Resource Consumption of Additive Manufacturing Technology

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2012

Thesis submitted for completion of
Master of Sustainable Product-Service System Innovation (MSPI)
Blekinge Institute of Technology, Karlskrona, Sweden.

Abstract: The degradation of natural resources as a result of consumption to support the economic growth of human society represents one of the greatest sustainability challenges. In order to allow economic growth to continue in a sustainable way, it has to be decoupled from the consumption and destruction of natural resources. This thesis focuses on an innovative manufacturing technology called additive manufacturing (AM) and its potential to become a more efficient and cleaner manufacturing alternative. The thesis also investigates the benefits of accessing the technology through the result-oriented Product-Service Systems (PSS) approach. The outcome of the study is the quantification of raw materials and energy consumption. The scope of study is the application of AM in the scale model kit industry. The methods used are the life cycle inventory study and the system dynamics modeling. The result shows that AM has higher efficiency in terms of raw material usage, however it also has higher energy consumption in comparison to the more traditional manufacturing techniques. The result-oriented PSS approach is shown to be able to reduce the amount of manufacturing equipment needed, thus reducing the energy and raw materials used to produce the equipment, but does not completely decouple economic growth from the consumption of natural resources.

Keywords: Additive Manufacturing, Result-oriented Product-Service Systems, Life Cycle Inventory Study, System Dynamics Modeling

Statement of Contribution

This thesis was a collaborative effort between Nanond Nopparat and Babak Kianian. The topic of additive manufacturing was initially conceived of by Nopparat based on his interest in these technologies, his background in materials engineering and his enthusiasm for scale modeling. The interest in AM was also shared by Kianian who was invited to join the thesis team. Babak Kianian has a background in mechanical engineering (Solid Design). Both members put their best effort by contributing their abilities and personal skills to the various components and stages of the thesis. The responsibilities and tasks are distributed as follows:

Research design – the development of goals, conceptualization, overall development of questions and methods were shared by both members.

Implementation methods – both members participated in the experiments used in this thesis. Nopparat was responsible for the design of experiment. Kianian supported the verification of the result.

Report writing duties – both members shared the responsibility for writing. Nopparat was responsible for the final editing of the writing.

Presentation of results – the responsibility of the presentation slides preparation and the contents were shared by both members.

Other duties–Nopparat: Overall project manager and main contact person for Click2detail, 3Delivered, Inc. and Winner Hobby Co. Ltd.

Kianian: Main contact person for TNS Netherlands and Shapeways, who both only participated in the initial phase of this thesis, meeting organizer and facilitator. Thesis process documentation, timeline record and moderator of the thesis webpage, *i-am-techshift.com.*

Karlskrona, Sweden, 2012

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Acknowledgements

The thesis team would like to express our gratitude to everyone who in one way or another made a contribution to the completion of this thesis.

A special thanks goes to Christopher Rodak of Click2detail and 3Delivered, Inc. who greatly contributed his time and effort to this thesis in the form of data and consultation. Rungdararat Pipattanarattanakorn of Winner Hobby Co., Ltd. also deserves a special thanks for the contribution of his time and information.

The team thanks the advisory team, Anthony W.Thompson and Massimo Panarotto, for their great support and feedback throughout the process. Their enthusiasm has been of great value to the thesis. Gratitude also goes to the following people who made direct contributions to this thesis: Berend Aanraad of TNS Netherlands;Tobias C. Larsson, PhD, MSPI program director;Sophie Hallstedt, PhD, head of the Department of Strategic Sustainable Development, BTH; and Mark Simmons.

Nannond Nopparat wishes to thank his family for their continuous support as well as his friends, Carolina Villamil, Sabine Mukaze, Gabriela Bossio, Isabella Wagner, Reed Evans, Saeky von Stuckrad and Teresa Walsh.

Babak Kianian would like to express his appreciation to his family, Dr. M.E Kianian, M. Amanpour and B. Kianian for their thought, love, support and advice during this project. He also wishes to thank also to his friends near and far, specially, Melinda Jolley and Emma Fancett.

Last but not least, the team would like to thank our shadow and opponent groups and the whole MSPI class of 2012 for their support in our journey.

Executive Summary

Introduction

This thesis is built around selected case companies, specifically relating to the application of additive manufacturing in the scale model kit industry. The benefit of the additive manufacturing as a cleaner manufacturing technology, as compared to other more traditional technologies, was investigated through the comparison of resource consumption. The resources selected for this study were raw materials and energy used in the manufacturing processes. The benefit of a result-oriented Product-Service Systems (PSS) approach in the additive manufacturing industry was also explored. Two research questions were set in this thesis.

Research Design

This thesis work uses a combination of qualitative and quantitative research approaches. The methods used to answer the research questions are based on a qualitative research approach. The representative case companies within the additive manufacturing industry were selected to provide quantitative data for analysis. Two research questions are identified in this thesis. The first research question explores the potential benefits of additive manufacturing technology in comparison to injection molding technique. The second research question investigates the application of the result-oriented PSS in the additive manufacturing industry.

Research Question 1: What is the difference in resource consumption between injection molding and additive manufacturing?

The question explores additive manufacturing as a means to enhance the efficiency of production according to Tukker and Tischner's proposed decoupling strategies. The focus is on additive manufacturing's potential to provide the same product functionalities with less production activity, based on the inherent differences of additive manufacturing and injection molding. While injection molding relies on a demand for a large amount of uniform products and is suitable for mass production, additive manufacturing offers smaller-batched, on-demand production.

Research Question 2: How does PSS affect the resource consumption of industries that use additive manufacturing technology?

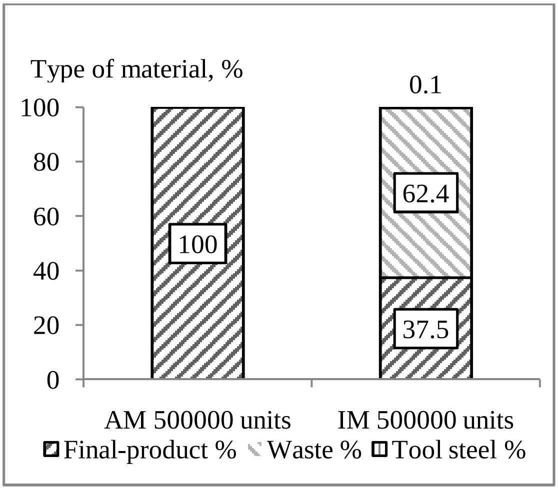
This question compared two approaches towards providing additive manufacturing capability to customers: one where the result-oriented PSS approach is used and one that uses the traditional ownership of production equipment.

Methods

Life cycle inventory study (LCI study) and System Dynamics (SD) modeling were the two main methods used in this thesis. LCI study was used to identify the resource consumption to answer the first research question, while SD modeling was used to address the second research question.

Results and Discussion

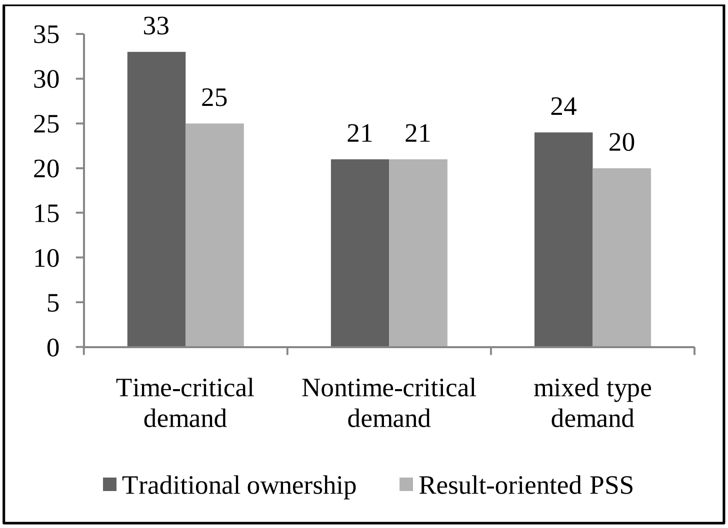
From the life cycle perspective, the result showed that additive manufacturingis more efficient than injection molding in terms of raw material consumption which additive manufacturing uses much lower quantity of raw materials. This is a result of the limitation of injection molding technology, inthat it requires the runner system for the molten polymers to flow into the molded cavity to form the parts. This runner system is solidified with the product but has to be removed later as waste. Additive manufacturing is able to produce the final product with much less wasted material.



The percent of materials in the products from AM and IM at the production volume of 500000 units.

In terms of energy consumption per unit produced, the additive manufacturing process uses much more energy during the production phase than injection molding at a higher production volume. However, additive manufacturing has advantages over injection molding at the low production volume.

Regarding the second research question on the benefits of the result-oriented PSS in the additive manufacturing industry, the results suggest that the result-oriented PSS supports the reduction in the amount ofresources used, i.e. the number of additive manufacturing devices. It showed that fewer resources could be used to supply the same or even more value to the customer. From a sustainability standpoint it is preferable if there is an alternative to provide the same value to a customer with lower resource input. This alternative could be deemed more sustainable, again with the qualification that the system is using the same substances and energy types. In the case of using a result-oriented PSS approach to provide fabrication services to multiple companies, the same amount of demand was shown to be answered with equal or less resources consumed, i.e. fewer number of AM devices, in this discussion.



The optimized minimum number of additive manufacturing devices required for each scenario.

Conclusion

The study found that additive manufacturing is more efficient in the way that materials used, as a higher proportion of materials ending up in the final product. Injection molding, on the other hand, wastes a significant proportion of the raw material in order to create components that are not part of the final product. If the same or similar raw materials are used in both manufacturing methods, additive manufacturing clearly holds the advantage.

In terms of energy consumption, additive manufacturing only has an advantage in this area when working with a very low production volume. This energy-based cross-over production volume varies with the choice of raw materials and the product's geometry. However, the analysis of the energy composition shows that most of the energy used in additive manufacturing is to create the final product, while injection molding only uses a fraction of the total energy to produce the final product.

The on-demand production capability of additive manufacturing offers the possibility to reduce the surplus production of goods. For a product with an uncertain amount of customer demand and a product where up-front investment is not affordable, additive manufacturing has a lot of benefits over injection molding by allowing the investor to actually only invest in the amount of product that is needed by the customers.

Applying the result-oriented PSS approach in the additive manufacturing industry reduced the required amount of equipment manufactured, which contributes to a reduction in energy and materials required, i.e. resource consumption, though it does not achieve the full benefits of decoupling strategies.

This thesis suggests that the result-oriented PSS, in general, achieved intensification in the use of the product, except in the case where the intensity was already near its maximum. This was largely due to the result-oriented PSS having flexibility to reallocate its function to where it is needed most. The reduced number of devices required contributes to a reduction in energy and materials required, i.e. resource consumption, though it does not achieve the decoupling of economical growth from the consumption of natural resources.

Glossary

3D printing – is fabrication of objects through the deposition of a material using a print head, nozzle, or another printer technology (ASTM 2010).

Additive manufacturing – is a 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 2010).

Cavity insert – is a circular or rectangular piece of alloy tool steel that carries the form of the molding in it (Jones 2008).

Computer-Aided Manufacturing (CAD) – is typically referred to systems that use surface data to drive CNC machines, such as digitally-driven mills and lathes, to produce parts, molds, and dies (ASTM 2010).

Computer Numerical Control (CNC) – is computerized control of machines for manufacturing (ASTM 2010)

Complex system – is a system that is constituted of a relatively large number of parts that interact in complex ways to produce behavior that is sometimes counterintuitive and unpredictable (Robert et al. 2010).

Dematerialization – is using less of a substance to produce the same goods and services, related to the concept of substitution (Robert et al. 2010).

Forecasting – is an approach used to project past and current trends and situations in order to predict the future (Robert et al. 2010).

Formative manufacturing – is the use of a tool to produce a part in processes such as injection molding, die casting, forging, etc. (Hague, R. 2004).

Industrial system – is an AM system used by industry for production, usually with a per unit price over $5000 (Wohlers 2011).

Injection molding – is a shaping process in which thermoplastic material is fed into a heated barrel, mixed, and forced into a mold cavity where it cools and hardens to the configuration of the mold cavity (Todd et al. 1994).

Life cycle assessment (LCA) – is the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle (ISO 2006).

Life cycle inventory analysis (LCI) – is a phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle (ISO 2006).

Life cycle impact assessment (LCIA) – is a phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product (ISO 2006).

Life cycle inventory study (LCI study) – LCI studies are similar to LCA studies but exclude the LCIA phase (ISO 2006).

Personal system – is an AM system used by an individual user.Usuallythis type of equipment issmall in size (Wohlers 2011).

Product-Service System (PSS) – is an integrated product and service offering that delivers value in use (Hockerts and Weaver 2002)

Product-oriented PSS – is promoting/selling the product in a traditional manner, while including in the original act of sale-additional services such as after-sales service to guarantee functionality and durability of the product owned by the customer (Baines et al. 2007).

Rapid manufacturing – is the production of end-use parts from additive manufacturing systems (Hague 2004).

Rapid prototyping – is the additive manufacturing of a design, often iterative, for form, fit, or functional testing, or combination thereof (ASTM 2010).

Result-oriented PSS – is selling a result or capability instead of a product (Hockerts and Weaver 2002).

Socio-ecological system – is the combined system that is made up of the biosphere, human society, and their complex interactions (Robert et al. 2010).

Stereolithography (SL) – is aprocess used to produce parts from photopolymer materials in a liquid state using one or more lasers to selectively cure to a predetermined thickness and harden the material into shape layer upon layer (ASTM 2010).

Subtractive manufacturing – is making objects by removing of material (for example, milling, drilling, grinding, carving,etc.) from a bulk solid to leave a desired shape, as opposed to additive manufacturing (ASTM 2010).

Sustainable development – is the active transition from the current, globally unsustainable society towards a sustainable society. Once the transition to a sustainable society is complete, sustainable development also refers to further social development within that society (Robert et al. 2010).

Sustainable society – is a society that could continue to develop without eroding its fundamental life supporting systems, creating human well-being within ecological limits (Robert et al. 2010).

Sustainability challenges – is the combination of the systematic errors of societal design that are driving humans' unsustainable effects on the socio-ecological system, the serious obstacles to fixing those errors, and the opportunities for society if those obstacles are overcome (Robert et al. 2010).

Sustainability principles (SPs) – are the four basic principles for society in the biosphere, underpinned by scientific laws and knowledge (Robert et al. 2010).

Use-oriented PSS – is selling the use or availability of a product that is not owned by the customer e.g. leasing and sharing (Hockerts and Weaver 2002).

Final product – is the product that requires no additional transformation prior to its use (ISO 1998).

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1 Introduction

This thesis is part of the Master in Sustainable Product-Service Systems Innovation (MSPI) program where the contribution of the Product-Service System (PSS) concept to sustainable development is explored.In this work, the main focus is on the potential benefits of implementing PSS in an emerging group of technologies known as additive manufacturing. The benefit of the additive manufacturing as a cleaner manufacturing technology, as compared to other more traditional technologies, is investigated through the comparison of resource consumption. The resources selected for this study are raw materials and energy used in the manufacturing processes. Even though it had been gaining wider use, the technology was still in its infancy. It is believed that by gaining early understanding of the impact of additive manufacturing technology, it would help guiding its future implementation and, in a way, fosters the sustainable development.

1.1 Additive manufacturing

Additive manufacturing (AM) is a relatively new manufacturing method that first came into use in late 1980's. In general, it forms 3D physical objects by solidifying the raw material layer upon layer. Depending on technologies, the solidification mechanism ranges from spraying of liquid chemical binder, to exposure of the material to various light sources, to electron beam bombardment. The materials used are also very diverse, including various types of polymers, metal and ceramics materials, providing they are in power or liquid form, and again depend on the technologies being used. Originally, due to its limited capacity and low resolution, the method had beenused for prototyping and model making, thus known as rapid prototype. It has since been gradually developed towards providing end-usepartsor direct part production, referred to as rapid manufacturing (Tuck et al. 2008).

AM advantages and applications

As of 2012, thanks to its various geometric possibilities AM has been adopted in many applications, including hi-end aerospace, sports equipment, andhighly personalized medical applications. One example of an application in the field of aerospace is the LaserCursing® from Concept-Laser. This application has been used successfully to create various aircraft components, including bionic brackets for commercial passenger aircraft and a component for an oxygen supply system for Eurofighter Typhoon fighter aircraft (Concept-laser 2011). Another example of application was in the area of art, Dr. Lionel Theodore Dean of FutureFactories, in cooperation with De Montfort University Design School, had demonstrated the capability of AM to create aesthetical design and decorative artifacts (Dean 2011).

