientific, New Jersey.

Ulrich,P., Probst, G. (1988), “Anleitung zum ganzheitlichen Denken und Handeln,” Stuttgart.

Vester, F., Hesler, A. (1980), “Sensitivitätsmodell,” in Frankfurt A. M. (Ed.), “Regionale Planungsgesellschaft Untermain,” Frankfurt.

Volkmann, M. (2000), “Target Costing,” Karlsruhe, URL: http://www.imihome.imi.uni-karlsruhe.de/ntarget_costing_b.html#lit, Visited: February 13, 2012.

Vry, W. (2004), “Beschaffung und Lagerhaltung: Materialwirtschaft für Handel und Industrie,” Herne, Kiehl.

Wassermann, W., Rudolph, W. (2003), “Das Zahntechnikerhandwerk zwischen Gesundheitspolitik und Markt,“ Eschborn.

Wikipedia (2012), “Injection molding,” URL: http://en.wikipedia.org/wiki/Injection_molding#Tolerances_and_surfaces, Visited: October 23, 2012.

Wikipedia (2011), “Komplexität,” URL: http://de.wikipedia.org/wiki/Komplexit%C3%A4t, Visited: October 17, 2011.

Wildemann, H. (Ed.) (2000), “Komplexitätsmanagement: Vertrieb, Produkte, Beschaffung, F&E, Produktion, Administration,” München.

Winterkorn, M. (2011), “Annual General Meeting - Strategy 2018,” URL: http://www.volkswagenag.com/content/vwcorp/info_center/de/talks_and_presentations/2011/05/Part_III.bin.html/binarystorageitem/file/06+Charts_Winterkorn_HV_Teil3_final.pdf, Visited: December 14, 2011.

Woehe, G. (1996), “Einführung in die Allgemeine Betriebswirtschaftslehre,” 19th Ed., Munich.

Womack, J., Jones, D. (1994), “From Lean Production to the Lean Enterprise,” Harvard Business Review, 72 (2), pp. 93–103.

Womack, J., Jones, D. (2003), “Lean Thinking: Banish Waste and Create Wealth in Your Corporation,” Free Press, London.

Womack, J., Jones, D., Roos, D. (1990), “The Machine that Changed the World: The Story of Lean Production,” Rawson Associates, New York.

XPress3D (2011), “Z Corp – 3D Printing,” URL: http://www.xpress3d.com/Zcorp3DP.aspx, Visited: August 29, 2012.

XPress3D.com (2011), “Prototype Finishes,” URL: http://www.xpress3d.com/Finishes.aspx, Visited: October 23, 2012.

Zäh, M. (2006), “Wirtschaftliche Fertigung mit Rapid-Technologien,” Munich.

Z Corporation (2012a), “ZPrinter 850,” URL: http://www.zcorp.com/en/Products/3D-Printers/ZPrinter-850/spage.aspx, Visited: August 30, 2012.

Z Corporation (2012b), “Funktionsweise des 3D-Drucks - Die Vision, die Innovation und die Technologien hinter dem Tintenstrahl-3D-Druckverfahren,” URL: http://www.zprinter.de/download/pub/it/3D-Printer/10-Datenblaetter-Produktinfo/ZPrinter_Whitepaper_3D-Drucker_Funktionsweise.pdf, Visited: September 6, 2012.

Zeiger, J. (2002), “Konstruktion des Prototyps einer demontagegerechten frontbeladenen Waschmaschine,” Berlin.

KEYWORDS

Additive Manufacturing, Complexity Management, Supply Chain Management, Supply Chain Performance, Mass Production, Supply Chain complexity performance measures, Mass Customization, Supply Cost Models, 3D Printing, Decision Models, Complexity Management Strategies

APPENDIX A: COMPLEXITY IN ENTROPY MEASURES

Based on the entropy measures, Isik (2010) proposes the following metrics for operational and structural complexity:

Operational Complexity:

$$\boldsymbol{H^{II}_{(O)} = -(1 - P)\sum_{i=1}^{M}\sum_{j=1}^{N}[log_2 p_{ij}]d_{ij}p_{ij}}$$

Structural Complexity:

$$\boldsymbol{H^{II}_{(S)} = -\sum_{i=1}^{M}\sum_{j=1}^{N}[log_2 p_{ij}]d_{ij}p_{ij}}$$

where

pij = Probability of resource i, (i = 1,…, M) being in state j, m (j = 1,…, N)

M = Number of resources

N = Number of possible states for resource i

P = Probability of the system being "in control" (scheduled) state

(1-P) = Probability of the system being "out of control" (unscheduled) state

dij = Deviation of outcomes from the expected outcome value for the state.

APPENDIX B: WASHING MACHINE SALES BY TYPE

Total Sold Items		
Type	Platform	Total
WLX20160OE	S10-S	55,992
WFC2063OE	Slimline	36,264
WLX16160OE	S10-S	34,518
WFC1663OE	Slimline	24,873
WLX20460OE	S10-E	23,802
WFCX2460OE	Slimline Plus	14,687
WLX24460OE	S10-E	13,232
WLF16060OE	S11-B	10,155
WLF16260OE	S11-C	9,593
WLF20260OE	S11-C	8,462
WTL5410UC	T9	7,510
WLF20060OE	S11-B	7,064
WLX20460PL	S10-E	5,965
WLX20460BY	S10-E	5,043
WS10X160OE	S10-S	5,004
WXTS1231	EuroTop Enhanced	4,767
WLF16260PL	S11-C	4,454
WLF20260PL	S11-C	4,367
WXT103E	EuroTop	4,354
WOP2001FF	EuroTop Enhanced	3,974
WLX16460PL	S10-E	3,927
WFC2067OE	Slimline Enhanced	3,798
WXT1050	EuroTop	3,718
WXT1250	EuroTop	3,616
WFC1667OE	Slimline Enhanced	3,581
WLX24440	S10-E	3,521
WOL2050	EuroTop	3,500
WS12X440	S10-E	3,477
WAS28740	F20-A	3,376
WS10X440OE	S10-E	3,301
WFC2067PL	Slimline Enhanced	3,189
WOL247S	EuroTop	3,140
WM14S740	F20-A	3,139
WOL2000FF	EuroTop	3,036
WXS1063OE	Slimline	2,949
WLX20420IT	S10-E	2,926
WFC1667PL	Slimline Enhanced	2,901
WM12S740EE	F20-A	2,892
WFC1264IT	Slimline	2,891
WS12X460BY	S10-E	2,839