Related works on AM

Much of academic research on AM has been done on the development of its technological aspects, mainly to improve the resolution and output rate. Research has also been conducted on energy consumption of AM technologies, which can be translated into cost and environmental impact and that will be the focus of this thesis. An early effort to study energy consumption of AM was the work of Luo et al. (1999) whose study showed the energy consumption measurement results from 3 main types of AM technology, including stereolithography (SL), laser sintering (LS), and fused deposit modeling (FDM). Other researches focused on the comparison between AM and other manufacturing techniques. One of them is a comparative study was done between AM and injection molding (IM) technology. The result showed that AM had an advantage in terms of energy consumption over IM, considering small production volume. The point where both technologies consume the same amount of energy, known as energy-based cross-over production volume, was found to range from a few hundred to thousands, depending on part size and geometry (Telenkoand Seepersad2011). In terms of AM production cost, at first it was assumed that AM would maintain a uniform cost distribution regardless of its production volume. The economic cross-over volume between AM and IM, the point where both technologies has equal cost per unit produced, was estimated at 14000 units (Hopkinson and Dickens 2003). Later Ruffo et al. (2006) adopted the full costing concept, the average cost per part of AM has increased, and the cross-over point dropped to around 9000 units. Another study by the same author explored the unique ability of AM to produce mixed products within the same manufacturing batch. This study showed that, by combining different parts, some overheadcost can be reduced and result in overall cost reduction (Ruffo and Hague 2007). Apart from benefits gained directly from different manufacturing method, the possibilities of on-demand production to indirectly reduce up-frontinvestment in materials and storage of spare parts had been investigated by Directspare, an EU-sponsored project under Seventh Framework Program (CORDIS 2009). The project is interesting in that it explores the possibility of AM technology to provide spare parts to the existing products, instead of producing the entirely new products. It shows that AM might be able to prolong the life of old product without the need to maintain a large quantity of spare parts and the manufacturing equipment involved.

Disadvantages of AM

AM is not without weakness. As has been pointed out earlier, AM only maintains competitive edges with traditional production method, like IM, at low production volume. At higher production volumes, the cost and energy consumption of AM per unit produced becomes much higher, up to 100 times in some cases (Wohlers 2011). In contrast, the energy consumption of the traditional methods like injection molding, even when including the energy used in transportation across the globe, is diluted among the huge production volume. In case of some aerospace applications, the environmental gain comes from the fuel saving due to weight reduction during the long use phase. The environmental benefit and cost savings thus outweighs the high consumption in the production phase. Unfortunately, the same cannot be applied to a similar part in an automobile which, with its life span of less than 10 years, will not be able to recover what the energy and cost used to produce it (ATKIN 2011).

1.2 Sustainability challenges

Based on a scientific conclusion that current society is on an unsustainable course (Steffen et al. 2004), in order for society to continue its prosperity in the future, it needs to overcome socio-ecological problems to reach the state of being a socially and ecologically sustainable society. The path to this goal is called sustainable development and the obstacles represented by the socio-ecological problems are sustainability challenges (Robert et al. 2010).

Sustainability and sustainable development have many different definitions from various perspectives. In this work, the Framework for Strategic Sustainable Development's definition of sustainability has been used to clarify the concept of sustainability. According to the framework, there are four scientific principles (conditions) that lead to sustainable society stating: in a sustainable society, nature is not subject to systematically increasing:

1) Concentration of substances extracted from the Earth's crust,

2) Concentrations of substance produced by society,

3) Degradation by physical means, and, in that society,

4) People are not subject to conditions that systematically undermine their capacity to meet their needs (Broman et al. 2000) (Holmberg 1995) (Holmberg and Robert 2000) (Ny et al. 2006).

To illustrate the socio-ecological problems the society is facing, the funnel metaphor is used as shown in figure 1.1.

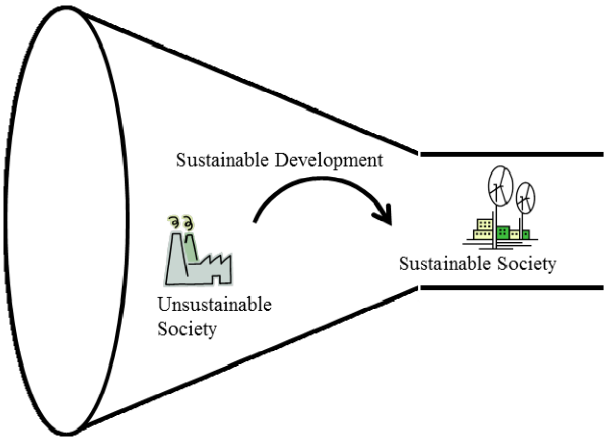


Figure 1.1.The Sustainable Development and the Funnel Metaphor (Robert et al. 2010).

Here the wall of the funnel represents the socio-ecological boundary confining society. As the pressure on the environment increases through increasing human population and increasing affluence of that population, the options for society decrease. The unsustainable development path of society will eventually exceed its limitations. In this context, any organization within the society faces the same limitations. An organization will find itself dealing with restrictions, including the increasing costs of resource, stricter legislation, loss of reputation, and failure to foresee the forthcoming demand on the market (Robert et al. 2010). On the other hand, an organization that moves towards creating solutions, will gain a competitive edge over its unsustainable competitors in a variety of ways. These are easier hiring of the best talent, higher retention of the top talent, increased employee productivity, reduced expenses for manufacturing, reduced expenses at commercial sites, increased revenue/market share, and easier financing, as has been pointed out in seven returns for business (Willard 2002).

1.3 Product-Service System

Product-Service Systems (PSS) have been introduced as a means to deliver value to the customer through an integrated product and service offering (Baines et al. 2007). It is a value proposition that consists of a tangible product component and an intangible service component, combined to fulfill final customer needs, and included in the network of infrastructure and the governing structure (Tukker and Tischner 2006). PSS can be classified in various ways, but the most common classification divides it into 3 main categories, including product-oriented PSS, use-oriented PSS, and result-oriented PSS (Baines et al. 2007) (Hockerts and Weaver2002). First, the product-oriented PSS is the traditional sale of product model that may include some after-sale services. With the use-oriented PSS, the producers maintain the ownership of the product, and sell the use, function or availability of that product. Finally, with the result-oriented PSS, the company sells only the capability or result that the customer wants (Baines et al. 2007). It should be noted that, while the customer focuses on the accessibility to the use of certain product in the use-oriented PSS, the user focuses more toward the result, regardless of the method, in result-oriented PSS.

In some early definitions of PSS, the environmental benefits were not included. For example, Goedkoop et al. (1999) focused on the idea that the mixed products and services are marketable. Mont (2000) added a description to PSS as a possible new strategy to answer sustainability challenges and solving environmental problems in addition to its aim to the fulfillment of customers' needs. While PSS by itself does not bring about sustainability, it does provide opportunity to reduce environmental impact by delivering the same value to customers at a reduced materials input (Baines et al. 2007). In a work of Tukker and Tischner (2006), it was proposed that PSS could be beneficial to the environment and the sustainable development. The development of human society and its economical growth were tied with the consumption and destruction of the natural resources. Since the natural resources have its limits, this development could not continue sustainably. PSS was proposed as a tool for decoupling of economic growth from the increase of pressure on the environment, from both the consumption of raw materials and the emission of pollution output, can be achieved with the following decoupling strategies (Tukker and Tischner 2006):

1. Enhancing the impact efficiency of production.

2. Enhancing the product efficiency of production.

3. Enhancing the intensity of use of product.

4. Reducing the product composition of expenditure.

5. Enhancing quality of life per euro spent.

It depends on the change in either the production system or the consumption patternin order for these strategies to be successful. The degree of change, marginal or radical, also affects the success of the decoupling (Tukker and Tischner 2006).

1.4 AM and PSS in sustainable development

As manufacturing technologies, it is believed that AM is having an increasing role in many industries. This view was supported by a continuously growing number of AM users and the number of AM systems sold (Wohlers 2011). From the strategic sustainability standpoint, the introduction of these manufacturing technologies raises the question of how they could contribute to sustainable development, in comparison to the existing technologies. This thesis aims to answer this question. By quantifying the input of raw materials and energyresources, it is expected that a comparative view of the manufacturing technologies could show their contribution to the sustainable development.

This thesis also investigates potential benefits of a result-oriented PSS approach for a service provider in the additive manufacturing industry. This is related to the work done by Wangphanich (2011), which showed how a result-oriented PSS intensified the use of washing machines. The result was a reduction in the overall number of washing machines required to provide service to the same number of customers due to the higher intensity of machine use. Wangphanich also demonstrated additional benefits from faster turnover of the machines, meaning that newer, higher performing and more environmentally friendly models could replace the older washing machines sooner. This result complied with Tukker and Tischner's proposed decoupling strategy of enhancing the intensity of use of products (Tukker and Tischner 2006), and the further clarification made by Thompson et al. (2010) that the alternative with less material and energy flow is the more "sustainable" one only when the types of materials and energy used are the same. To clarify, "using less is more sustainable" is only true if the substances and energy types used in the two systems are the same. If one system has a toxic substance, but had less material or energy use, then a statement about which is "more sustainable" would have to be considered in more depth to make any judgment about it. Therefore, the result-oriented PSS had potential to be a more sustainable solution than, for example, the traditional single product per owner approach. Based on this finding, this thesis sets out to explore if similar benefits could be realized in a different product category, i.e. the AM industry.

2 Research design

This thesis work uses a combination of qualitative and quantitative research approaches.The initial approach to the formulation of research questions follows the qualitative research design guideline, suggested by Maxwell (2005). The guideline comprises the following key aspects:

1. Goals: Why are you doing this study?
2. Conceptual framework: What do you think is going on?
3. Research questions: What specifically do you want to understand?
4. Methods: What will you actually do in conducting this study?
5. Validity: How might you be wrong in conclusions and results?

The results of the initial study are two selected areas of interest to be explored in this research. One is in the area related to benefits of AM in comparison to traditional manufacturing methods and the other is in the area of PSS application in the AM industry. A research question is proposed for both of these areas. The methods used to answers the research questions are based on the qualitative research approach. The representative case companies within AM industry are selected to provide quantitative data for analysis.

2.1 Research questions

Two separated research questions are proposed in this thesis. The first research question explores the potential benefits of AM technology in comparison to injection molding (IM) technique. The second research question investigates the application of the result-oriented PSS in the AM industry. Each question is presented with its hypothesis.

2.1.1 Research question 1

Regarding the benefits of AM in comparison to other manufacturing method, most works have agreed that AM is both relatively energy intensive and economically expensive at high production volume (Telenko and Seepersad 2011) (Hopkinson et al. 2003) (Ruffo et al. 2006) (Ruffo and Hague2007). At lower production volume, AM still holds advantages due to its lower up-front investment, especially in the case with IM which requires a large investment in tooling (Telenkoand and Seepersad 2011). Depending on what factors are taken into consideration, a comparative study of energy consumption of SLS and IM has shown that the energy-based cross-over volume can be as low as 50 units of 130 mm-sized product when compared against IM with recycled steel mold. The energy-based cross-over volume indicates the production volume at which both manufacturing method being compared has equal energy consumption per unit produced. In this way, one manufacturing method has lower energy consumption per unit produced than the other at lower production volume. After the production volume increases over the cross-over point, the energy consumption per unit produced of the two method reverses. This cross-over volume rose to around 300 units if compared to IM that used either virgin steel mold or recycled aluminum mold (Telenkoand and Seepersad 2011). When part size was reduced to 45 mm, the energy-based cross-over production volume increased to 1500 to 3200, compared to IM with virgin steel mold and 20% recycled aluminum mold respectively. On the cost comparison side, the economic cross-over volume varied greatly according to factors taken into consideration. An AM manufactured product of 35 mm size is estimated to have the cross-over volume of 14000 units against IM (Hopkinson et al. 2003). It dropped to 9000 units when the operation overhead cost of AM was considered (Ruffo et al. 2006).

This thesis attempts to compare AM and IM, considering the ability of AM to reduce waste in the production process and inventory. IM is selected as a representative of traditional manufacturing methods. This leads to the first research question.

What is the difference in resource consumption between injection molding and additive manufacturing?

The question explores AM as a means to enhance the efficiency of production according to Tukker and Tischner's proposed decoupling strategies (Tukker and Tischner 2006). The focus is on the AM's potential to provide same product functionalities with less production activities, based on the inherent differences of AM and IM. While IM relies on a large amount of uniform products and is suitable for mass production, AM offers smaller-batched on-demand production. The seemingly low cost per unit of IM is made possible by its high production volume, which dilutes the cost along the huge production quantity. However, it has a high up-front investment cost in form of expensive tooling, meaning that a low production volume is prohibitively expensive. The large-batch production also results in a large amount of products being stocked up in advance, waiting for distribution. Part of this stock up is a result of the attempt to foresee the customer needs in advance, in order to be able to respond quickly. The resulting build-up of inventory stock can be explained by the bullwhip phenomenon. In this phenomenon, every time a supply agent attempts to predict customer demand to make an order for its suppliers, some degree of variability is added to the demand. When agents further up the supply chain try to predict the demand order of the agent further down the supply chain, even more degrees of variability occur (Lee et al. 1997). The result is higher stock built-up than what is actually in demand. In this excess stock, there is an amount of energy that could otherwise have been used for other purposes and there are raw materials that could have been spared. Both energy and materials represent the unnecessary environmental impact and the loss of investment. In contrast, AM operates at a lower production rate but is relatively flexible in terms of production batch size and can combine different products in one batch. This ability of AM to manufacture a combination of various products at the same time has been studied and found to increase the cost benefit for AM in comparison to IM (Ruffo and Hague 2007)**.** This leads to the hypothesis that AM will have a production volume that is closer to actual market demand, a lower amount of inventory and waste that fit well with the concept of lean manufacturing.

2.1.2 Research question 2

In the work of Wangphanich (2011), a case of result-oriented PSS in a washing machine distribution model was found to be environmentally beneficial through the intensification of use that reduce the total demand in number of washing machine. Based on this work, this thesis attempts to study the potential benefits of similar PSS application in the industries that use AM technologies in the second research question.

How does PSS affect the resource consumption of industries that use additive manufacturing technology?

This question compared two approaches towards providing additive manufacturing capability to customers. This requires two primary functions. The service unit (SU) provides the first necessary function: converting a customer's ideas for a physical artifact into a CAD drawing that can be produced by the AM devices. The manufacturing unit (MU) provides the second primary function: receiving the CAD drawing and then produces that actual physical artifact by fabricating it with the AM devices.

The type of AM device used by manufacturing companies is not a standalone piece of equipment. Usually it includes various supporting units, e.g. a post processing unit. Thus a set of equipment is termed an AM system. In this thesis, the term 'AM device' is used to describe an AM system.

The first approach (Figure 2.1) was the traditional ownership of production equipment. In this case, the company comprised a service unit that dealt with customer demand and a manufacturing unit that produces the artifacts in response to that demand. This implies that the company is responsible for its own AM devices.

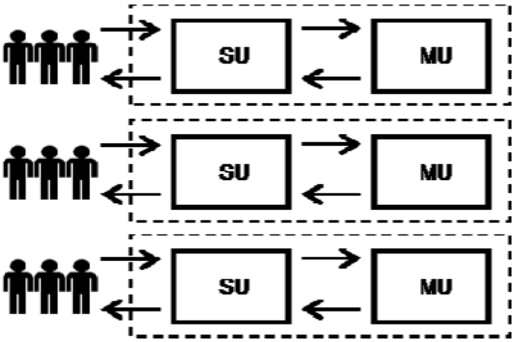


Figure 2.1.In a traditional ownership approach, the manufacturing company functions as both Service Unit (SU) and Manufacturing Unit (MU).

The second approach (Figure 2.2) was based on a result-oriented PSS. In this case, the manufacturing unit was taken out of the company's boundary, and placed in the boundary of a third party agent. The agent's primary function mostly concerned the function of a MU i.e. the fabrication of physical artifact using an AM device. In this paper, the agent is termed fabricator. In effect, a manufacturing companywas split into two to distinguish the service unit from the manufacturing unit.

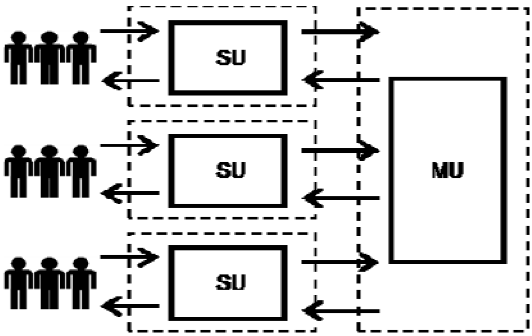


Figure 2.2. In a result-oriented PSS approach, the function of the Manufacturing Unit (MU) is provided by fabricator. The Service Unit (SU) remains within the company (manufacturer).

The proposed result-oriented PSS approach hassome similarities with ‘product pooling’ where the manufacturers could be organized as in Figure 1 and share their production capacity with the other manufacturers when one manufacturer has surplus demand and another manufacturer has available capacity. However, the main difference in the second approach is that the manufacturing unit is entirely the responsibility of the fabricator in the result-oriented PSS, while it is still under the manufacturers’ responsibility in product pooling.

2.2 The case companies

This thesis received cooperation from3Delivered, Inc., and Click2detail. 3Delivered, Inc. is an AM service provider who offers manufacturing capability using AM technologies. Click2detail is one of the customers of 3Delivered, Inc. Its main product is scale model kits. While Click2detail interacts with their end-customers through their website, providing both pre-designed products and design consultancy for customers seeking to develop new products, they rely on service from 3Delivered, Inc. for production capability and final product delivery. Both companies expressed much interest in the topic and were consequently selected as partner companies for this thesis.

Since this thesis is also aiming at the comparison between AM and IM in the regard of their ability to meet actual consumption of the final product, the consumption data of the scale model kit is obtained under cooperation from the company, Winner Hobby Co. Ltd., which is the main distributor of scale model products in Thailand.

This cooperation resulted in the focusing on the use of AM technologies in scale model kit manufacturing. However, it is expected that the findings in this thesis are also applicable to the AM industry as a whole. This would mean that other companies and academia related to the AM industry could benefit from this work. The scope and limitation of this thesis are thus set based on these case companies.

2.3 Scope and limitation

The scope of this thesis is based on the quantitative data provided by 3Delivered, Inc., and Click2detail. 3Delivered, Inc., with Click2detail provides product dimensional data and 3Delivered, Inc. provides production performance and technical data. It focuses on the AM service as used in scale model kit industry applications. The product and its physical characteristics described in this study is a scale model kit. Both companies are based in the United States of America; therefore the data applicable to the region is used whenever geographical aspect is involved.

3 Method

In this thesis two main methods are used in an attempt to answer the research questions. One methodis life cycle inventory study, which is asub-type of environmental management techniques called life cycle assessment (LCA). It is used to understand the resource consumption and its environmental impact from a life cycle perspective of a product, within a defined boundary (ISO 2006). Another method used, system dynamics (SD) modeling, is a modeling technique for understanding the behavior of complex systems that change over time.

3.1 Life cycle inventory study (LCI study)

The life cycle inventory (LCI) study is used in an attempt to quantify and compare the resource consumption of AM and IM in the first research question. This method follows ISO14040 Environmental management — Life cycle assessment — principles and framework (ISO 2006). The life cycle assessment (LCA) is an environmental management technique used to identify the environmental performance of products (ISO 2006). An important phase of LCA is the life cycle impact analysis (LCIA), which provides additional information regarding the environmental significance of the products (ISO 2006). LCI study differs from LCA in that it does not have the LCIA phase. Instead the interpretation is made directly from life cycle inventory (LCI). In an LCI study, there are three main phases: 1) the goal and scope definition phase, 2) the inventory analysis phase and 3) the interpretation phase. The primary results from the LCI study were expected to show resource consumption of AM and IM based on their technical characteristics. After this initial resource consumption data set is obtained, it was combined with estimated sale data of the final product obtained from the scale model kit distributor to create the second data set. The difference between the two data sets and its implication are discussed in chapter 6 of this thesis.

Within this chapter, the goal and scope definition phase, and the inventory analysis phase are presented in detail, while the result interpretation will be discussed in chapter 5.

3.1.1 Goal and scope definition of the LCI study

The main goal of the LCI study is the quantification and comparison of the resource consumption between AM and IM, as manufacturing methods for the scale model kit production. The resource consumption is defined as raw materials and energy input. The study aims to determine the efficiency of transforming raw materials and energy into the final product of AM and IM.

Functional unit

In this study, a final product of a selected representative scale model kit is used as functional unit. A final product of scale model kit includes those parts that constitutes the finished model kit but excludes the extra carrier materials e.g. runner system of injection molded product, as shown in figure 3.1.

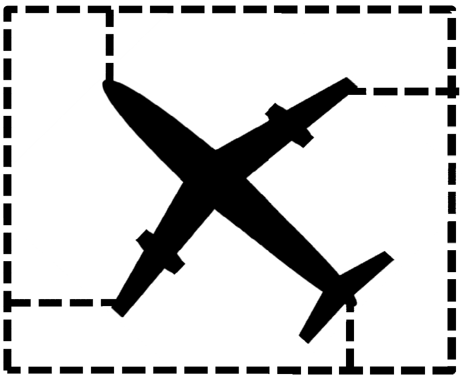


Figure 3.1. The illustration of an IM product, the final product is shown in the middle and the runner system is shown in dashes line.

The representative product selected for this study is a scale model kit of T-1A Jayhawk Air Force Trainer in 1:72 scales, a product of Click2detail, shown in figure 3.2. The product was selected for two reasons. First, there was enough technical data available from Click2detail to support the study. Secondly, the product is similar to many other common injection molded scale model kit products, which allow the conclusions to be applicable to them as well.

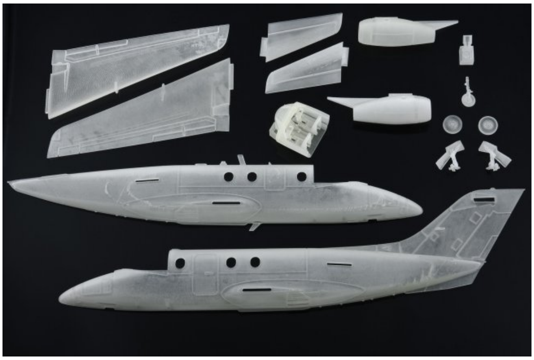


Figure 3.2. An example of AM final product, the T-1A Jayhawk Air Force Trainer in 1:72 scales (courtesy of Click2detail).

System boundary

The boundary of the LCI study includes the manufacturing and the distribution of components in the scale mode kit supply chain. The input into the system includes raw materials and energy used to produce the final product. The output is the final product and the waste produced. Due to the unavailability of data for energy consumption of the photopolymer and the production of support material in AM, the energy for the production of the raw materials is excluded from this study.

In the case of AM process, the energy input includes the specific energy consumption of the AM device. The material input is the photopolymer used to form the physical shape of the final product and the support material that is removed during the finishing process. This removed material is also defined as waste of AM process. The input and output materials of the AM process are shown in figure 3.3.

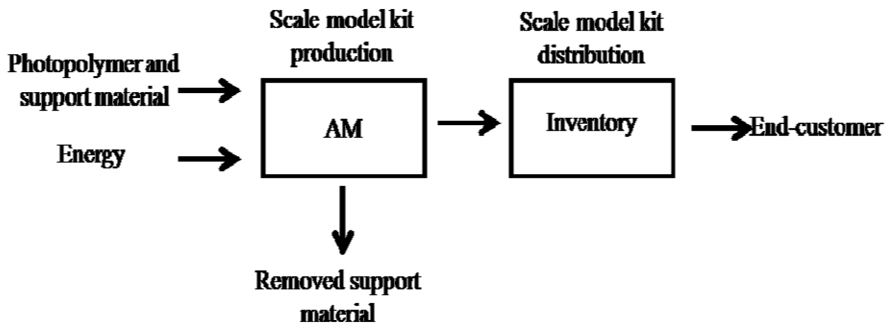


Figure 3.3. The input and output of materials and energy of the focused AM system.

For the IM process, in addition to the energy input from specific energy consumption of the IM machine, there is energy needed for the manufacturing of the injection molds and for manufacturing of the mold material. The injection-molded product usually includes excess material in form of a runner system that has to be removed. For scale model kit products, this runner system is delivered with the product and not removed until the end-customer is doing so. This excess material is defined as waste from the IM process. The IM process is shown in figure 3.4.

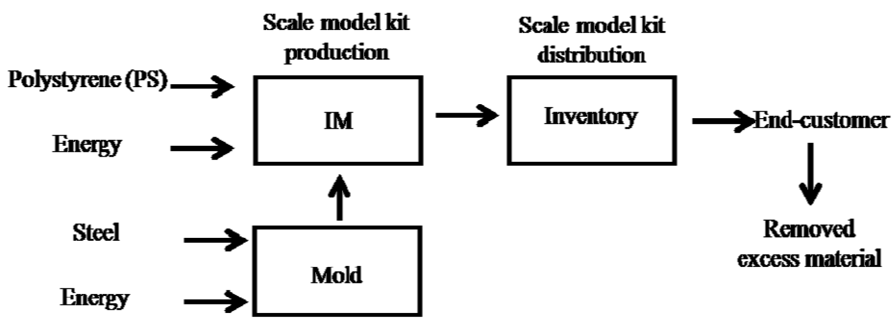


Figure 3.4. The input and output of materials and energy of the focused IM system.

Since the partner companies that provided data for this thesis only comprisean AM technology user and a scale model kit distributor, much of the up-stream data is notavailable and not included in the study. Specifically, this thesis excludes data on energy and materials that go into the manufacturing of AM devices and IM equipment, packaging material and transportation of scale model kit products, resources consumed in supporting activities and infrastructure.

During the use phase of scale model kit, no energy is consumed, nor does it release any measurable output. It does require some chemicals such as paint and glue during the use phase, but these are not in measurable quantities. Therefore this phase is excluded from the study. Although AM is speculated to be able to localize the manufacturing and reduce the distance of product shipment (Englert 2008), this study focuses only on the different in resource consumption from production process and excludes the transportation involved. The end of the life of the product is also excluded from the study.

Data quality requirement

Data for the type and quantity of materials used in each final product and waste for the AM process is obtained from Click2detail and 3Delivered, Inc. The data on energy consumption of the HD 3000 system being used by Click2detail is not available. Instead, a range of specific energy consumption data of stereolithography (SL) technology is estimated from a study by Luo et al. (1999).

For the IM process, the data for the mold production is calculated from the product dimensional data of the representative product from Click2detail and the dimensional data for mold is calculated based on the mold design guideline by Peter Jones (2008). The energy consumed during the production of the mold is obtained from a study by Dahmus and Gutowski (2004). The energy consumption of the IM process is obtained from a study by Thiriez and Gutowski (2006). The energy consumption of the steel production is from Inventory of Carbon and Energy version 1.6a (Hammond and Jones 2008).

3.1.2 Life cycle inventory analysis (LCI)

During the life cycle inventory analysis stage all the input and output data for the whole life cycle, within the defined system boundaries, is collected and calculated.

Data used in this study has various sources, both direct and indirect, and is categorized as AM raw materials input, AM energy input, AM waste, IM raw materials input, IM energy input, IM molds input and IM waste.

AM data collection and calculation

AM raw material input per functional unit (i.e. one final product of the T-1 Jayhawk scale model kit) was determined to be35 g of VisiJet® SR 200 photopolymer. This material is a chemical mixture of triethylene glycol dimethacrylate ester and urethane acrylate polymer of unspecified type (3Dsystem 2012a).

AM energy input is taken from a study of Luoet al.(1999). The specific energy consumption data for SL technology is estimated to range between 20 to 40 kWh per 1kg of material built.

Since the AM process can produce the physical artifact with very small amount of excess material being the support structure, it is not taken into account for this study. Therefore, it is determined that the analyzed product does not produce any wasted material.

IM data collection and calculation

IM raw material input is calculated from data of the CAD file of the representative product from Click2detail. Assuming that the product does not require any dimensional changes, the volume of materials required was determined to be 80 cm^3, equal to 84g of polystyrene (PS) materials at PS density of 1.05 g/cm^3.

Data of the IM energy consumption is based on a study by Thiriez and Gutowski (2008). In this thesis, the specific energy consumption for a US-based all-electric injection molding system amounts to 1.86 kWh per 1 kg of material produced.

The energy and materials consumption for the mold production in the IM process is determined using the dimension of the representative product. The two-plate mold type is selected for the product in this study. A set of mold comprises many parts. The part that contains the cavity forms, i.e. the space where molten plastic is injected into to form the final part, is called cavity insert. This cavity insert is the interchangeable component of the mold and is determined to be the input from mold production for each product. The cavity insert for a set of two-plate mold of the selected product is calculated to have the minimum size of 20 cm x 20 cm x 3 cm. Since the mold plate has to be obtained in a premade size from the plate manufacturer, the closest plate dimension available from DME Co. is 25.09 cm x 30.17 cm x 3.49 cm (DME 2012). The steel type is AISI P20 nickel chrome alloy steel (Jones 2008), selected based on a SPI class 103 medium production mold (AMBA 2012). The volume of two plates of steel is 5290 cm^3. The volume of steel that has to be removed to produce the cavity insert is calculated to be 1262 cm^3. The energy required to produce the steel plates is 558 kWh (Hammond and Jones 2008) and the energy required to machine the steel into the cavity inserts is 21 kWh (Dahmus and Gutowski 2004). Thus, the total energy required for the injection mold is 579 kWh.

The last part is the IM waste calculation. The waste of the IM process is determined to be the PS material in the accompanying runner system. The amount of runner system required by the representative product is calculated by Click2detail. Each final product has a runner system made up of 1270 mm in length and 5 mm in diameter, or equal to 50 cm^3 of PS material.

3.2 System dynamics model

System Dynamics (SD) is a modeling technique for studying dynamic behavior of complex systems. A SD model is used in this thesis to reveal the difference in the number of AM devices required for the traditional ownership approach on one hand and the result-oriented PSS approach on the other. It is used to simulate the flow of customer’s demand at varied production capacity input.

3.2.1 Conditions for the SD model

Three demand scenarios areexplored in the SD model based on the characteristic of customers' demands.

1. Time-critical demand is characterized by urgency of the order. If a manufacturer cannot complete the order within one day, the order is cancelled.

2. Non-time-critical demand is of less urgency. Usually the customer can afford some waiting time. In this paper the satisfactory waiting time was modeled as completing the order within 7 days.

3. Mixed demand represents a more realistic scenario where different customers have different time demands, with the time-critical order having priority over its noncritical counterpart.

Three hypothetical manufacturers with their own sets of demands are chosen for each of the three scenarios. The simulations are run under the following assumptions:

1. The manufacturing is assumed to be on-demand production, meaning that the product is built only when an order is placed.

2. Each manufacturer is expected to have a demand of around 10000 units per year. This demand represents a random daily range between 0 and 54 units.

3. The AM device and the data referred to in this simulation are based on information for stereolithography (SL) technology used by 3Delivered, Inc. One device is assumed to be in operation for 20 hours per day, 365 days per year. The other 4 hours are allocated to nonproduction activities e.g. device maintenance.

4. The products from the AM devices are assumed to have an identical build time of 5 hours per unit. Therefore, an AM device has an output of 4 units per day.

5. The simulation is run to cover a period of 365 days i.e. one year.

The demand and production capacity are used as input data for the simulation. The output includes the optimal number of AM devices required, the intensity of equipment usage and the percentage of orders able to be fulfilled in the required time.

3.2.2 The simulation models

Three different SD models are constructed for this thesis. Each one is based on the characteristic of the customers' demands.

Time-critical demand model (TC model)

In the TC model, the simulation receives 2 variable input parameters. One is the randomized value for demand each day and the other is the number of AM devices. The third input parameter is the output per AM device which is set at constant being 4 units per day. The output of the simulation is the number of products made during the period of simulation, which is 365 days, and the number of cancelled products (products that could not have been produced due to lack of production capacity). In the TC model, products are cancelled if the quantity of an order exceeds the production capacity. Figure 3.5 shows the flow diagram of the TC model.