WS12X440OE	S10-E	2,519
WXTS1001FF	EuroTop Enhanced	2,515
WM14S790	F20-A	2,765
WFC2067BY	Slimline Enhanced	2,614
WXS863OE	Slimline	2,371
WOP2431	EuroTop Enhanced	2,352
WLX12160IT	S10-S	2,245
WOL1651IL	EuroTop	2,208
WLX16420IT	S10-E	2,207
WOL2450	EuroTop	2,185
WXSP120AOE	Slimline Plus	2,092
WAS28790	F20-A	2,080
WM14S490	F20-E	2,069
WOL1801FF	EuroTop	2,039
WOL1251IL	EuroTop	2,032
WS12X160OE	S10-S	2,019
WXTS131A	EuroTop Enhanced	1,979
WM16S740	F20-A	1,979
WS10X460BY	S10-E	1,932
WM16S790	F20-A	1,927
WS10F260OE	S11-C	1,921
WAS32740	F20-A	1,880
WAS28440	F20-E	1,866
WOP131A	EuroTop Enhanced	1,862
WOL120AEU	EuroTop	1,826
WOP111A	EuroTop Enhanced	1,822
WLF12060IT	S11-B	1,799
WOL100A	EuroTop	1,753
WS10X460PL	S10-E	1,734
WXTS111A	EuroTop Enhanced	1,728
WLX24460BY	S10-E	1,721
WLX24162GB	S10-S	1,652
WM14S440	F20-E	1,648
WLX16160IT	S10-S	1,626
WAS24720IT	F20-A	1,613
CR60851IL	EuroTop	1,610
WXT100A	EuroTop	1,609
WLF20060BY	S11-B	1,550
WXT750HK	EuroTop	1,527
WXS107AOE	Slimline Enhanced	1,487
WXT120A	EuroTop	1,467
WAS20420IT	F20-E	1,414
WLF20260BY	S11-C	1,411
WLF20061BY	S11-B	1,393

WFC2063BY	Slimline	1,377
WLF16060BY	S11-B	1,377
WAS28490	F20-E	1,351
WFCX2061BY	Slimline Plus	1,326
WXTS1031	EuroTop Enhanced	1,308
WAS24440EE	F20-E	1,296
WAS28720FF	F20-A	1,281
WLX16160BY	S10-S	1,260
WXTS1201FF	EuroTop Enhanced	1,253
WAS32790	F20-A	1,236
WLF20261BY	S11-C	1,207
WFC1667IT	Slimline Enhanced	1,203
WLF16060PL	S11-B	1,196
WOL2400	EuroTop	1,156
WS12X460PL	S10-E	1,104
WXT1000FF	EuroTop	1,075
WS12X460FF	S10-E	1,067
WXT951IL	EuroTop	1,019
WLF16260BY	S11-C	1,019
WAS24740OE	F20-A	1,008
WLX20160BY	S10-S	1,000
WAS28790NL	F20-A	992
WLX20160	S10-S	990
WXTS1301FF	EuroTop Enhanced	984
WOL2040	EuroTop	978
WS10F260BY	S11-C	963
WFC1663BY	Slimline	962
WXS1267BY	Slimline Enhanced	959
WS10F260PL	S11-C	925
WXT1370NL	EuroTop	902
WM14S493GB	F20-E	893
WM16S480SN	F20-E	872
WAS20440OE	F20-E	862
WXS1063BY	Slimline	844
WFC2067IT	Slimline Enhanced	829
WFC1667BY	Slimline Enhanced	821
WM14S740EE	F20-A	803
WFCX2061PL	Slimline Plus	781
WS08X460PL	S10-E	781
WM16S760DN	F20-A	778
WS10X420IT	S10-E	746
WM16S740NL	F20-A	743
WM10S720IT	F20-A	729
WOP2201FF	EuroTop Enhanced	722

WXSP1241PL	Slimline Plus	708
WXTS1101FF	EuroTop Enhanced	701
WAS28740OE	F20-A	695
WLX24460FF	S10-E	692
WS10X160	S10-S	691
WS08X460IT	S10-E	689
WAS24440	F20-E	689
WAS24440OE	F20-E	685
WOP2031	EuroTop Enhanced	665
WAS32440	F20-E	660
WAS28440EE	F20-E	633
WM16S490	F20-E	621
WXT901FF	EuroTop	613
WM10S740EE	F20-A	607
3TS84100A	F20-E	605
WM12S440	F20-E	594
WOP2401FF	EuroTop Enhanced	594
WOP2471FF	EuroTop Enhanced	570
WM16S440	F20-E	567
WXSP1240	SlimLine Plus	561
WM16S740FG	F20-A	540
WAS32490	F20-E	535
WM14S794GB	F20-A	533
WAS20440EE	F20-E	523
3TS84120A	F20-E	520
WM16S790FF	F20-A	514
WLX20160FF	S10-S	513
WLF16060IT	S11-B	510
WXSP100AOE	Slimline Plus	503
WXS863PL	Slimline	503
WAS327A0NL	F20-A	500
WM14S790FF	F20-A	491
WM12S720IT	F20-A	485
WAS28790EE	F20-A	484
WOL2430NL	EuroTop	480
WAS28720IT	F20-A	477
WAS28740NL	F20-A	475
WAS32740FG	F20-A	469
WAS32760NN	F20-A	467
WXSP861PL	Slimline Plus	463
WFC2467FF	Slimline Enhanced	463
WAS28466GB	F20-E	460
WOPFU02CH	EuroTop Enhanced	456
WM14S740FG	F20-A	455