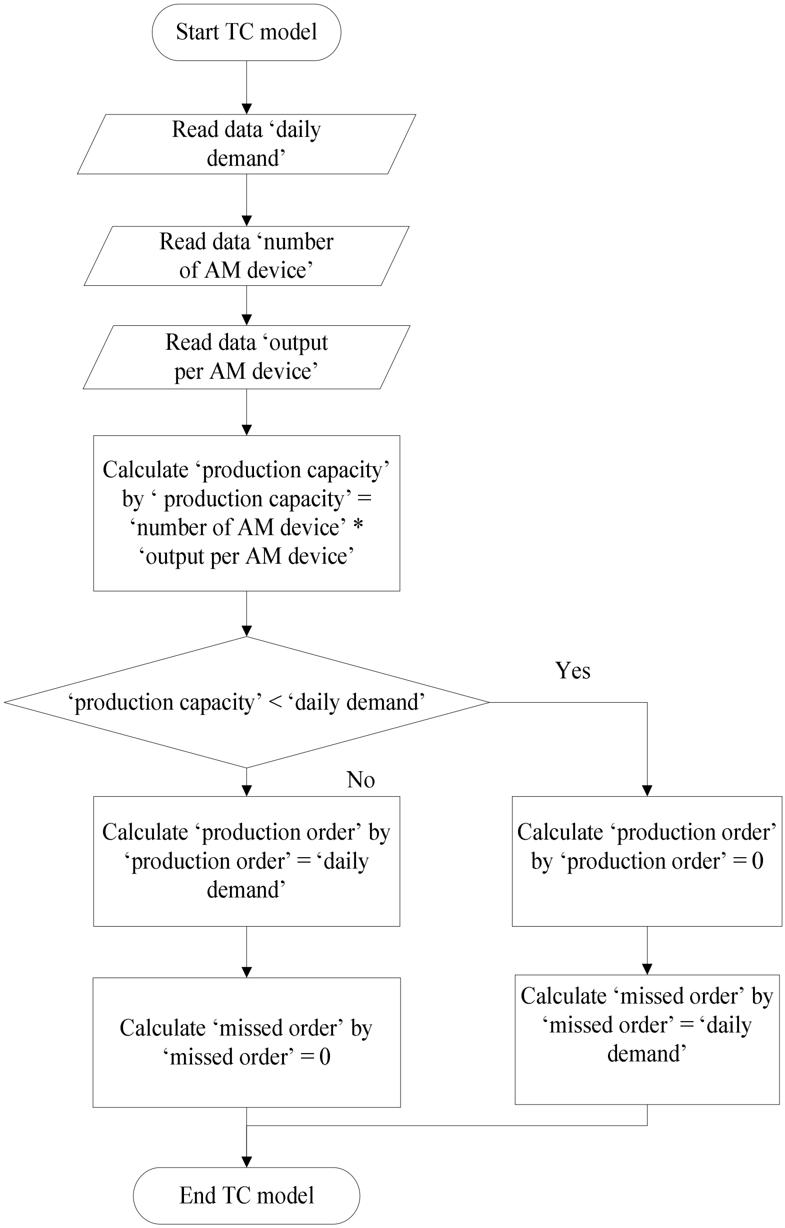


Figure 3.5. Flow diagram of the time-critical demand model.

Non-time-critical demand model (NC model)

The NC model simulates a different type of customer demand than the TC model. The non-time-critical demand can afford a 7-day waiting period after the order is placed. The input parameters are the same as for the TC model e.g. daily demand and number of AM devices. In addition, the NC model has a NC backlog module to simulate the surplus demand (see appendix A). The handling and calculation of the surplus demand for the NC backlog module is done in the support module (see appendix B). The daily surplus demand is placed in one of seven backlog categories, indicating how long the order has been delayed. The model gives priority to the order with the longest waiting period, after which the surplus production capacity is allocated to lower priority orders. This means that the order that has been waiting for 7 days has a higher priority and will be produced before an order with less waiting days. An order that still cannot be produced after 7 days of waiting time is counted in the over delay. The model yield represents the total of products made and the number of waiting days. Figure 3.6 shows the flow diagram of the NC model.

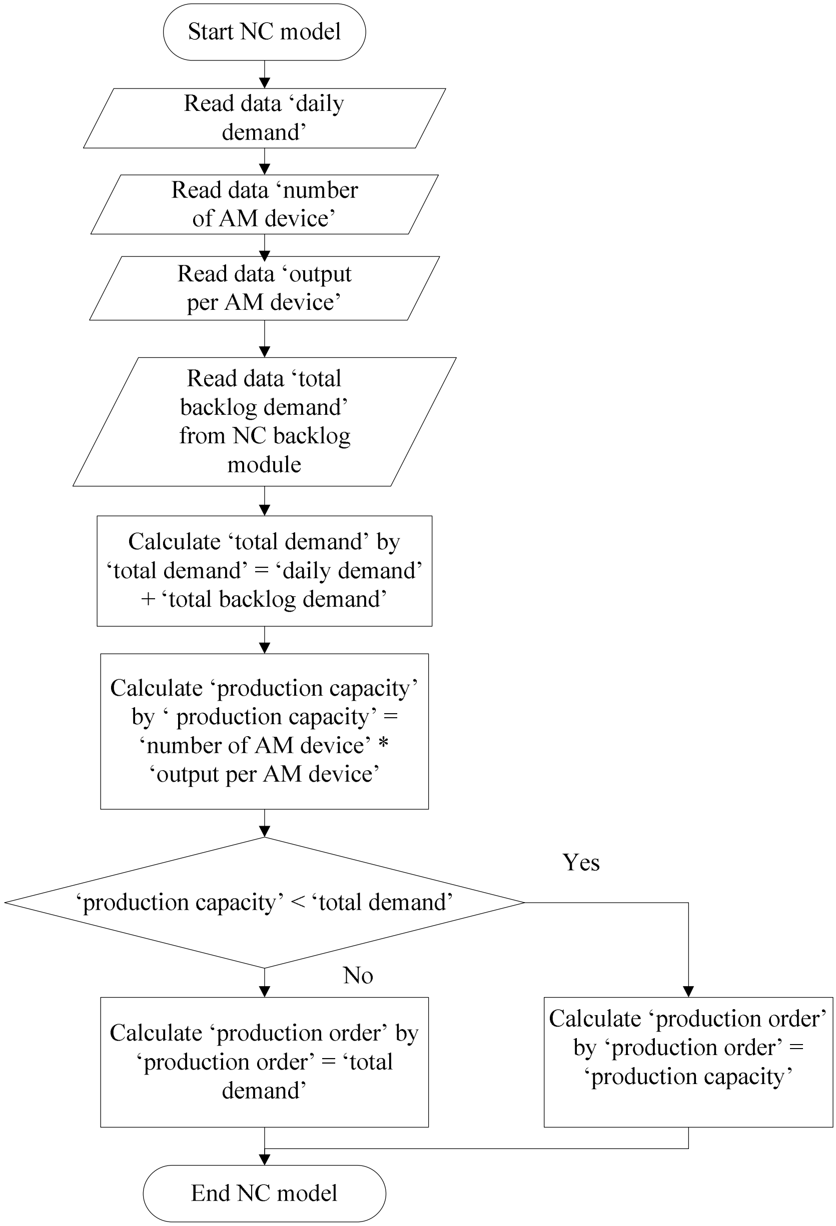


Figure 3.6. Flow diagram of the non-time-critical demand model.

Mixed demand model (MX model)

The MX model includes functions from both TC and NC models, including a backlog module and a support module. The input parameters are the daily demand and he number of AM devices. Part of the daily demand includes a time-critical demand and the rest is non-time-critical demand. The MX model gives the time-critical demand the highest priority for production, regardless of the waiting time for the non-time-critical demand. If the time-critical demand exceeds the production capacity, it is cancelled and the production capacity is allocated to its non-time-critical counterpart. Figure 3.7and 3.8 shows the flow diagram of the MX model.

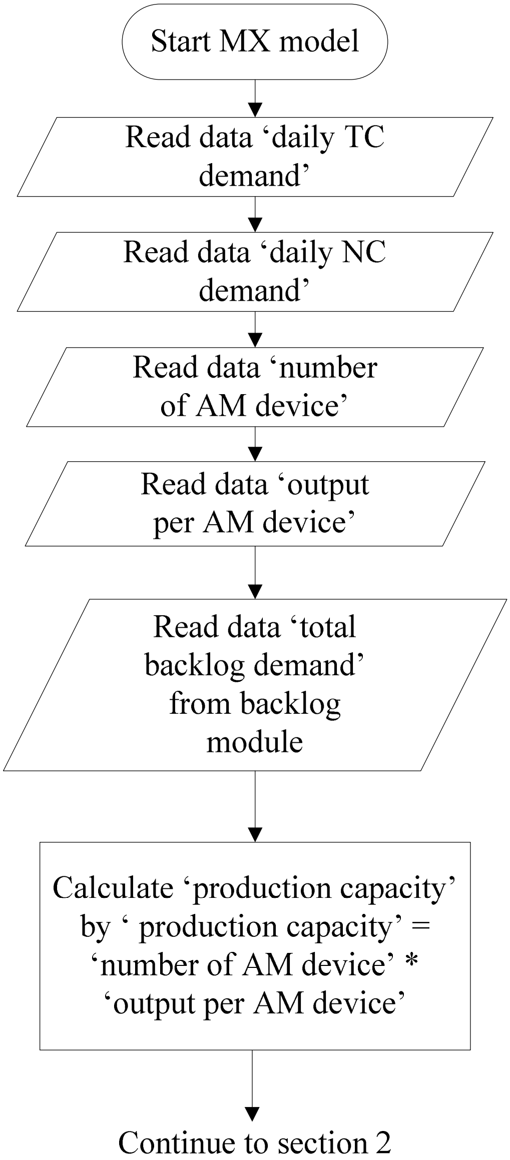


Figure 3.7. Flow diagram of the mixed demand model (section 1).

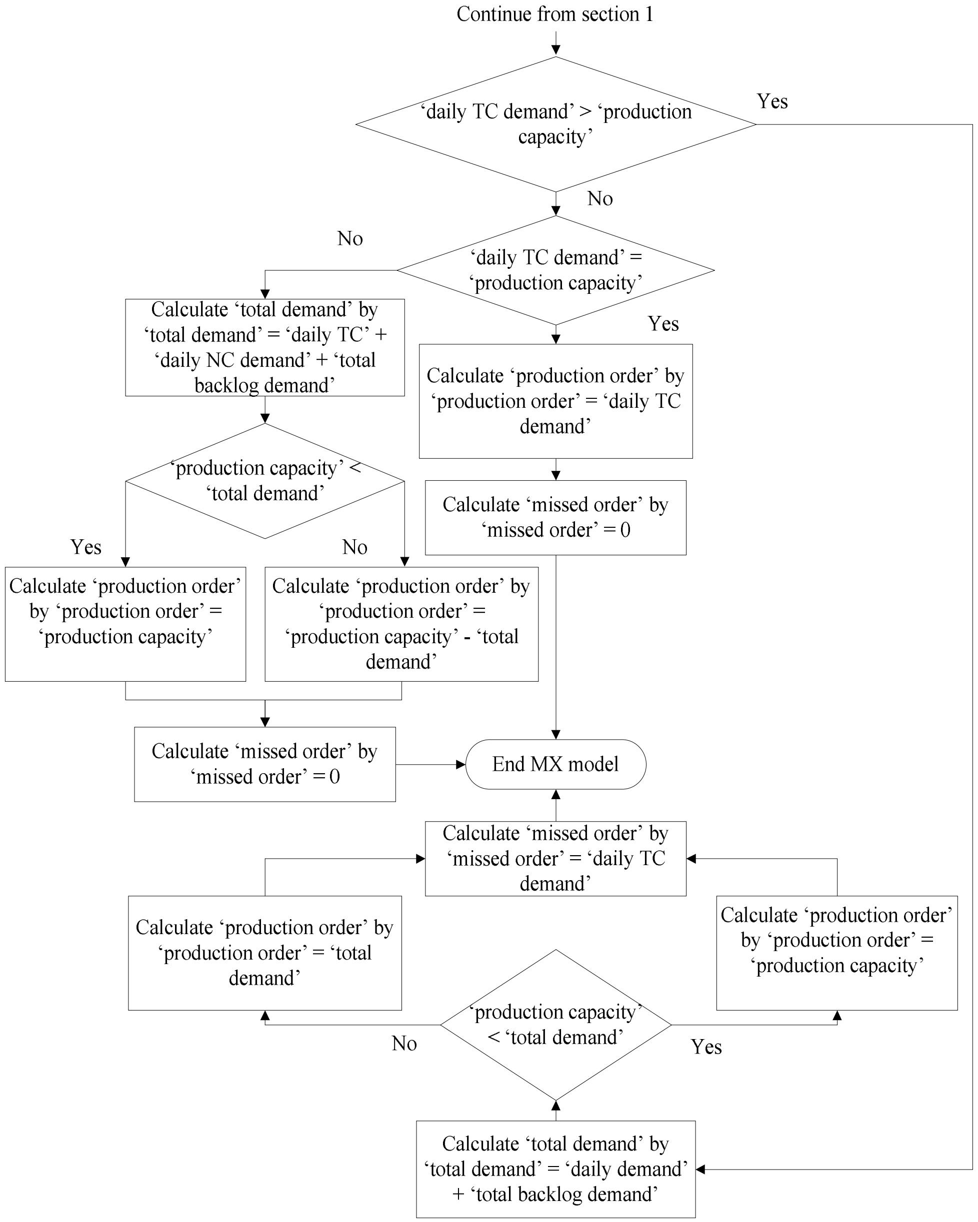


Figure 3.8. Flow diagram of the mixed demand model (section 2).

3.2.3 Model simulation and optimization

Two simulations are conducted with each of the SD models. One for the traditional ownership approach and one for the result-oriented PSS approach. In the traditional ownership approach, the simulation is repeated three times with three different sets of demand, representing three different manufacturers. In the result-oriented PSS scenario, all three sets of demands are simulated together to represent the three manufacturers receiving services from the fabricator.

Once the input parameters are fed into the SD model, the model is adjusted to yield the optimal output. The output is optimized to meet the following success criteria:

1. Cancellation of time-critical demand is less than 10%.

2. Non-time-critical demand is met within 7 days.

The controlling input for the model optimization is the production capacity, which is calculated from the number of AM devices. The result is the minimum number of AM devices required to meet the success criteria.

4 Theory

The theoretical background of this thesis is related to three main areas: 1) sustainability, 2) Product-Service Systems (PSS), and 3) innovation. The sustainability part provides the system level definition of how sustainability is defined and used in this thesis. The theory on PSS and innovation provides background for the two research questions. In addition, the Bullwhip effect phenomenon (and the challenge it causes to the mass-production technique) is briefly presented at the end of this chapter.

4.1 Sustainability

The definition of sustainability used in this thesis is based on the framework for strategic sustainable development (FSSD). The framework itself is based on a generic five-level framework for planning in complex systems (5LF), which is universally applicable and can be used to plan in any complex system (Waldron et al. 2008). The five levels of the framework and how FSSD is derived from it is presented in figure 4.1. The purpose of FSSD is to provide clarity and insight to plannning and decision-making towards a sustainable society (Waldron et al. 2008). In level 1 of the 5LF, the system is first defined and agreed upon. After that, the success of the system is defined in level 2. The approaches to the success of the system then become the strategic guidelines in level 3. Level 4 and 5 define the necessary actions and tools to support the strategic guidelines. The FSSD, the system is defined as the biosphere within which the human society is situated. The sustainably existence of the system is vital to the survival of human society, thus it is defined as the success or ‘sustainability’ of the system. In order to come to the conclusion of how to make the system survive, it first asks how the system can be destroyed. The system can be destroyed if one of the four system conditions is met, and by avoiding these four conditions the four sustainability principles that lead to sustainable society are conceived.

It states that: in a sustainable society, nature is not subject to systematically increasing:

1) Concentration of substances extracted from the Earth’s crust,

2) Concentrations of substance produced by society,

3) Degradation by physical means. And in that society,

4) People are not subject to conditions that systematically undermine their capacity to meet their needs (Broman et al. 2000) (Holmberg 1995) (Holmberg and Robert 2000) (Ny et al. 2006).

Level	**Generic 5-Level Framework for Planning in Complex Systems**	**Framework for Strategic Sustainable Development (FSSD)**
1. Systems	The system that is relevant to the goal	Society (within the biosphere)
2. Success	The definition of success	Compliance with sustainability principles
3. Strategic	The strategic guidelines used to select actions to move the system towards success	Backcasting Return on Investment Flexible Platform Moving toward success
4. Actions	Concrete actions that follow the strategic guidelines	….
5. Tools	Tools that support the process	….

Figure 4.1.Generic Five-level Framework and FSSD (Thompson 2010) (Waldron et al. 2008).

Another useful technique that allows planners to focus on the goal and its context is backcasting. Backcasting changes the perspective of time from one that exist the present to that of the desired future (Thompson 2010). When planning with the FSSD in which the success is the compliance with the sustainability principles, it is called ‘backcasting from sustainability principles’. It provides flexibility and appropriate allocation of resources to the movement toward a sustainable future (Holmberg and Robert 2000).

As a result, while this thesis attempts to identify the potential sustainability benefit of the AM technology and the organization that uses them, the term sustainability refers to the sustainability of global socio-ecological system in which the technology and the organization also belong. It does not refer to the sustainability of any specific technology or organization.

4.2 Product-Service Systems (PSS)

In the introduction chapter, the authors present the concept of PSS and the classification which categorizes PSS into three categories: 1) product-oriented PSS, 2) use-oriented PSS, and 3) result-oriented PSS. This classification is based on the work of Hockerts and Weaver (2002), in which the five options for servitization is proposed. In this section of theory chapter, more detailed information of each classification is presented.

The first category is the product-oriented PSS, which the ownership of the tangible product is transferred to the customer. It may also include additional after-sale services i.e. maintenance and support services. In the use-oriented PSS, the ownership of the tangible product remains with the service provider. The customer purchases only the function of the tangible product via modified distribution and payment system. The examples include product sharing and leasing. The last category is the result-oriented PSS, which tries to replace the tangible product with a service. An example in this category is the voicemail, which replaces the need for a personal answering machine (Hockerts and Weaver 2002). This classification is still broad and general. To give it more detail, Tukker (2004) further subdivided these three categories into eighth sub type. Although the term ‘service’ was used in Tukker’s work, and ‘PSS’ is used in Hockerts and Weaver’s work, they were used by both authors to classify the different types of PSS. In this thesis, it is determined that they are used interchangeably.

The category that is the focus of this thesis is the result-oriented PSS, also called the result-oriented service. There are three sub-categories proposed by Tukker (2004): 1) activity management/outsourcing, 2) pay per service unit, and 3) functional result. In the activity management/outsourcing, a part of an activity in a company is contracted to the third party. The company uses performance indicators to ensure the quality of the outsourced works. With the pay per service unit, the customer does not pay for the use of the product, but rather pay for the 'output' of the product according to the level of use. It included the pay-per-print formula used by copier manufacturers. Finally, the functional result is the category, which the client and the service provider agree upon the delivery of the result. The service provider has liberty to deliver the result without any restriction regarding the means of obtaining the result.

There is alsoPSS in industrial applications, called Industrial Product-Service Systems (IPSS) that has been proposed as a flexible solution that enables manufacturers to adapt to changing customers' demands (Meier et al. 2010). The flexibility and availability of production capacity given by an IPSS is significant since it can benefit from long-term relationships with customers (Richter et al. 2010). Customers also benefit from having the manufacturing taken care of by a service provider, e.g. they are able to concentrate on their core competency (Schweitzer and Aurich 2010). The total cost of ownership of production equipment is removed from the customer side (Richter et al. 2010).

This thesis considers the use of AM fabrication service as a form of outsourcing the manufacturing of products to the AM fabricator, which falls into the result-oriented PSS category.

4.3 Innovation

Innovation is a new product, service, process or idea that implies inventions, which is the creation of those idea, product, service and process, which is put into practice (Fagerberg et al. 2006). It is important to distinguish between innovation and invention, although they are closely related.

In the work of Fagerberg et al. (2006), the classification of innovation by Schumpeter is presented in five types: new products, new methods of production, new source of supply, exploitation of new markets, and new ways to organize business. Most attention is paid to the first two types, which are commonly called 'product innovation' and 'process innovation'. The former is the occurrence of a new or improved products and services, and the latter is improvement in the methods to produce those goods or services (Fagerberg et al. 2006). In addition, it is worth having a definition of the product and process within the context of innovation. A product is defined as a good or service that is offered to the customers, while a process is considered as a way of delivery or mode of production of a product (Barras 1986). Therefore, the product innovation is defined as a new good or services aiming to satisfy customers' needs and, in general, market demands. The process innovation is considered as new factors, parts or components, e.g. input of new materials, sources of energy, task specification, work and information mechanism and equipment, added to an organizational production and service operation in order to manufacture products, provide services and deliver to the customers (Ettlieand Reza 1992) (Knight1967) (Utterback and Abernathy 1975). In addition, more detailed definition of the product and process innovation are described as follows: the product innovation is mostly customer driven initially and focuses on the market demand, whereas the process innovation is primarily efficiency-driven and has an internal focus (Utterback and Abernathy1975).The implementation of product innovation requires that an organization integrates and understands customers' demands pattern, design and manufacturer of the product. The organization is required to apply a technology in order to improve the efficiency of the product improvement and commercialization (Tornatzky and Fleischer 1990).

Regarding the process innovation, Edquist et al. (2001) suggested dividing process innovation into two categories of thetechnological process innovationandthe organizational process innovation. The former addresses new types of machinery, whereas the latter relates to new ways of organizing work. Organizational process innovation is not only limited to the new ways of organizing the production (Fagerberg et al. 2006).

Additive manufacturing is a relatively new method of manufacturing and can be considered an innovative technology, relating to both product innovation and process innovation. Primarily, AM technology is classified as a process innovation as it provides an entirely new way of producing the physical artifacts, previously not able to be produced due to the limitations of other traditional manufacturing methods (Wohler 2011). In addition, because AM removes the limitation in terms of design and product's geometry, required for other manufacturing methods, the designers and customers are free to create new types of products with the different ways of thinking. In this way, AM is considered a potential catalyst for the product innovation as well.

4.4 Lean manufacturing and bullwhip effect

Lean manufacturing is a set of approaches, management philosophy and tools that focuses on the eliminationof waste in the process of providing a product or service to end customers. From a lean manufacturing point of view, the use of resources that end up not adding value to end customers' demands should be eliminated (Holweg 2006). Therefore, lean thinking focuses on theresources that become values, and the activities that consume time, materials, energy, man-power or space are considered waste of resource. There are seven types of waste according to lean approach with acronym TIM WOOD, which are transportation, inventory, motion, wait, over-processing, over-production and defect. The lean approach is mostly derived from the Toyota Production System (TPS), which has three categories of waste called Muda, Mura and Muri, while lean thinking focus mostly on the first type of waste (Holweg 2006) (Robinson 1990).

One cause of the waste in the production process is the mismatch between the actual customers' demands and the production volume. The distorted demand information in a supply chain includes but not limited to the excessive inventory, poor product forecasts, insufficient or excessive capacities, poor customer service, and high costs for corrections (Lee et al.1997).The term used to describe this phenomena is "Bullwhip effect."It is demand amplification that takes place when demands order variables are amplified along the value chain when it moves upstream along the supply chain (Lee et al.1997).

Studies have identified the major four causes of Bullwhip effect as follows; 1) demand forecast updating, 2) order batching, 3) price fluctuation, 4) rationing and storage gaming. These main causes influence and are related to the interaction of each element/part in supply chain and the related process with the infrastructure of the chain. Therefore, manufacturing companies could counteract the causes of the Bullwhip effect by first taking the initiative to innovate some steps to understand and modify the process and chain infrastructures and facilitate this understanding for decision makers and other influencers in value chain (Lee et al. 1997).

In addition, there are three main categories or initiative steps to avoid the Bullwhip effect. These are information sharing, channel alignment and operational efficiency. With information sharing, the demand order information is conveyed from one end of chain to the other more efficiently. Channel alignment helps to coordinate some factors like pricing, inventory planning, transportation and ownership between up and downstream more smoothly. Finally, operational efficiency facilitates activities such as reducing cost and lead time to improve performance (Lee et al. 1997).

One part of this thesis tries to identify the connection between the lean approach and AM's on-demand production capability. It is expected that AM technology will be able to reduce and counteract the consequences of the Bullwhip effect in the manufacturing process and the product value chain.

5 Results

5.1 Life cycle inventory study results

5.1.1 Initial results

The initial data set of the LCI study is based on technical characteristics of AM and IM. The final product uses 0.035 kg of photopolymer with AM, while 0.030 kg of PS is used in the case of IM. In terms of wasted materials, IM uses another 0.050 kg of PS for the runner system, while AM uses all of the material to produce just the final product without thewaste. IM also requires 41 kg of tool steel for the injection mold. However, how much mold material contributes to IM material consumption depends on the total volume of production. The type of mold selected for this study is class 103 medium production mold, made from AISI P20 tool steel. This type of mold is recommended for upto 500000 cycles. Figure 5.1 illustrates the materials composition per centage for the representative products from IM and AM at low production volume, while figure 5.2 illustrates the high production volume.

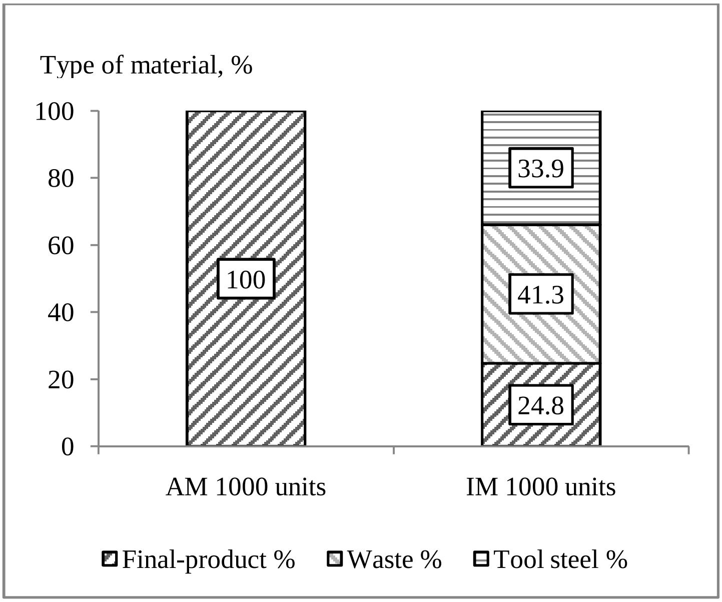


Figure 5.1. The percent of materials in the products from AM and IM (1000 units).

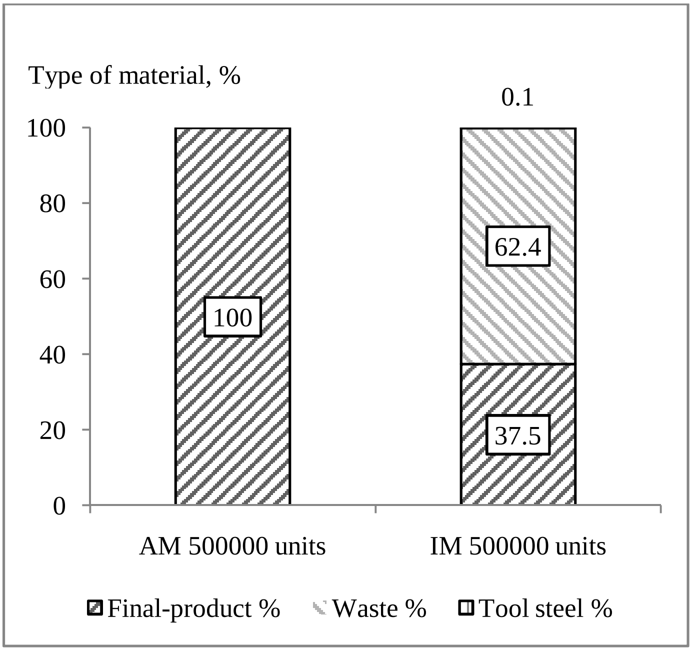


Figure 5.2. The percent of materials in the products from AM and IM (500000 units).

The initial data set for the comparison of energy consumption between AM and IM shows that AM has lower energy consumption per unit produced than IM at lower production volume. As the production volume increases, the energy consumption per unit of IM gradually decreases while that of AM remains relatively constant.Depending on the range of energy consumption of an AM device, the energy-based cross-over production volume is found to be from 450-500 units for the upper energy rang to 1050-1100 units for the lower energy range. The type of AM device in this study is SL type. Figure 5.3 illustrate the energy consumption per unit produced of AM and IM.

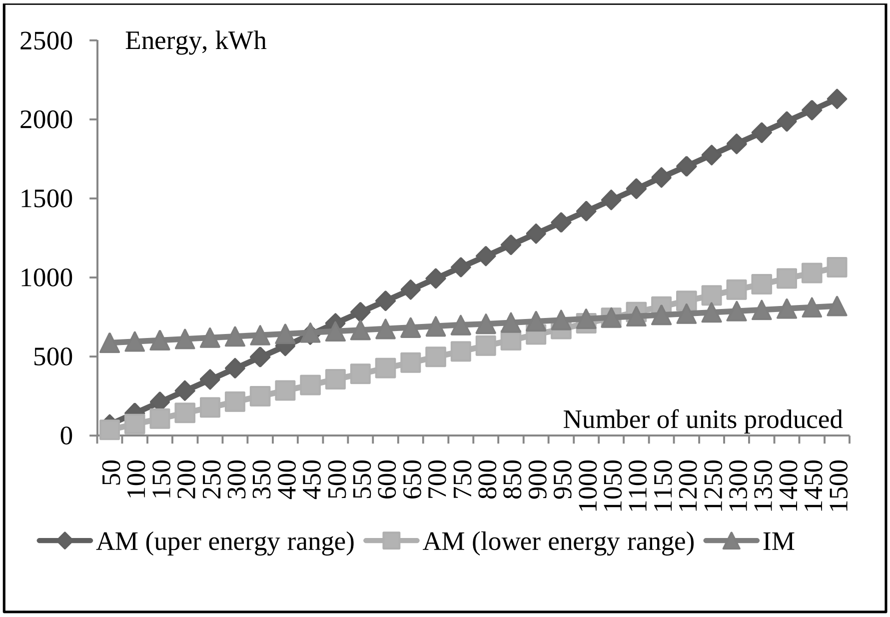


Figure 5.3. Energy-based cross-over production volume of AM and IM.

Since energy during the production process is used to produce both product and the accompanying waste, there is different energy composition in products from AM and IM. While it is not known how much energy is used to form the wax support material in AM, it is assumed that most of energy is used in the light source to cause the polymerization of the photopolymer and to movement of the moving components. As a result, the majority of production energy in AM is directed into the final product. In the case of IM, every unit made up of 37.5% or PS for final product and 62.5% of PS for the runner system, results in just over a third of production energy that result in the final product. This can be seen in figure 5.4. Although IM wastes its production energy to produce the wasted materials, the increase in the overall energy consumption of the IM process is only marginal. This is due to the low production energy consumption of only 1.86 kWh/kg for IM. The change of the energy used to injection mold these wasted materials is therefore relatively small when compared to the total energy used.

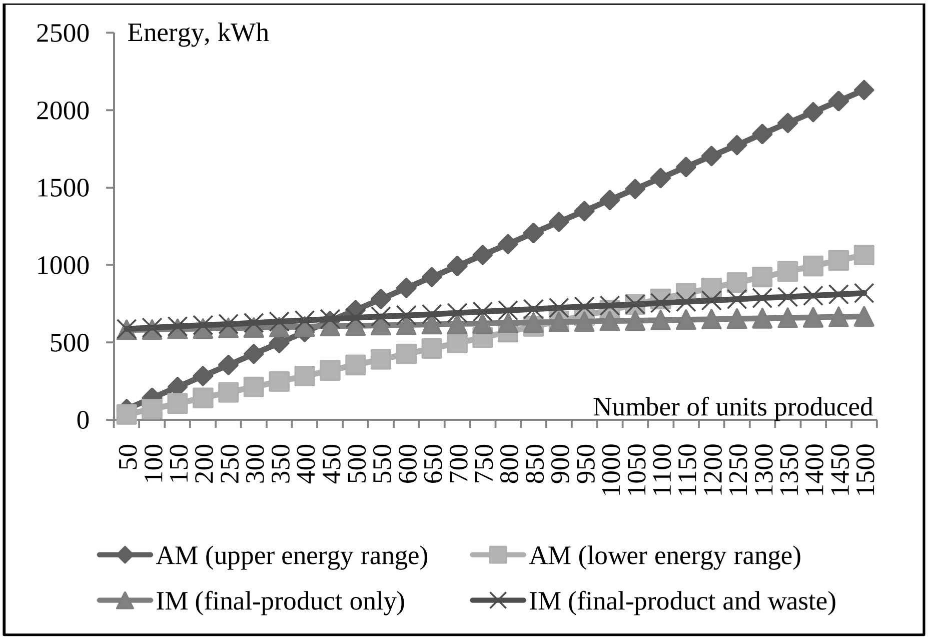


Figure 5.4. Energy-based cross-over production volume of AM and IM. IM is shown with final product only, and final product with waste.

5.1.2 The result with final product consumption data

One more factor that affects the resource consumption of any manufacturing method is the actual consumption of the final product. For mass-production method like IM, the production volume is planned in response to anticipated demand. This thesis assumes that there is some difference in the predicted demand and the actual consumption, as can be described with Bullwhip effect phenomenon. In order to demonstrate this effect in the scale model kit industry, the distributor's inventory level data of 7 scale model kit products of different sale level was obtained from Winner Hobby Co., Ltd. The 12-month data from 2011 shows different remaining quantities of each product. Even though the better-sold products have lower remaining inventory, if the sales stop or the product is no longer demanded by customers, there is usually some excess products left. This excess quantity can be considered a waste of resources. In figure 5.5, it is shown that the excess quantity ranges from an average of 17% for high demand products, 34% in medium demand products to 85% in low demand products. It should be noted that the distributor first imported the products before the start of the year, and then replenished their stock again in June as seen with the rise in inventory level.