WAS32790NL	F20-A	450
WFCX1661IT	Slimline Plus	444
WFC2467GB	Slimline Enhanced	443
WM16S790NL	F20-A	430
WOP131ANL	EuroTop Enhanced	384
WS10F060BY	S11-B	383
WM12S44AOE	F20-E	373
WXS1063PL	Slimline	372
WM16S740EE	F20-A	367
WFC1267IT	Slimline Enhanced	348
WAS28445	F20-E	345
WAS32466GB	F20-E	344
WXS867IT	Slimline Enhanced	332
WM10S420IT	F20-E	322
WXSP1261FF	Slimline Plus	317
WFC1663PL	Slimline	314
WXS1067BY	Slimline Enhanced	313
WS12X420IT	S10-E	310
WS10F260IT	S11-C	306
WM10S44AOE	F20-E	302
WM14S4G0	F20-E	296
WAS32720FF	F20-A	295
WOP2601FF	EuroTop Enhanced	293
WM14S760SN	F20-A	292
WFCX2440	Slimline Plus	291
WOP2051BY	EuroTop Enhanced	288
WM14S480SN	F20-E	287
WXSP1061PL	Slimline Plus	273
WM12S760TR	F20-A	271
WXS1067IT	Slimline Enhanced	258
WOP2407GB	EuroTop Enhanced	256
WM14S440NL	F20-E	250
WM14S490NL	F20-E	248
WS10X160PL	S10-S	243
WFC2467BY	Slimline Enhanced	238
WAS28490CH	F20-E	234
WLX16160PL	S10-S	228
WM16S760FG	F20-A	228
WXSP861IT	Slimline Plus	225
WAS28440NL	F20-E	207
WAS24420IT	F20-E	200
WM12S740CH	F20-A	199
WM16S440NL	F20-E	198
WM16S740CH	F20-A	197

WM16S490NL	F20-E	194
WAS32790EE	F20-A	187
WXS1267FF	Slimline Enhanced	182
WM16S794GB	F20-A	180
WM16S740OE	F20-A	179
WXSP1061IT	Slimline Plus	177
WFC206KBY	Slimline Enhanced	177
WXT1250EU	EuroTop	176
WM14S44AOE	F20-E	169
WM14S740NL	F20-A	163
WXS863BY	Slimline	163
WS08X160PL	S10-S	162
WM14S740BY	F20-A	157
WM14S740CH	F20-A	156
WAS24740CH	F20-A	148
WAS28760SN	F20-A	123
WAS28740CH	F20-A	122
WAS32740NL	F20-A	120
WAS28460SN	F20-E	115
3TS84140A	F20-E	114
WXSP1261BY	Slimline Plus	105
3TS84160A	F20-E	89
WAS24460BY	F20-E	82
WTXL250H	T10	54
WAS32440NL	F20-E	50
Grand Total		520,220

APPENDIX C: MATERIALS USED PER SUB-COMPONENT

Overview of the major materials used for sub-platforms S/F 10/20. Total number of analyzed control panels = 328. Detailed weight data for keys are not available. Material used for keys is ABS. Source: Home Appliance Manufacturer, Author's own analysis.

Sub-Component	Platform used	Material used	Average weight in grams	Minimum weight in grams	Maximum weight in grams
Acrylic Glass Hood	W_F10-E	PMMA	42,6	42,0	43,0
Acrylic Glass Hood	W_F10-S	PMMA	42,5	42,0	43,0
Acrylic Glass Hood	W_F20-A	PMMA	42,3	37,0	45,0
Acrylic Glass Hood	W_F20-E	PMMA	41,8	37,0	45,0
Acrylic Glass Hood	W_S10-E	PMMA	42,6	42,0	43,0
Acrylic Glass Hood	W_S10-S	PMMA	42,7	42,0	43,0
Panel Body	W_F10-E	ABS	227,3	217,0	239,0
Panel Body	W_F10-S	ABS	237,0	230,0	247,0
Panel Body	W_F20-A	ABS	219,7	202,0	230,0
Panel Body	W_F20-E	ABS	214,0	214,0	214,0
Panel Body	W_S10-E	ABS	230,2	217,0	239,0
Panel Body	W_S10-S	ABS	235,7	230,0	247,0
Bowl Handle	W_F10-E	ABS	118,5	111,0	127,0
Bowl Handle	W_F10-S	ABS	117,6	111,0	127,0
Bowl Handle	W_F20-A	ABS	108,8	100,0	114,0
Bowl Handle	W_F20-E	ABS	107,2	100,0	114,0
Bowl Handle	W_S10-E	ABS	120,6	111,0	127,0
Bowl Handle	W_S10-S	ABS	116,3	111,0	127,0
Display Window	W_F10-E	PMMA	27,6	18,0	36,0
Display Window	W_F20-A	PMMA	41,7	28,0	65,0
Display Window	W_F20-E	PMMA	26,3	16,0	37,0
Display Window	W_S10-E	PMMA	24,6	17,0	36,0
Rotary Switch	W_F10-E	ABS	17,1	16,0	18,0
Rotary Switch	W_F10-S	ABS	17,2	16,0	18,0
Rotary Switch	W_F20-A	ABS	16,8	16,0	18,0
Rotary Switch	W_F20-E	ABS	17,0	16,0	18,0
Rotary Switch	W_S10-E	ABS	16,8	16,0	18,0
Rotary Switch	W_S10-S	ABS	17,4	16,0	18,0
Electronic Housing	W_F10-E	PC-ABS	140,1	134,0	147,0
Electronic Housing	W_F10-S	PC-ABS	139,3	134,0	147,0
Electronic Housing	W_F20-A	PC-ABS	88,1	87,0	90,0
Electronic Housing	W_F20-E	PC-ABS	88,5	87,0	90,0
Electronic Housing	W_S10-E	PC-ABS	141,8	134,0	147,0
Electronic Housing	W_S10-S	PC-ABS	137,7	134,0	147,0
Light Guide	W_F10-E	PC	14,8	12,0	17,0
Light Guide	W_F10-S	PC	6,0	6,0	6,0
Light Guide	W_F20-A	PC	0,2	0,2	0,2
Light Guide	W_F20-E	PC	19,5	19,0	20,0
Light Guide	W_S10-E	PC	15,4	13,0	17,0
Light Guide	W_S10-S	PC	6,6	6,0	8,0