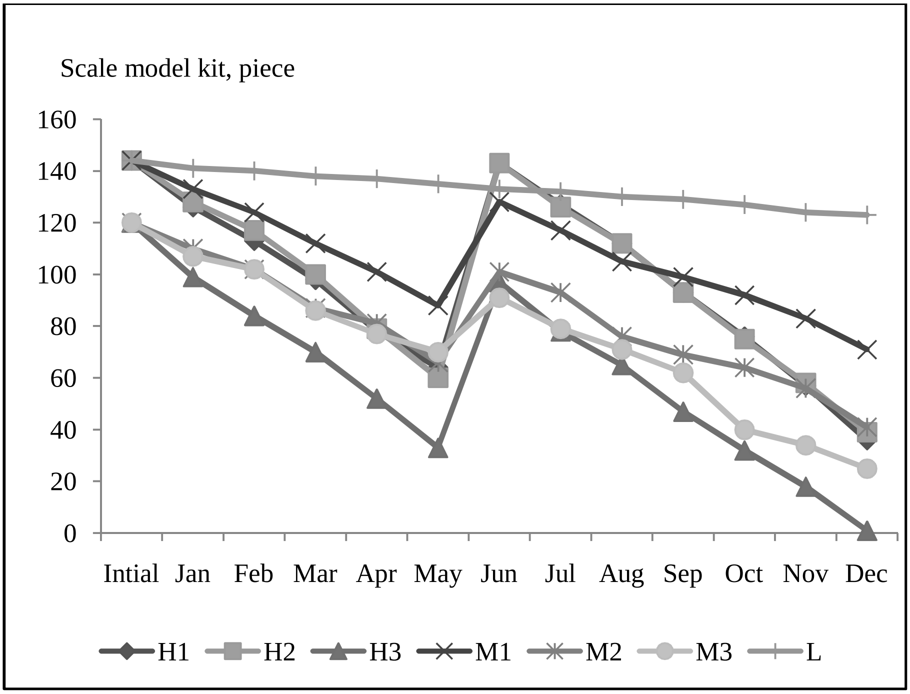


Figure 5.5. The Monthly inventory levels for 2011 of a scale model kit distributor's inventory level. There are 3 high demand products (H), 3 medium demand products (M) and 1 low demand product (L).

This data implies that mass-production methods could lead to a surplus of manufactured items in quantities from 17% to 85% of the total production volume above the actual consumption. For IM production volume of 500000 units, this means 85000 to 425000 surplus units. AM is viewed as on-demand production that only start building the product when an order is placed by the customer. This data is added to the initial data set and the result of materials composition percentage is shown in figure 5.6.

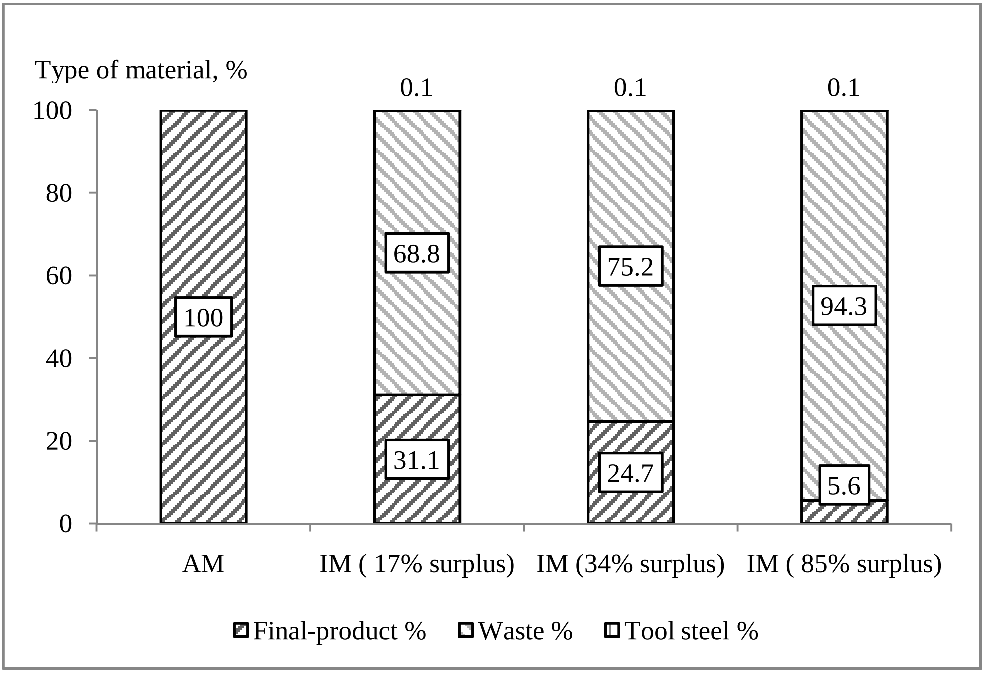


Figure 5.6. The percent of materials in the product of AM and IM at different surplus quantity.

In terms of energy consumption when adjusted with actual consumption, AM is able to benefit from its ability to match the actual consumption better. When the consumption is low, AM can reduce its production while IM has to produce in advance. The result is that IM has additional waste of production energy in the form of surplus products.Figure 5.7 shows this increase in the production energy of IM when wasted surplus quantity is considered. In order to clearly show the change in IM energy consumption, the estimated mean energy consumption value of 30 kWh/kg is used for AM. The inclusion of surplus product as waste for IM results in the change of energy-based cross-over production volume. The cross-over volume is 530 units when considering only the final product from IM without the wasted materials. It rises to 585 units when the waste is also considered. For an IM product that has a 17% surplus quantity, the cross-over volume is

600 units. At 34% surplus, it becomes 615 units. With the highest wasted surplus product of 85%, IM has the cross-over volume of 675 units.

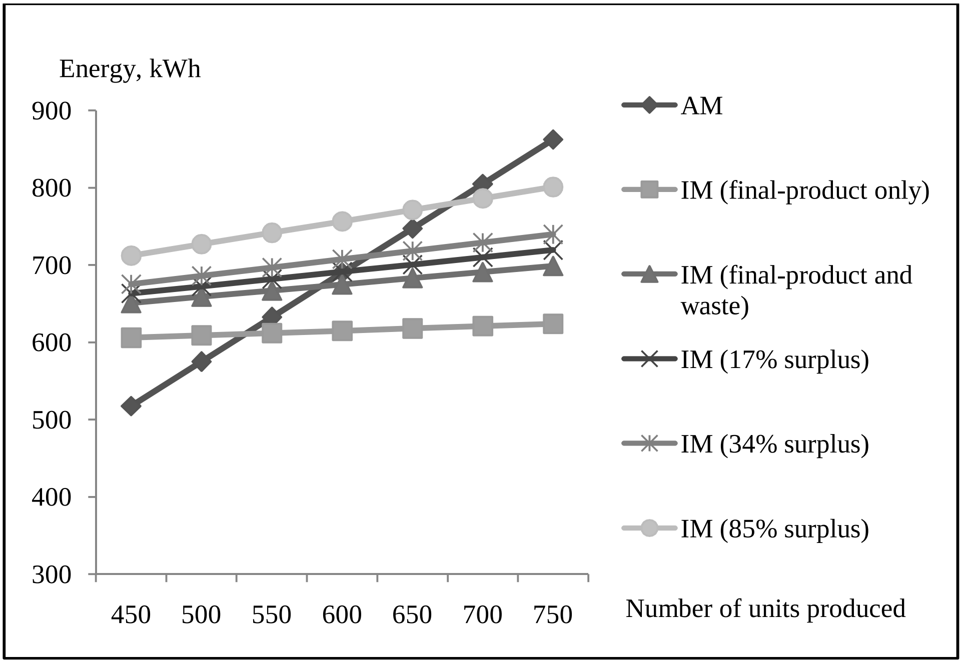


Figure 5.7. The energy-based cross-over production volume shift of IM at different waste composition.

5.2 System dynamics model results

5.2.1 Number of AM devices needed

For a manufacturing unit to be able to respond to demand, it must install manufacturing equipment in order to have production capacity. The number of devices (and therefore production capacity) was determined by the quantity of demand and the pattern of demand fulfillment. For example, a high quantity demand could be answered with low production capacity, providing that the customer could wait up to several days for the order to be fulfilled. Generally, the high priority of time-critical demands contributed to the higher number of AM devices needed, while the non time-critical demand could be sustained with a lower number of AM devices. The result-oriented PSS approach was able to reduce or maintain the minimum number of AM device in all three scenarios, as shown in figure 5.8. It should be noted that the figure for the traditional ownership approach is a summation of what each of the three manufactures had installed in their manufacturing unit.

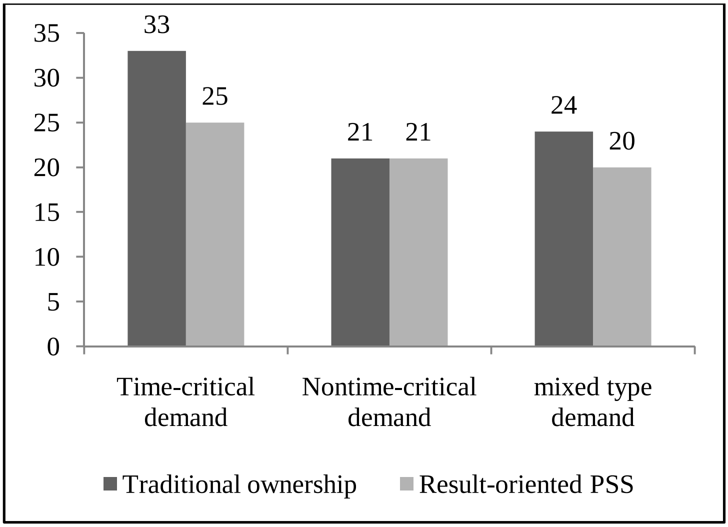


Figure 5.8. The optimized minimum number of AM devices required for each scenario.

5.2.2 Capacity utilization performance

Another measurement of the performance of a manufacturing unit was its production capacity utilization. It showed how much time the manufacturing equipment was used, and how much time it was idle. The result from the SD model showed that the manufacturing unit with high priority, time-critical customers, had low production capacity usage, while other cases had higher utilization. In result-oriented PSS approach scenarios, the capacity utilization was higher, as shown in figure 5.9.

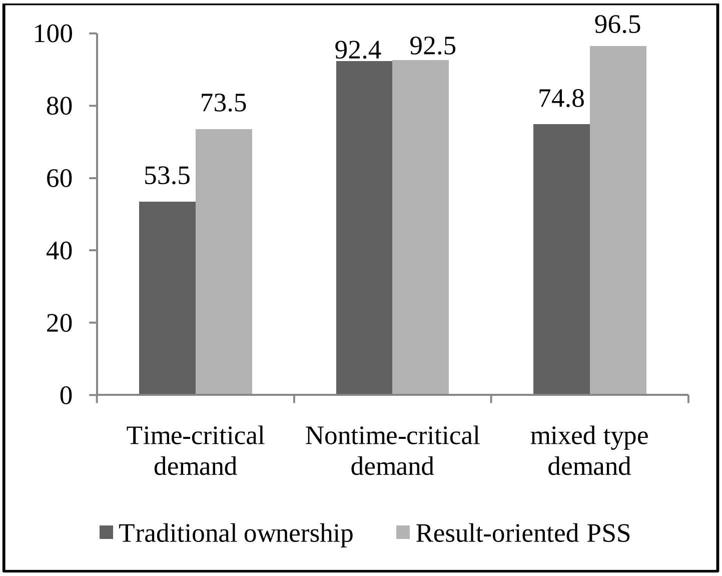


Figure 5.9. The production capacity utilization (% of AM device capacity that is utilized) for each scenario.

5.2.3 Demands fulfillment performance

Based on the optimized production capacity presented earlier, the customer's demand was satisfactorily met based on the success criteria, e.g. less than 10% cancelation of total number of time-critical order and no more than 7 days waiting (backlog) time for non time-critical order. The result was shown in table 5.1.

Table 5.1. The demand fulfillment performance of each scenario.

	Traditional ownership			Result-oriented PSS		
	Time-critical demand	Nontime-critical demand	Mixed type demand	Time-critical demand	Nontime-critical demand	Mixed type demand
Orders received, units	28371	28371	28371	28371	28371	28371
Product built, units	25753	28371	26209	26836	28371	28181
Same day shipping, %	90.8	32.6	77.8	94.6	35.6	63.1
1 day backlog, %	-	34.2	12.3	-	51.7	17.2
2 day backlog, %	-	20.5	2.1	-	12.6	13.2
3 day backlog, %	-	9.9	0.2	-	0.0	5.5
4 day backlog, %	-	2.7	0.0	-	0.0	0.3
5 day backlog, %	-	0.1	0.0	-	0.0	0.0
6 day backlog, %	-	0.0	0.0	-	0.0	0.0
7 day backlog, %	-	0.0	0.0	-	0.0	0.0
Over 7 days, %	-	0.0	0.0	-	0.0	0.0
Cancelled order, %	9.2	0.0	7.6	5.4	0.0	0.7

6 Discussion

The discussion follows the results from the two methods used to answer the research questions. The result from LCI studies of AM and IM is discussed separately from the result of SD model for the effect of the result-oriented PSS in the AM industry.

6.1 AM and IM: the LCI study

6.1.1 Raw material consumption

In terms of the quantity of raw material input, both AM and IM consume the same volume of raw materials for the representative product, which is 31.2 cm^3. Since the photopolymers used in the AM process and PS used in the IM process has different density, the weight of the products is different as a result. The raw material input per a unit produced amounts to 35 g of photopolymer for AM and 30 g of PS for IM. The main difference lies in the additional materials required to produce the final product of the IM process, which requires more materials and energy for the injection mold and support structure.

In the case of IM process, the first is the mold material, which is 41 kg of tool steel for the product in this study. This amount is relatively small for a single product; especially when considering the large quantity that can be made from one set of mold. However, since any individual product requires its own set of mold, the amount of material increases with the increasing diversity in product choices. The characteristic of IM, which forms the physical shape of the product by injecting molten materials into the cavity also results in that parts of materials have to be solidified in the flowing channel i.e. the runner system. Different products have different requirements for the amount of runner system required. While some products only need a small amount of runner system relative to the mass of the product, other products need a much more extensive runner system. The latter case is true for scale model kit products. Scale model kits usually have a small size, usually less than 50 cm in length, and contain a large number of small pieces that make up the model. Part of the reason that there are many pieces in injection-molded products is because of the geometrical limitation of IM. Products have to be designed in a way that avoids complex shapes in order to facilitate the removal of the products from the molds and reduce the chance of part distortion when the products are cooling down. The more complicated the product is, it either has to be broken down into more pieces or a more complicated mold has to be used, resulting in higher production costs. As a result, an extensive array of runner system has to be incorporated into scale model kit designs so that the molten plastic can access these multiple parts. The solidified runner system holds these parts together, helping the handling of the finished IM products.

In this thesis, it is found that up to 62.5% of the PS contained in the product is the material for the runner system, while 37.5%form the pieces of the scale model kits. In this study, the usual defect and material lost during the IM process are not taken into account. This was done partly because of a lack of information and because these materials are usually put back into the process. In many injection-molded products, the runner system is removed and recycled back into the production process. However, the characteristics of a scale model kit require that it usually remains with the product and be removed by the end customer. The recycling of these materials back to the industrial process is difficult. Whether the materials are put back in the recycling process, or disposed with other household trash is up to the end customer and the recycling system available.

For the AM process, various designs of products only require different CAD files. This disconnects the diversity of product design from the material investment of production tooling. The ability of AM to manufacture parts of complex geometries also minimizes the need to breakup the design into small pieces. The final products are produced with minimum excess material. It is known that AM requires a certain amount of support materials to help the formation of certain product geometries. The support material used by 3Delivered, Inc. is known to be a type of hydroxylated wax, called VisiJet® S100 Support Material (3Dsystems 2012b). However, due to the fact that the detail classifications of the material and its related energy consumption are not disclosed, it is not included in this thesis.

These results show that AM is more efficient than IM in terms of quantity of materials used to make the final product. However, the materials used in this study differ between AM and IM. Although the energy consumption of the manufacturing of PS is available, similar information and characteristics for the photopolymer (mixture of triethylene glycol dimethacrylate ester and urethane acrylate polymer) is not fully disclosed by the manufacturer. Although triethylene glycol dimethacrylate is known to be released into nature and accumulate in soil and water, there is not enough data to determine its environmental impacts (Toxnet 2012). PS is known to be relatively safe in its polymer form. However, its styrene monomer is found to be possibly carcinogenic for humans (IARC1987). Due to the lack of detailed information, this study excludes the comparison of the environmental impact for the two raw materials.

From a sustainability point of view, both materials are petrochemicals derivatives. If the substances and energy types used in the two materials are the same, it can be assumed that the manufacturing method having the higher resource usage efficiency and producing less waste is considered to be the more sustainable one.

From an economic standpoint, the reduction in the amount of raw material usage is usually offset by the cost of the materials. PS is a considerably low cost material, making the high percentage of waste affordable. For AM on the other hand, the currently available materials are far more expensive than PS, especially the photopolymer used in the SL devices in this study. However, SL represents only one among many AM technologies and the materials used are as diverse as the technologies. Many AM technologies use similar or even the same materials as other traditional manufacturing methods, including many different metals, nylon and ABS. These technologies also have a high efficiency in material usage as demonstrated with the SL technology. For the technologies that use same or similar materials as in the more traditional manufacturing methods, a clear reduction of wasted materials is expected.

6.1.2 Energy consumption

There is a high difference in energy consumption between AM and IM process. While the energy consumption of the AM (SL technology) is estimated in this thesis, accounting for 20-40 kWh/kg, the figure for IM amounts to 1.8 kWh/kg. Since the final products from both methods are comparable in terms of weight per unit, on a weight-to-weight basis AM consumes much more energy to produce a unit of final product being 0.7-1.4 kWh whereas IM only consumes 0.05 kWh. Nevertheless, other factors not taken into account in this study have to be considered as well in order to provide a complete picture of the entire energy consumption.

While the AM process uses more energy to produce the final product than IM, it requires less additional energy input. Within this thesis, it is assumed that AM product does not require any further energy input, as described in chapter 3. For the IM process, the additional energy input that is added to the direct energy consumption during the production comes from the energy needed to produce the injection mold and the runner system, which is regarded as waste. The mold represents a high amount of energy input, especially with a low production volume. To produce the steel mold used in this study 579 kWh of energy are needed. The AM process does not have high up-front energy consumption like IM does. This represents an advantage for lower production volumes from an energy perspective. When only the final product is considered, the energy-based cross-over production volume is 530 units. This means that the energy consumption per unit of IM is lower than AM at production volume higher than this cross-over point. When the wasted material is considered (the runner system of the scale model kit), another 0.09 kWh are added to the total energy input of IM, bringing the total to 0.14 kWh per unit produced. Since the IM energy consumption per unit increases, the cross-over volume is raised to 585 units. Due to the low overall energy consumption of the IM process, the influence of the waste material is relatively low even if up to 62.5% of the energy input is usedto produce the materials that become waste. This change in cross-over volume can be considered very marginal and does not change the fact that the energy consumption per product unit of AM is still much higher than for IM for any substantial production quantity. However, this thesis is trying to point out that AM as a whole is still an immature technology and there is a potential for the reduction of the energy consumption in the future. Since most of the energy used in AM goes into the product it builds, any energy reduction is likely to contribute to a drop in energy content of the product. On the other hand, IM is a relatively mature and well-developed technology. The energy content in the mold and the support structure is inherited in the characteristic of the technology and is not expected to be reduced much further.

6.1.3 End customers' consumption

Most works on AM and IM comparisons so far have focused on the resulting products within the boundary of the manufacturer, based on technical characteristics of the manufacturing equipment. This thesis expands the boundaries and brings the stock and distribution of the products to the discussion. This is based on the assumption that IM is a mass-production technique, in which the manufacturers up the supply chain set their production volume based on the anticipated demand. Since it is almost impossible that each supply agent can accurately estimate the actual customer demand, the production volume is usually higher than actually needed by customers. The amplification of this demand estimation is explained by the Bullwhip effect (Wangphanich 2011). The data from the scale model kit distributor, provided by Winner Hobby Co. Ltd., shows that numbers of left over products vary from 17% to 85%. Assuming that at a certain point in time there is no demand for these products from the customers any more, these products will become waste of both materials and energy used to produce them, and also the lost of investment. When this leftover product is added as waste to IM, the material usage efficiency decreases the energy-based cross-over production volume increases as compared to AM. For AM on the other hand all the materials used end up in the final product and no excess quantity of products is produced, as AM is able to produce exactly the quantity needed by the customers. The difference is shown in the percentage of materials in the final product that reduced from 37.5% when the entire quantity of product is consumed, to 31.1% when 17% of product is wasted. When the surplus quantity increases to 34% and 85%, the materials present in the final product reduced to 24.7% and 5.6% respectively. The energy-based cross-over production volume increases gradually from 585 units with no surplus products to 675 units with an 85% surplus quantity. Again the change is marginal when considering that the actual product quantity could reach up to 500000 units, meaning that IM still uses less energy overall than AM. However, this study has shown that the excess production quantities of IM process can contribute to the additional consumption of energy and raw materials, while AM is able to match the actual customers' demand more closely and reduce the waste of resources.

It has to be noted that the figures of left over inventory in this thesis are only used for the purpose of pointing out the possibility of a surplus production. The actual production volume, the leftover stock level, and the actual quantity demanded by the end customers are very hard to determine. The Bullwhip effect is a well-known phenomenon in logistic and supply chain, and there are various measures to minimize its impact (Wangphanich 2008). The distributor in this study tried to adjust the import quantity when they replenished their inventory. The product that has not been well accepted by the market is not re-ordered. By the nature of scale model kit products, they do not have an expiration date and the product can be stored for almost indefinitely. Although the recovery of investment is slow in this case, it is unlikely that the surplus products will become a total loss of investment. The pricing and marketing strategy also play a large role in deciding whether the product will be sold or not which makes it hard to determine what the real demand from the customer side is. The conclusion is that AM offers an alternative on-demand process that can address uncertain or varied market demand situations with limited up-front investment and storage requirement.

6.1.4 Production of raw materials discussion

Although the production of raw materials is not included in the boundary of this study, the difference in the amount of wasted materials between AM and IM has an important implication to the overall energy consumption of both manufacturing technologies. Since the IM process uses a considerable amount of PS material in the runner system that has to be discarded from the final product, the actual energy wasted is the energy embedded in the 62.5% of PS material. For a production volume of 500000 units, the waste is 25000 kg of PS. This is equal to 722500 kWh of energy input, assuming the energy needed to produce virgin PS is 28.9 kWh/kg (Hammond and Jones 2008). This amount of energy is larger than the total energy AM uses to produce the 500000 product units, which is 710000 kWh. Unfortunately, the information regarding the energy needed for production the AM materials, the photopolymer, is not available to enable the full comparison. Nevertheless, if the comparison is conducted on the materials that use similar amount of energy to produce, the result is expected to show the benefits of AM more clearly. Figure 6.1 illustrates how the energy consumption could look like if the materials of the same production energy are used for both manufacturing techniques. Assuming that both materials require 28.9 kWh/kg to produce and the production volume is 500000 units, AM uses 17500 kg and IM uses 50000 kg, of which 25000 kg is wasted. The energy consumption of the AM process is an average of 30 kWh/kg and the IM process is 1.86 kWh/kg.

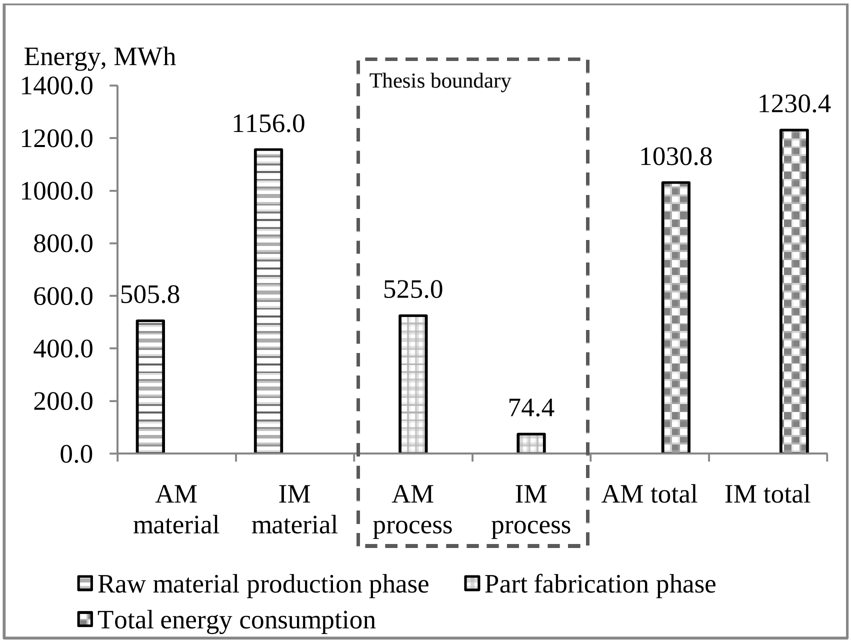


Figure 6.1. The estimated energy consumption of AM and IM, if the raw material production phase is included.

From figure 6.1, if the raw material production phase is included, and the production energy for both materials is equal, AM can actually has lower total energy consumption than IM. The real disadvantage of IM is the wasted materials and the energy embedded in them. AM still consumes more energy than IM but it does not produce much wasted materials. If future developments lead to reduced energy consumption, it is expected that AM will become more energy efficient.In addition, the discussion so far is based on the premise that the energy is valuable due to the limited and depleting energy resources. In an environment where energy is more abundant – as a result of the advance in the development of alternative energy sources – and the materials become more “valuable” than the energy, the ability of AM to reduce the wasted of raw materials and conserve the limited natural resources is highly desirable.

6.2 The result-oriented PSS in AM industry

6.2.1 Required number of AM devices

The results of the SD model suggest that the result-oriented PSS supports the reduction of resource use, i.e. the number of AM devices. It showed that less resource (fewer devices) could be used to supply the same or even more value to customer.

In the first approach (traditional ownership) of the time critical scenario, there were three individual manufacturers. Each operated 11 AM devices under their ownership. Even though there was a combined total of 33 devices, they were separated by each manufacturer’s boundary. This meant that at any time when the demand rose above the capacity of these 11 devices, the manufacturer had to cancel the orders that exceeded the capacity. These 11 devices were determined to be enough to meet the success criteria in the SD model. Since the demand was not always high, these manufacturers left the equipment sitting idle when the demand was low. The result was an average of 53.5% utilized production capacity. In the case of result-oriented PSS, all 33 devices could have been placed under the fabricator's boundary, giving them ample production capacity. The fabricator could then optimize their production capacity to meet success criteria with only 25 systems in this case. The fabricator had additional flexibility due to the wider base of demand. In this SD model, the narrow demand base of individual manufacturers was represented by a single source of demand, while the fabricator had three different sources of demand. Due to the randomized demand input, the three sources of demand were not likely to rise at the same time. Thus, some of the over-capacity demand could be accepted and produced with excess production capacity of other customers. Even though every customer happened to have high demand at the same time, the fabricator still had choices of either denying one or more sources of demand. In this simulation, it was set to deny the lowest demand first, keeping the higher ones. This helped the fabricator to utilize the production capacity more effectively, increasing from 53.5% to 73.5%.

The importance of available production capacity to be reallocated within a fabricator was clearly seen in the second scenario with the non-time-critical demand. Because the production capacity was already optimized and effectively used at 92.5%, the fabricator did not have much room to maneuver their customer's demand. Although not perfectly clear, it seems an improvement could still be made to reduce the order backlog, meaning that the customers receive their orders a little faster. However, this improvement was deemed insignificant to the case being discussed based on the assumption that the time to delivery did not affect the customer satisfaction if it was shipped out within seven days.

In the third scenario, the demand was randomly mixed between time-critical demand and non-time-critical demand. The result for the traditional approach was near the midpoint of the two previous scenarios. The higher production capacity utilization was attributed to the non-time-critical demand that could be put as backlog when the time-critical demand was high. The interesting part was the drastic increase in equipment utilization of the result-oriented PSS approach, which was the resulting benefit of having two types of demand. First, because of the high production capacity available within the boundary of a service center, there was very little chance that the time-critical demand would exceed the production capacity. This point was confirmed by a much lower number of order cancellations, at 0.7% of the total number of orders received. In addition, whenever the time-critical demand was high, the non-time-critical demand could be pushed into backlog to be produced in the later days. These two factors helped and brought the production capacity utilization up from 74.8% to 96.5%, while the number of devices needed was reduced from 24 devices to 20 devices.

6.2.2 Economic discussion

From a manufacturer's point of view, the outsourcing of their manufacturing unit to a fabricator could potentially yield many benefits. Based on the output of the SD model shown in this paper, the ability to be able to meet their customer's demand was demonstrated through a reduction in cancelled orders. This means they would miss fewer business opportunities and likely have a better reputation for being able to deliver. They also do not have to have to take responsibility for the manufacturing equipment and the supporting expense, which is not within their main competency. This is offset to some extent by the relatively higher cost paid to the fabricator. Another point worth discussing is that AM technologies actually came in many forms. The SL technology used in this paper is just one technology among many options. Each technology has its own characteristics. The fast pace of development in the AM industry that introduces newer AM devices with a higher performance almost on an annual basis is an additional factor to be taken into account. For a manufacturer choosing to invest in a certain technology, it is likely that the technology defines what they will be able to produce, and which customer group they target. As soon as the investment is made, the investor is somewhat limited to the technology until the investment is recovered. On the other hand, the manufacturer who chooses to use a fabricator for manufacturing would be able to change or add another fabricator with different or higher performing technologies, according to a change in demand. This follows the argument for the value of flexibility described by Richter et al. (2010).

From the fabricator side, the opportunity to capture the production demand of AM product consumers was notable. Since AM is a relatively new technology, more customers are expected to adapt this new manufacturing technique, resulting in more demand for both the AM-made final products and the AM process capacity of in the future (Wohlers 2011). The fabricator would be in a very good position to offer these new comers a choice of producing their creations without up-front investment in manufacturing equipment. The same offer was also available from other manufacturing techniques e.g. injection molding. However, the competitive edge of AM lays in its distinct characteristic of having no tooling required. This means that there is practically a very low minimum production volume, as opposed to a very large production volume required to cover the injection molding tool. The fabricator is also able to provide the same production capacity to multiple companies at a lower investment, in the form of lower number of devices required, than would be the case of those companies who invest in their own production line.

So far, the discussion has been made in favor of result-oriented PSS and the outsourcing of manufacturing units to a fabricator. Therefore, it would be appropriate to consider the other side of the coin as well. As had been illustrated in the non-time-critical scenario, the benefit of using a result-oriented PSS was only marginal. Thus, it would not make much difference for a manufacturer who could guarantee their constant demand, keeping their capacity utilization near 100%. In this case, the manufacturer may consider investing in the equipment and enjoy (presumably) relatively lower production cost. Another reason to take ownership of the production capacity could be the sensitive and confidential nature of the product; since the AM product is built up from CAD file, a compromise or disclosure of the CAD file could mean the loss of intellectual property to potential competitors.

6.2.3 End customer value discussion

From an end customer’s perspective, whatever happened behind the shop front of a manufacturer is largely unknown or irrelevant to them. Whether the manufacturer is doing in-house production, or outsourcing it to a fabricator, the route that provides most reliable and satisfactory result would logically be more preferred. These benefits can be found in fabricator.

6.2.4 Sustainability discussion

From a sustainability standpoint it is preferable if there is an alternative to provide the same value to a customer at a lower resource input. This alternative could be deemed more sustainable, again with the qualification that the system is using the same substances and energy types. In the case of using a result-oriented PSS approach to provide fabrication services to multiple companies, the same amount of demand was shown, through the SD model, to be answered with equal or less resources consumed, i.e. fewer number of AM devices, in this discussion. The result seems to follow Tukker and Tischner's strategy for decoupling (Tukker and Tischner 2006) by enhancing the intensity of use of the product.

However, this does not decouple the number of devices required from the product demand. This approach increases the utilization of the devices, thus changing the relationship between product demand and required devices to meet that demand. Since utilization cannot go beyond 100%, as utilization approaches that threshold, additional devices must be added to meet the demand, thus the number of devices remains coupled with the product output.

The higher intensity of use of the product achieved by the result-oriented approach still had another potential environmental benefit. As discussed by Wongphanich (2011), the higher intensity of use could result in the product using up its life capacity sooner. Therefore, it was expected to be replaced by a newer technology that has a higher performance and is more environmentally friendly (i.e. material and energy efficient) product. The benefit was the gradual improvement of its environmental performance than would be the case with the older, less environmental friendly product being used for a longer period of time. In the case of the AM system used by 3Delivered, Inc., the lifetime of the system was estimated by the company to be independent of the intensity of use. The life-limiting factor was the print head, which was designed to last 10 years. This meant that no matter how intensively it was used, the device would not be replaced any sooner as a result of the pattern of use. In any case, the print head was a consumable part and can be replaced. The replacement would not result in any improvement in its environmental performance.

In order to have the environmental impact decrease incrementally each time the product is replaced also relies on an assumption that the subsequent AM devices are improving environmentally as well. The washing machine studied by Wangphanich was found to have its performance continuously improved during the period of 30 years. Thus, the environmental benefit of replacing the machine sooner was realized. For the AM industry, it appears that the environmental aspect, for example the energy consumption, has not been the focus of AM device manufacturers (Wohlers 2011). Although the performance in building speed and resolution has constantly improved, it might not be the case with the energy consumption.

7 Conclusion

In an attempt to compare resource consumption of AM and IM, it is found that AM is more efficient in the way that materials are used, as ahigher proportion of raw materials ending up in the final product. IM, on the other hand, wastes a significant proportion of raw material in components that are not part of the final product. If the same or similar raw materials are used in both manufacturing methods, the advantage is clearly with AM.