APPENDIX D: HEADCOUNT AND RESOURCE MODEL OF PANEL SUPPLIER

	Headcount				Shift model			
Official Figures	Manage-ment	First line super-visor	Non supervisor (salaried and	Hourly direct	Manage-ment	First line superviso	Non supervisor (salaried and clerical)	Hourly direct
Fabrication								
Injection								
Supervisor		1				Day shift		
Operators				6				Early/late/night shift
Printing								
Supervisor		1				Day shift		
Operators				7				Early/late/night shift
Prepare Klischees								Day shift
Wire harnesses								
Supervisor		1				day shift		
Operators				2				Early/late shift
Packaging				2				Early/late shift
"Jumper"				1				Early/late shift
Assembly								
Supervisor		2				Day shift		
Shift supervisors		3				Early/late shift		
Assembly operators								
Assembly One								
Operator				24				Early/late shift
Packaging				4				Early/late shift
Assembly Two								
Cable assembly				14				Early/late shift
Control panel assembly								
Control surface				2				
Seal assembly				2				
Ultra sonic				4				
Display assembly				2				
Marriage cable panel				2				
Final test and preparation				6				
Packaging				4				
Shipping/recieving/material handling/stores								
Logistics management	1				Day shift			
Warehouse management		1				Day shift		
Storing				2				Early/late shift
Material handling for assembly one				2				Early/late shift
Material planning/control			3					
Plant and Manufacturing Engineering		1				Day shift		
Maintenance (incl. Related projects)								
Technician mechanic/electric			2				Day shift	
Mechanic/electrician				2				Early/late shift
Injection maintence/setter				1				Day shift
Printing cliché stetter				1				Day shift
Printing Setter				3				Early/late/night shift
Quality								
Head of quality	1				Day shift			
Tech drawing		1				Day shift		
QM			1				Day shift	
Process control				3				Early/late shift
Incoming inspection				2				Day shift
Rework/Inspection				2				
Accounting/Finance	1		2		Day shift		Day shift	
Human Resources		1				Day shift		
Purchasing and Procurement			1				Day shift	
Material and Production planning/control								
Production planning/control		1				Day shift		
Material planning/control							Day shift	
IT								
Production/site mgmt	1		1		Day shift			
Other (Clean ladies/canteen)				3				Early/late shift

APPENDIX E: OVERVIEW OF ADDITIVE MANUFACTURING PRINTERS

Overview of selected additive manufacturing printers for commercial use (Source: Various Company Websites, accessed on August 28, 2012)

Manufacturer	3D Systems / Z-Corp	Beijing Tiertime Technology Co. Ltd.	Blueprinter	Dimension / Stratasys	Dimension / Strataysy
Modell	ZPrinter® 850	D290	Blueprinter	BST 1200es	SST 1200es
Technology	Direct Printing 3DP	Direct Printing 3DP	Laser Sintering	FDM	FDM
Materials					
ABS	yes (like)	yes	yes (like)	yes	yes
PMMA	no	no	no	no	no
PC-ABS	no	no	no	no	no
No. of colors per print	390000	one	one	one	one
Building area					
Length [mm]	508	255	160	254	254
Width [mm]	381	290	200	254	254
Height [mm]	229	320	140	305	305
Layer thickness Z - Dimension mm	0,089	0,02	0,1	0,254	0,254
Building Speed	5-25 mm / hour	60ccm/h	10 mm /hour		
Source:	http://www.3dsystems.com/	www.tiertime.com	http://www.blueprinter.dk/	http://www.dimensionprinting.com/	http://www.dimensionprinting.com/

Manufacturer	Dimension / Strataysy	EOS	Fortus / Stratasys	Fortus / Stratasys	HP / Stratasys
Modell	Elite	EOSINT P 800	Fortus 900mc	Fortus 400mc	HP Designjet 3D / Uprint SE
Technology	FDM	SLS	FDM	FDM	Direct Printing 3DP
Materials					
ABS	yes	no only PA, PEEK, PS	yes	yes	yes
PMMA	no		no	no	no
PC-ABS	no		yes	yes	no
No. of colors per print	one	one	one	one	one
Building area					
Length [mm]	203		914	406	203
Width [mm]	203		610	356	203
Height [mm]	305		914	406	152
Layer thickness Z - Dimension mm	0,178		0,178	0,127	0,25
Building Speed					
Source:	http://www.dimensionprinting.com/	www.eos.info	http://www.fortus.com/	http://www.fortus.com/	http://www.hp.com/go/designjet3D

Manufacturer	Objet / Stratasys	Rapidshape	Solid Scape	Voxeljet
Modell	Connex 500	S60 maxi	DF76plus	VX800
Technology	Direct Printing / Photopolymerization	SLA	WAX Printing	Direct Printing 3DP
Materials				
ABS	yes (like)	yes (like ABS/PP material only)	no	no
PMMA	yes (like)	not in one production one / only by material	no	yes
PC-ABS	no	yes (like ABS/PP material only)	no	no
No. of colors per print	2 (from 8 print heads)	one	one	one
Building area				
Length [mm]	490	150	152	1060
Width [mm]	390	85	152	600
Height [mm]	200	200	101	500
Layer thickness Z - Dimension mm	0,16	0,01	0,0254	0,12
Building Speed	20 mm/hour	10mm per 10 minutes at 50µ slice thickness		36 mm/hour
Source:	http://www.objet.com/	http://www.rapidshape.de/	http://www.solid-scape.com/	http://www.voxeljet.de/

not in scope	comment
Exone	only for sand and metals
MCOr	only paper based
SLM Solutions	only metals
Solidscape	only wax
Optomec	only electronics
Essential Dynamics	extrusion only for small applications
Aaroflex	only photopolymers
Asigia	only photopolymers
Envisiotec	only photopolymers

APPENDIX F: COST MODEL DETAILS

Table 34: General cost parameters

Parameter		Source	Comment
Internal Interest Rate / WACC	5%		
Costs per FTE p.a.	42.213 €	Control Panel Supplier Data (2010)	Average costs for blue and white collar
Costs per FTE p.h.	22 €	Calculated	Based on 240 Working Days per year; 8 hours per day
Costs per sqm space p.a.	90,00 €	Assumption - including additional costs	
Costs per km truck transport	1,20 €	Assumption	

Table 35: Logistics cost calculation

Logistics Costs per Control Panel

	Traditional		Additive Manufacturing	
Warehousing				
People	-	1)	- €	4)
Space costs per Control Panel	0,07 €	2)	- €	4)
Equipment	-	3)	- €	3)
Working Capital Costs				
Finished Goods	0,002 €	5)	- €	7)
Work in progress	0,008 €	6)	- €	8)
Transportation				
Route 1 - Supplier Site - Production Site (Control Panel)	0,02 €	9)	- €	11)
Route 2 - Supplier Site - Production Site (Wire Harness)	- €	10)	- €	12)
Total Logistics Costs per Control Panel	**0,10 €**		**- €**	

Comments

			Source/Detailled description
1	Already included in resource model of the production		
	Space Finished Goods Warehouse in sqm	410	
2	Number of produced control panels p.a.:	510.129	Estimated based on Turkish Panel Production Site Layout (Space / # of produced control panels)
	Space costs per Panel (Costs per sqm p.a.* space finished goods warehouse in sqm / # of produced control panels):	0,07 €	
3	No significant equipment used (some forklift trucks), so assumption is that this is still required for the additive manufacturing as well		
4	not required any more		
	Inventory Turns Finished Goods p.a.	443	Based on information provided from Control Panel Supplier for Turkish Production Site on Inventory Turns (Calculation COGS /average finished goods inventories (incl. Own inventory on forwarders, customers and in distribution centers)
5	COGS	**11.008.000,00 €**	Based on information provided from Control Panel Supplier for Turkish Production Site
	Average Inventory value (COGS / Inventory turns)	**24.848,76 €**	Calculated
	Average Working Capital Costs per Control panel (Average inventory value x WACC / number of produced control panels p.a.)	0,002 €	
	Inventory Turns Work-in-Progress material p.a.	136	Based on information provided from Control Panel Supplier for Turkish Production Site on Inventory Turns (Calculation COGS /average work-in-progress goods inventories
6	COGS	**11.008.000,00 €**	Assumption: Assumed 80% of COGS of finished goods to caluculate COGS for Work in progress goods (no information available from supplier)
	Average Inventory value (COGS / Inventory turns)	**80.941,18 €**	Calculated
	Average Working Capital Costs per Control panel (Average inventory value x WACC / number of produced control panels p.a.)	0,008 €	Calculated
7	not required any more		
8	Just in sequence production, so no costs assumed as WIP		
9	No details available so calculation based on Assumptions		
	Trucking costs per km	2,00 €	
	Kilometres Supplier - Homeappliance Manufacturer Site	90	One way: 45 km, but empties needs to be returned in a 1 to 1 relations
	Truck capacity required per Control Panel		
	Total Capacity per Truck in cbm	63	Assuming truck 13.6 m length x 2.4 m width and 2.4m height with 80% utilization
	Costs per cbm to transport (trucking costs per km x kilometres to transport/ total capacity per truck in cbm)	2,87 €	
	Cbm Required for packed Control Panel	0,01	Calculated based on average outer dimensions of control panel (595 x 110 x 87 mm) + 15% surcharge on calculated packaging requirements
	Total transportation costs (cbm for packed control panel x costs per cbm to transport)	0,02 €	
10	for simplicity purposes no difference assumped between additive manufacturing and traditional manufacturing		
11	not required any more		
12	for simplicity purposes no difference assumped between additive manufacturing and traditional manufacturing		

Table 36: Production costs details

Production Costs

		Traditional		Additive Manufacturing	
Machining Costs per panel	**CA**	**1,47 €**		**3,40 €**	
Depreciation Costs per Panel	KA	0,71 €	**1a)**	**2,41 €**	
Machining Costs per hour	Cah			1,39 €	**2a)**
Hours per Panel				1,7h	
Financing Costs	KZ	0,23 €	1b)	0,71 €	2b)
	KI	0,02 €	1c)	0,07 €	2c)
	KR	0,42 €	1d)	0,12 €	2d)
	KE	0,09 €	1e)	0,09 €	2e)
	U		7)		7)
Labor Costs per Control Panel	**CI**	**8,94 €**	**3)**	**3,72 €**	**4)**
Material Costs	**CM**	7,05 €	5)	113,80 €	6)
Total Production Costs	**CA+CM+CI**	**17,45 €**		**120,92 €**	

	Comments		***Source/Detailled description***
1a)	Calculation Basis is the Turkish Plant; Simplified Calculation total depreciation per year divided by number of produced panels (360.000 € / 510.129 panels); includes also wire harness equipment costs and other costs like general IT Equipment		
1b)	Financing Costs p.a.	117.000,00 €	Calculation: Total annual costs x Depreciation in years [13 years] * 0.5 * interest rate
	Financing Costs p. Panel	0,23 €	Calculation: Financing costs p.a. / Produced panels p.a. [510.129]
1c)/2c)	Assumption: 3% of depreciation costs per panel	0,02 €	
1d)	Space Costs per Panel: Sqm Used x Costs per Sqm p.a. / Produced Panels p.a.	0,42 €	Estimated squaremeter requirements for panel production only based on Turkish Production Site of Control Panel supplier (partially estimated ~ 2400 sqm)
1e)	Total Energy Consumed p.a / # of panels produced p.a.	0,09 €	Costs for utilities were 90.000 Euro p.a. For total plant; assumption is that 50% is dedicated to control panel production
	Costs per Printer	97.724,91 €	Offer from Horn System Haus, Kulmbach Germany
	Costs per Annum depreciated	7.517,30 €	Calculated - Based on depreciation period of 13 years; taken from depreciation table for injection molding machines from the
2a)	Costs per hour 100 % Utilization	1,25 €	Calculation: 240 Working Days / 24 hours operation / 100% Utilization
	Costs per hour 85% Utilization	1,39 €	Calculation: 240 Working Days / 24 hours operation / 90%
	(Height per Panelin mm / Print speed per hour in mm/# of panels produced in parallel)	1,7h	calculated - based on a speed of a building speed of 25mm/h and 2 p
	Print speed in mm/h	25	Z-Corporation
	Height per Panel in mm	87	
	# of panels produced in parallel	2	
	Financing Costs (1/2 Purchase Price x interest rate) p.a.	2.443,12 €	
2b)	Financing Costs per Panel (Financing costs p.a. / # of Panels produced per Annum)	0,71 €	
	# of Panels produced per annum per machine	3.462	Calculation: (251 Working Days * 24 hours operation) / print time pe
2d)	Space Requirment Equipment only in sqm	2,24	Zcorporation
	Functional Space (Floors, Buffers, others) 100% surplus to original equipment space i	2,24	Estimation
	Total Space Requirement (Equipment + Functional space) in sqm	4	Calculation
	Space costs per annum per total space requirements (Zprinter 850)	403	Calculation
	Space Costs per Control Panel (Space costs p.a. Per total space requirements	0,12 €	Calculation
2e)	No assessment possible; assumption that energy consumption is equal to traditional manufacturing method		
	Given Resource Model # FTE	108	Control Panel Supplier - Turkish Production site
3)	Total FTE Costs (# of FTE x Costs per FTE)	4.558.950 €	
	Costs per Control Panel (Total FTE Costs/Divided by number of produced control panels)	8,94 €	
	Adjusted Resources Model		
	Total number of FTE's	45	
4)	Total FTE Costs (# of FTE x Costs per FTE)	1.899.563 €	
	Costs per Control Panel (Total FTE Costs/Divided by number of produced control panels)	3,72 €	
	Compare Chapter 4.2 Total costs calculated:	7,05 €	Home Appliance Manufacturer (2008)
	out of this		
	Plexiglas-Hood	1,75 €	
	Panel body	1,20 €	
5)	Bowl handle	0,70 €	
	LED display mechanic	1,00 €	
	Display window (0,2-0,8)	0,50 €	
	Rotary switch (only one calculated)	0,30 €	
	Keys	0,60 €	
	Electronic housing	0,40 €	
	Light guide	0,30 €	
	Language legend	0,30 €	

6)	Costs calculated on average weight across platforms (Material input as follows)				Source
	Acrylic Glass Hood	42,428 grams	equals	35,65 cm³	methacrylate)",
	Bowl Handle	114,830 grams	equals	109,36 cm³	onsite.com/de/TechnologySele
	Display Window	30,025 grams	equals	25,23 cm³	methacrylate)",
	Electronic Housing	122,585 grams	equals	102,15 cm³	onsite.com/de/TechnologySele
	Light Guide	10,409 grams	equals	8,67 cm³	onsite.com/de/TechnologySele
	Panel Body	227,299 grams	equals	216,48 cm³	onsite.com/de/TechnologySele
	Rotary Switch	17,034 grams	equals	16,22 cm³	onsite.com/de/TechnologySele
	Total	**564,609 grams**	equals	513,77 cm³	
	Required ZP150	**627,098 grams**	equals	513,77 cm³	Sprauer (2009), p. 22; calculation based on a denisty of 1.2205
	Costs ZP150 per kg	69,00 €			Offer Horn Systems
	Costs control Panel for ZP 150	43,27 €			
	Binder requirements in l	0,16 litre			Offer Horn Systems / Assumes 0.25 l binder per kg powder material
	Costs binder per l	448,58 €			Offer Horn Systems (Based on weighted average price for a mix of crystal, black, cyan, magenta and yellow
	Costs per control panel for Binder	70,53 €			Calculated

Table 37: Comparison of full-time employee resources for traditional manufacturing and additive manufacturing

Traditional Manufacturing Methodology					Derived Resource Model - Additive Manufacturing Methodology					
	Headcount					Headcount				
Official Figures	Management	First line supervisor	Non supervisor (salaried and clerical)	Hourly direct work	Official Figures	Management	First line supervisor	Non supervisor (salaried and clerical)	Hourly direct work	Assumptions / Comments - Bridge to existing Resource model
Fabrication					**Fabrication**					
Injection Molding					3D Printing - Additive Manufacturing					
Supervisor		1			Supervisor		1			Assumed that resource level will not change
Operators				6	Operators				6	Assumed that resource level will not change
Printing					Printing					
Supervisor		1			Supervisor					process included in 3D Printing Operation
Operators				7	Operators					process included in 3D Printing Operation
Prepare Klischees					Prepare Klischees					process included in 3D Printing Operation
Assembly					**Assembly**					
Supervisor		2			Supervisor		1			Only one FTE for supervision for packaging and quality control operations required
Shift supervisors		3			Shift supervisors					Will be included in supervision function
Assembly operators					Assembly operators					process included in 3D Printing Operation
Assembly One					Assembly One					process included in 3D Printing Operation
Operator				24	Operator					process included in 3D Printing Operation
Packaging				4	Packaging					No packaging required because it will be incorporated into the production line
Assembly Two					Assembly Two					
Control panel assembly					Control panel assembly					process included in 3D Printing Operation
Control surface				2	Control surface					process included in 3D Printing Operation
Seal assembly				2	Seal assembly					process included in 3D Printing Operation
Ultra sonic				4	Ultra sonic					process included in 3D Printing Operation
Display assembly				2	Display assembly					process included in 3D Printing Operation
Final test and preparation				6	Final test and preparation				6	Assumed that resource level will not change
Packaging				4	Packaging					No packaging required because it will be incorporated into the production line
Shipping/recieving/material handling/stores					**Shipping/recieving/material handling/stores**					
Logistics management	1				Logistics management	0,5				Resource Reduction based on eleminating internal storage Only Inbound deliveries and shipments needs to be taken into account
Warehouse management		1			Warehouse management		1			
Storing				2	Storing				1	Resource Reduction based on eleminating internal storage
Material handling for assembly				2	Material handling for assembly				1	Simplified Material Handling Requirements
Material planning/control			3		Material planning/control			0,5		Reduction through less planning efforts due to no sequencing efforts and production planning
Plant and Manufacturing Engineering		1			**Plant and Manufacturing Engineering**		1			incorporated into the production line
Maintenance (incl. Related projects)					**Maintenance (incl. Related projects)**					
Technician mechanic/electric			2		Technician mechanic/electric			2		incorporated into the production line
Mechanic/electrician				2	Mechanic/electrician				4	Increased resources required to cover increased number of machines to be maintained
Injection maintence/setter				1	Injection maintence/setter					process included in 3D Printing Operation
Printing cliché stetter				1	Printing cliché stetter					process included in 3D Printing Operation
Printing Setter				3	Printing Setter					process included in 3D Printing Operation
Quality					**Quality**					
Head of quality	1				Head of quality	1				incorporated into the production line
Tech drawing		1			Tech drawing		1			incorporated into the production line
QM			1		QM			1		incorporated into the production line
Process control				3	Process control				3	incorporated into the production line
Incoming inspection				2	Incoming inspection				2	incorporated into the production line
Rework/Inspection				2	Rework/Inspection				2	incorporated into the production line
Accounting/Finance	1		2		**Accounting/Finance**	1		2		incorporated into the production line
Human Resources		1			**Human Resources**		1			incorporated into the production line
Purchasing and Procurement			1		**Purchasing and Procurement**			1		incorporated into the production line
Material and Production planning/control					**Material and Production planning/control**					
Production planning/control		1			Production planning/control		0			Will be included in the overall production planning of the home appliance manufacturer
Material planning/control					Material planning/control					
IT					**IT**					
Production/site mgmt	1		1		**Production/site mgmt**	1		1		incorporated into the production line
Other (Clean ladies/canteen)				3	**Other (Clean ladies/canteen)**				3	incorporated into the production line
Totals	4	12	10	82	**Totals**	3,5	6	7,5	28	

Table 38: Setup costs calculation

Set-Up Costs calculation

Step	Value	Source / Comment
FTEs required for set-up	5	Basis Turkish Production Site of the supplier (Printer cliché set-up / injection moulding setter)
Available Set-up Capacity in hours	8440	Assumes 211 working days (30 days vacation / 10 days sickness / 104 days weekends/10 days public holidays); 8 hours per days
Set-ups p.a.	302,5	Based on sales figures 2005 / 2006 Turkish Plant Home Appliance Manufacturer Calculation assumes one set-up per variant per 5.000 machines Average of 2005 and 2006 data
Time per set-up (Available set-up capacity / set ups p.a.) in hours	27,90	Calculated
Costs per Set-up (Time per set-up x costs p.hour)	**613,42 €**	**Calculated**
Cross Calculation: Costs per Panel (Costs for FTEs / Annually produced control panels)	0,41 €	Basis Turkish Production site production numbers of the supplier (510129 pcs)
Average lot size (Costs per Set-up / Costs per Panel)	1.483	

APPENDIX G: COMPLEXITY MEASURES

Numerous metric

Based on my calculation, the numerous metric for the remodeled supply chain is 353, mainly driven by the number of products provided, which did not change during the remodeling. This metric considers the number of elements in the supply chain, including companies, interacting persons, inter-company business processes, employed systems, and offered products as detailed below.

Table 39: Numerousness metric calculation for remodeled supply chain

Element of Supply Chain (J)[1]	Number	Comment
Companies	5	Tier 2, Tier 1, OEM, Transports I and II
Interacting persons	72	Employees at Tier 1 and OEM (reduction in production from 108 to 45) and assumed reduction of three full-time employees for internal transport at OEM *(Tier 2 excluded)*
Inter-company business processes	16	Base process less seven consolidated process steps (e.g., injection, molding, printing) through AM
Employed systems	2	Supplier and manufacturer ERP[3] systems
Offered products	258	Control panel variants
Numerousness Metric	**353**	

Source: Author's assumptions and data from Home appliance manufacturer, 2006

[1] **Number of supply chain elements**

[2] **See Figure 38, "High-level supply chain processes for control panel"**

[3] **Enterprise resource planning**

Table 39: Numerousness metric calculation for remodeled supply chain provides details of the NM calculation. The calculation includes the entire supply chain but focuses mainly on Tier 1 suppliers and OEMs and less on Tier 2 suppliers.

Variety metric

The VM_j is calculated as follows:

$$VM_j = \left[1 - \frac{Number\ of\ simliar\ element\ types_j}{Total\ number\ of\ types_j}\right] x100 = 1 - \left[\frac{25}{353}\right] x100 = 92.92$$

Table 40: Number of similar product types

Element of Supply Chain (J)[1]	Number of Types	Comment
Companies	4	Transportation Company II, Tier 1 suppliers, Tier 2 suppliers, OEMs
Interacting persons	3	Based on worker type[1a]; based on Tier 1 processes[2]
Inter-company business processes	16	All high-level process steps[3] and Tier 1 supplier internal production processes
Employed systems	1	Supplier and OEM ERP[4] systems
Offered products	1	Control panels
Total	**25**	

Source: Author's assumptions and data from the home appliance manufacturer, 2006

[1] Number of supply chain elements, [1a] Warehousing, additive manufacturing (3D printing), transportation, [2] See Figure 40, "High-level processes in control panel production"; includes OEM warehouse, storage, and internal transportation staff, [3] See Figure 38, "High-level supply chain processes for control panel", [4] Enterprise resource planning

To determine the number of similar element types, a clustering was made within the type of elements, resulting in 25 element types. The total number of types is the same as the number of supply chain elements (J = 353). Table 40 provides details on the calculation of this metric.

There are different levels of detail possible to calculate the number of similar element types. However, the level of detail should be the same across the entire process—as the total number of types the numerous metrics is chosen.

Production technology numerousness metric

From my calculation, the NM_{PT} is 97.17. I calculated it as follows:

$$NM_{PT}(\%) = \left(1 - \frac{10}{353}\right) x\ 100 = 97.17$$

Table 41: Production technology-related supply chain elements

Element of Supply Chain (J)[1]	Number of types	Comment
Supply chain companies	3	Tier 1 suppliers, Tier 2 suppliers, OEMs
Interacting persons	4	Based on worker type[2]; based on Tier 1 processes[3]
Employed systems	0	Systems affected by production technology
Inter-company business processes	3	Consolidation of injection molding, decoration printing, tampon printing, assembly, packaging, storing and shipping into 1 step at OEM instead of Tier 1 supplier internal production processes
Offered products	0	Products affected by production technology
Totals	**10**	

Source: Author's assumptions and data from the home appliance manufacturer, 2006

[1] **Number of supply chain elements (e.g., warehousing, additive manufacturing, injection molding, decoration printing, tampon printing, assembly, packaging, transportation)**

[2] **See Figure 40, "High-level processes in control panel production"; includes OEM warehouse, storage, and internal transportation staff**

[3] **See Figure 38, "High-level supply chain processes for control panel"**

There are 10 production technology-related elements in the supply chain (Table 4). The total number of supply chain elements is shown in Table 39.

Production technology variety metric

The number of similar production technology-driven element types (PT_j) is 10 (Table 41). To calculate the VM_{PT}, I need to determine the total number of production technology-related types. To this end, I assess which of the supply chain elements are related to production technology. Table 42: Total number of production-related elements in the supply chain shows that approximately 26 elements in the supply chain are related to production technology. Thus, the VM_{PT} is 61.54%.

$$VM_{PT}(\%) = \left[1 - \left(\frac{10}{26}\right)\right] x100$$

$$VM_{PT}(\%) = 61.54$$

Having calculated the VM_{PT}, I was able to calculate the VMR_{PT} as follows:

$$VMR_{PT} = \frac{VM_{PT}}{VM_j} = \frac{61.5}{92.9} = 0.69$$

Table 42: Total number of production-related elements in the supply chain

Element of Supply Chain (J)[1]	Number of elements	Comment
Companies	3	Tier 1 suppliers, Tier 2 suppliers, OEMs
Interacting persons	20	Tier 1 supplier employees excluding non-production technology-related indirect and logistics full-time employees
Inter-company business processes	3	All high-level process steps[2] and Tier 1 supplier internal production processes
Employed systems	0	Systems affected by production technology
Offered products	0	Products affected by production technology
Total	**26**	

Source: Author's assumptions and data from Home appliance manufacturer, 2006

[1] **Number of supply chain elements**

[2] **See Figure 38, "High-level supply chain processes for control panel"**

APPENDIX H: CLEAR ALIGNER SUPPLY CHAIN COSTS CALCULATION

According to Hertrich (2012) a dental professional is allowed to charge for setup model (for the upper and lower jaws), based on the agreed upon pricing table for dentists in Germany (BZAEK, 2012; Table 43: Setup model creation cost based on BZAEK). This pricing includes the adjustment of all teeth, which might be required for only a minority of the cases (see ZT # 0030 – Table 43: Setup model creation cost based on BZAEK).

Table 43: Setup model creation cost based on BZAEK

GO #	Quantity	Measurement	Total Price in Euro
006	1	Impression	33.62
801	1	Alignment/measurement	23.27
802	1	Upper jaw model assembly	51.75
804	1	Lower jaw model assembly	25.87
ZT #			
0054	2	Setup model	15.24
0030	28	Setup per segment	133.28
Total			**283.03**

Source: BZAEK as cited in Hertrich, K., 2012, pp. 42

Thus, assuming that only 15% of the segments are relevant, that is, the dental professional only needs to saw and trim seven segments would actually, the cost for the setup model and its adjustments decreases to €168.78. The price for the aligner itself will be assumed to be €50.65 based on the cost reimbursed by private health insurance companies (PKV 2009). Thus, for three aligners, the cost will be approximately €151.95.

These sales prices are adjusted based on costs. According to Jankowski (2012), in 2012, the overall cost for materials, labor, rent, investments, and financing was 66.6 percent of overall revenue. This figure assumes that the total cost for an aligner set (soft, medium, hard) is €213.61, which is also in accordance with Gaugel's (2010) estimated laboratory cost of €150–200 per set of three aligners. Thus, the approximate total cost per aligner is €70 or US$91 as of this writing.

LIST OF ABBREVIATIONS

ABS	Acrylonitrile butadiene styrene
AM	Additive manufacturing
ASTM	ASTM International
CM	Connectivity metric
CU	Capacity utilization
DFX	Design for X
DM	Dynamics metric
DOS	Inventory days on stock
FDM	Fused deposition modeling
FMEA	Failure mode and effects analysis
FPC	Flexible printed circuit
IfM	Institute for Manufacturing
ITO	Inventory turnover
KPI	Key performance indicator
KPM	Known process metric
LS	Laser sintering
MFD	Modular function deployment
NM	Numerousness metric
OCT	Order cycle time

OEM	Original equipment manufacturer
OTD	On time delivery
PBF	Powder bed fusion
PC	Polycarbonate
PE	Polyethylene
PMMA	Polymethyl methacrylate
POS	Point of sale
PS	Polysulfone
PVC	Polyvinyl chloride
PVS	Polyvinyl siloxane
QFD	Quality function deployment
QPM	Quantum performance measurement
SC	Supply chain
SCC	Supply chain costs
SCCT	Supply chain cycle time
SCM	Supply chain management
SCOR	Supply chain operation reference
SEC	Securities and Exchange Commission
SL	Stereolithography
SLS	Selective laser sintering
TM	Trademark
VM	Variety metrics

VMR	Variety metrics ratio
VMEA	Variant mode and effects analysis
VW	Volkswagen

CURRICULUM VITAE

NAME:	André Kieviet
ADDRESS:	Große Bergstr. 145 22767 Hamburg Germany
DOB:	Germany, Melle – December 10th, 1977
EDUCATION & TRAINING:	Diploma in Industrial Engineering, Private Fachhochschule für Wirtschaft und Technik, Vechta 1997 - 2001
	Diploma in Management Studies Buckinghamshire Chilterns University College 2004 – 2005
	Master of Business Administration Hochschule Osnabrueck 2008 - 2010
	Master of Science in Industrial Engineering University of Louisville 2009 – 2010
PROFESSIONAL EXPERIENCE:	Wilhelm Karmann GmbH, Osnabrueck Logistics Planner 1997-2004
	Accenture GmbH, Duesseldorf Management Consultant 2004-2006
	A.T. Kearney GmbH, Duesseldorf Management Consultant 2006-2010

Ceva Logistics, GmbH
Manager Corporate Services
2010-2013

Scandferries Holding GmbH
Director
Since 2013