In terms of energy consumption, AM only has an advantage in this area when working with a very low production volume. This energy-based cross-over production volume varies with the choice of raw materials and the product's geometry. However, the analysis of the energy composition shows that most of the energy used in AM is to create the final product, while IM only uses a fraction of the total energy to produce the final product. AM technologies are still very new but have the potential for development and reduction of energy consumption in the future. Added to this potential is the higher material usage efficiency of AM, which reduces the waste of materials and the energy embedded in them. These two factors are likely to position AM as cleaner manufacturing alternative.

The on-demand production capability of AM offers the possibility to reduce the surplus production of goods. For a product with an uncertain amount of customer demand and a product whereup-front investment is not affordable, AM has a lot of benefits over IM by allowing the investor to actually only invest in the amount of product that is needed by the customers.

This thesis suggests that the result-oriented PSS, in general, achieved an intensification of the product usage, except in the case where the intensity was already near its maximum. This was largely due to flexibility of the result-oriented PSS to reallocate the functionality to where it is most needed.

For a relatively constant demand, using a result-orientated PSS could lead to a reduction in the number of products needed to provide the required functionality, by increasing the intensity of the usage of each product.

A reduction in the required number of devices contributes to a reduction in energy and materials required, i.e. reduced resource consumption, though it does not achieve the desired decoupling.

Increased intensity of the use of a product could result in earlier replacement of the product, only when the lifetime of the product is independent of the intensity of use. The environmental benefit of more frequent product replacement depends on whether the subsequent product has an improved environmental performance or not.

For fabricators e.g. a service provider, like 3Delivered, Inc., having multiple customers with different demand priorities could lead to an increase in the flexibility of production capacity allocation and could support the optimization of the use of the production equipment.

Future work

As pointed out in the discussion (section 6.1.4), one of the key elements to understand the full life cycle perspective of energy consumption is the energy used in the production of raw materials. An investigation into the energy consumption of raw materials production is needed in order to complete the understanding of energy consumption of AM technology.

The thesis highlighted a resource consumption issue related to the surplus production in the mass-production technique. Although the data used in this research has pointed out that surplus and unconsumed products can lead to waste, the actual amount of waste requiresfurther study. This result could help clarify the actual waste of resources in different manufacturing technologies.

The possibility of AM to localize the product manufacturing is also observed in this thesis. Since most of the major scale model kit manufacturers have their manufacturing sites centralized in parts of Asia and China, the distribution of their products relies heavily on transportation to their customers all around the world. For example, Winner Hobby Co. Ltd., imports the scale model kits from Academy Co. Ltd., which is an international scale model kit manufacturer in South Korea. The case of Click2detail brings manufacturing back to North America, near the customers in that region. However, Click2detail is still a small start-up company and their scale of production is not comparable to those of major manufacturers. Nevertheless, this is an area that could be investigated in order to understand the potential of resource consumption reduction due to the localization of manufacturing, with the prospect of future technology development and the wider adoption of the market.

References

3D systems. 2012a. Material Safety Data Sheet: VisiJet® SR 200 Plastic Material. http://www.3dsystems.com/products/datafiles/visijet/msds/july08/SR200/23100-S12-01-B_SDS_EU_English_SR200_042406.pdf (accessed 17 May 2012).

3D systems. 2012b. Material Safety Data Sheet: VisiJet® S100, S300 Support Material. http://www.3dsystems.com/products/datafiles/visijet/msds/july08/S100/23126-S02-02-A_MSDS_US_VisiJetS100_S300.pdf (accessed 17 May 2012).

American Mold Builders Association (AMBA). 2012. *How to Specify Molds*. http://www.amba.org/index.php?pr=How_to_Specify_Molds (accessed 17 May 2012).

ASTM Standard F2792-$10^{\varepsilon 1}$.2010. *Standard Terminology for Additive Manufacturing Technologies*. Pennsylvania: ASTM International.

ATKIN. 2011. *The Environmental & Economic Considerations of Additive Manufacturing*. http://www.econolyst.co.uk/publications.php?CategoryNo=1 (accessed 17May 2012).

Community Research and Development Information Service (CORDIS). 2009. *Strengthening the industries competitive position by the development of a logistical and technological system for spare parts that is based on on-demand production (DIRECTSPARE).* http://cordis.europa.eu/fetch?CALLER=FP7_PROJ_EN&ACTION=D&DOC=230&CAT=PROJ&QUERY=012774ecd476:0b09:37c8aa04&RCN=90450 (accessed 17May 2012).

Baines, T. S., H. Lightfoot, E. Steve, A. Neely, R Greenough, J Peppard, R Roy, E Shehab, A. Braganza, A. Tiwari, J. Alcock, J. Angus, M. Bastl, A. Cousens, P. Irving, M. Johnson,J. Kingston, H. Lockett, V. Martinez, P. Michele, D. Tranfield, I. Walton, and H. Wilson. 2007.State-of-the-art in product-service systems.*Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture* 221, no. 10: 1543-1552.

Barras, R. 1986. 'Towards a theory of innovation in services'. *Research Policy*, 15: 161–73.

Baumers,M., C. Tuck, R. Wildman, I. Ashcroft and R. Hague. 2011. *Energy Input to Additive Manufacturing: Does capacity utilization matter?*. Loughborough University.

Broman, G., J. Holmberg and K.-H. Robert. 2000. Simplicity Without Reduction: Thinking Upstream Towards the Sustainable Society. *Interfaces* 30(3): 13-25.

Concept-laser. 2012. *Individual solutions for aerospace*. http://www.concept-laser.de (accessed 17May 2012).

Dahmus, Jeffrey B. and Timothy G. Gutowski. 2004. An Environmental Analysis of Machining. *Proceedings of the 2004 ASME International Mechanical Engineering Congress and RD&D Exposition*. November 13-19. Anaheim. California.

Dean, Lionel T. 2011. *State of the art: cutting-edge digital technologies explored through the creative design of Product Artist Lionel Theodore Dean*. Lincolnshire: FutureFactories.

DME Co. 2012. *D-M-E Mold plates*. http://www.dme.net/wwwdme/DME_D_catalog_2008%20copy/Mold%20 Bases%20&%20Plates/MB%20259-276.pdf#page=3 (accessed 17 May 2012).

Edquist, C., L. Hommen, and M. McKelvey. 2001. *Innovation and Employment, Process versus. Product Innovation.* Cheltenham: Elgar

Englert, Rob. 2008. Localized Manufacturing and the Future of Products: How new technology and the micro consumer market segment will change how products are made. Rochester Institute of Technology.

Ettlie, J. E. and E. M. Reza. 1992. Organizational Integration and Process Innovation.*Academy of Management Journal* 35(4).

Fagerberg, J., D. Mowery and R. Nelson, Eds. 2006. *The Oxford Handbook of Innovation*. Oxford, Oxford University Press.

Hague, R., S. Mansour, N. Saleh and R. Harris. 2004. Materials Analysis of Stereolithography Resins for Use in Rapid Manufacturing. *Journal of Materials Science* No.39: 2457-2464.

Hammond, Geoff and Craig Jones. 2008. Inventory of Carbon and Energy version 1.6a. UK: University of Bath.

Hockerts, K. and N. Weaver. 2002. Towards a Theory of Sustainable Product Service Systems - What are the Dependent and Independent Variables of S-PSS? *INSEAD-CMER Research Workshop* "Sustainable Product Service Systems -Key Definitions and Concepts".

Holmberg, J. 1995. Socio-ecological principles and indicators for sustainability. Doctoral. Institute of Physical Resource Theory. Chalmers University of Technology and University of Gothenburg.

Holmberg, J. and Robert, K-H. 2000. Backcasting from non-overlapping sustainability principles – a framework for strategic planning.*International Journal of Sustainable Development and World Ecology* 7: 291 -308.

Holweg, Matthias. 2006. The genealogy of lean production. *Journal of Operations Management* 25: 420–437.

Hopkinson, N. and PhillM.Dickens. 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: 31-39.

International Agency for Research on Cancer (IARC). 1987. *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans. Overall Evaluations of Carcinogenicity: An Updating of IARC Monographs Volumes 1 to 42.* Lyon: World Health Organization.

ISO. 1998. *Environmental management — Life cycle assessment — Goal and scope definition and inventory analysis. ISO 14041*. Geneva, Switzerland: ISO.

ISO. 2006. *Environmental management — Life cycle assessment — Principles and framework. ISO 14040*. Geneva, Switzerland: ISO.

Jones, Peter. 2008. *The Mold Design Guide*. UK: SmithersRapra Technology Limited.

Knight, K. E. 1967. A Descriptive Model for the Intra-Firm Innovation Process.*The Journal of Business* 40(4).

Lean Enterprise Institute. 2012. *What is lean?*. http://www.lean.org/whatslean/ (accessed 17 May 2012).

Lee, Hau L., V. Padmanabhan, and SeungjinWhang. 1997. The Bullwhip Effect In Supply Chains. *Sloan Management Review* 38(3): 93-102.

Luo, Y., Z. Ji, L. Ming, and R. Caudill. 1999. Environmental Performance Analysis of Solid Freeform Fabrication Processes. *Proceedings of the 1999 IEEE International Symposium on Electronics and the Environment*, May 11-13.

Meier H, Roy R and Seliger G. 2010. Industrial Product-Service Systems—IPS2. *CIRP Annals - Manufacturing Technology* 59: 607–627.

Mont, Oksana. 2000. *Product-Service Systems*. Stockholm: Swedish Environmental Protection Agency.

Ny, H., J. P. MacDonald, G. Broman, R. Yamamoto and K.-H. Robert. 2006. Sustainability constrains as system boundaries: an approach to making life-cycle management strategic. *Journal of Industrial Ecology* 10(1): 61-77,

Richter, A., T, Sadek. and M. Steven. 2010. Flexibility in industrial product-service systems and use-oriented.*CIRP Journal of Manufacturing Science and Technology*3:128–134.

Robinson, J.B. 1990. Future under glass - A recipe for people who hate to predict. *Futures* 22(9): 820- 843.

Ruffo, M., C. Tuck and R. Hague. 2006. Cost estimation for rapid manufacturing – laser sintering production for low–medium volumes. Part B: Journal of Engineering Manufacture 220: 1417–1428.

Ruffo, M. and Richard Hague. 2007. Cost estimation for rapid manufacturing — simultaneous production of mixed components using laser sintering. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture* 221, no. 11: 1585-1591.

Steffen, W., R.A. Sanderson, P.D. Tyson, J.Jäger, P.A. Matson, B.Moore III, F. Oldfield, K. Richardson, H.-J.Schellnhuber, B.L. Turner andR.J.Wasson. 2004. Global Changeand the Earth System: A Planet Under Pressure. New York: Springer-Verlag Berlin Heidelberg.

Schweitzer, E. and J.C. Aurich. 2010. Continuous improvement of industrial product-service systems, *CIRP Journal of Manufacturing Science and Technology* 3: 158–164.

Telenko, Cassandra and Carolyn Conner Seepersad. 2011. A Comparative Evaluation of Energy Consumption of Selective Laser Sintering and Injection Molding of Nylon Parts. *Proceedings of the 2011 Solid Freeform Fabrication Symposium*: 41-54.

Thompson, A. W. 2010.Towards Sustainable-driven Innovation through Product-Service Systems. Licentiate Dissertation. Blekinge Institute of Technology.

Thompson, A. W., H. Ny, P. Lindahl, G. Broman and M. Severinsson. 2010. Benefits of a Product Service System Approach for Long-life Products: The Case of Light Tubes. *2nd CIRP International Conference on Industrial Product-Service System (IPS^2)*. The International Academy for Product Engineering (CIRP). Linköping, Sweden.

Todd, Robert H., Dell K. Allen and Leo Alting. 1994. Manufacturing Processes Reference Guide. New York: Industrial Press Inc.

Tornatzky, L. G. and M.Fleischer.1990. T*he Processes of Technological Innovation*. Lexington, MA: Lexington Books.

Toxnet. 2012. Hazard Substance Data Bank: Triethylene Glycol Dimethacrylate. http://toxnet.nlm.nih.gov/cgi-bin/sis/search/f?./temp/~ibEFlw:1 (accessed 17 May 2012).

Tuck, Christopher, Richard J.M. Hague, M. Ruffo, M. Ransley and P, Adams. 2008. Rapid manufacturing facilitated customization. *International Journal of Computer Integrated Manufacturing* 21, no. 3: 245-258.

Tukker, A. 2004. Eight Types of Product-service Systems: Eight ways to sustainability? Experiences from SusProNet. *Business Strategy and the Environment* 13(4): 246.

Tukker, Arnold and Ursula Tischner. 2006. *New Business for Old Europe*. Sheffield: Greenleaf Publishing Inc.

Utterback, J and W. Abernathy. 1975. A dynamice model of process and product innovation. *Omega: The international Journal of Management Science* 3(6).

Waldron, D., K.-H. Robert, P. leung, M. Mckay, G. Dyer, R. Blume, R. khaleei, and T. Connell. 2008. Guide to the Framework for Strategic sustainable Development. Blekinge TekniskaHögskola.

Wangphanich, Pilada. 2008. A Simulation Model for Quantifying and Reducing the Bullwhip Effect. Ph.D. diss., The University of New South Wales.

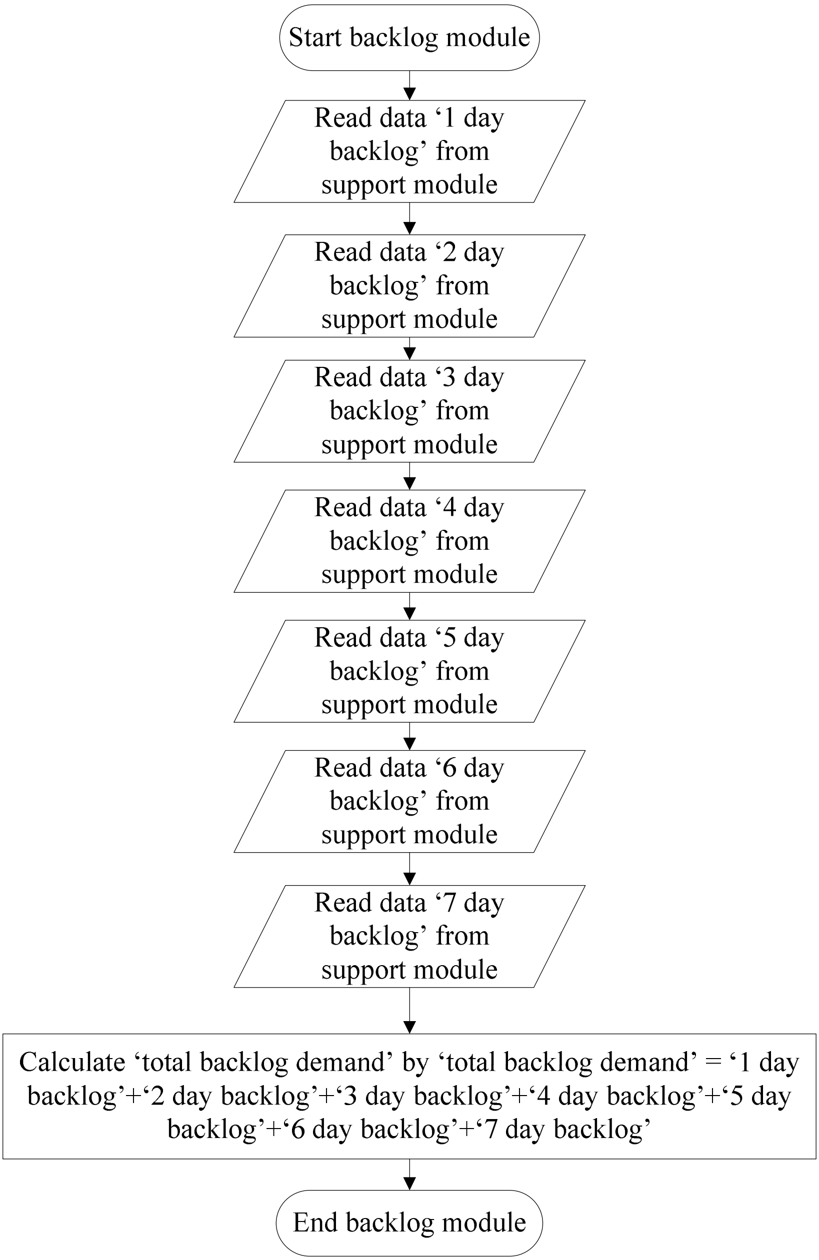
Wangphanich,Pilada. 2011. Simulation Model for Quantifying the Environmental Impact and Demand Amplification of a Product-Service System (PSS). *Management Science and Industrial Engineering (MSIE), 2011 International Conference on Management Science and Industrial Engineering*.

Willard, B. 2002. The Sustainability Advantage: Seven Business Case Benefits of a Triple Bottom Line. Gabriola Island: New Society Publishers.

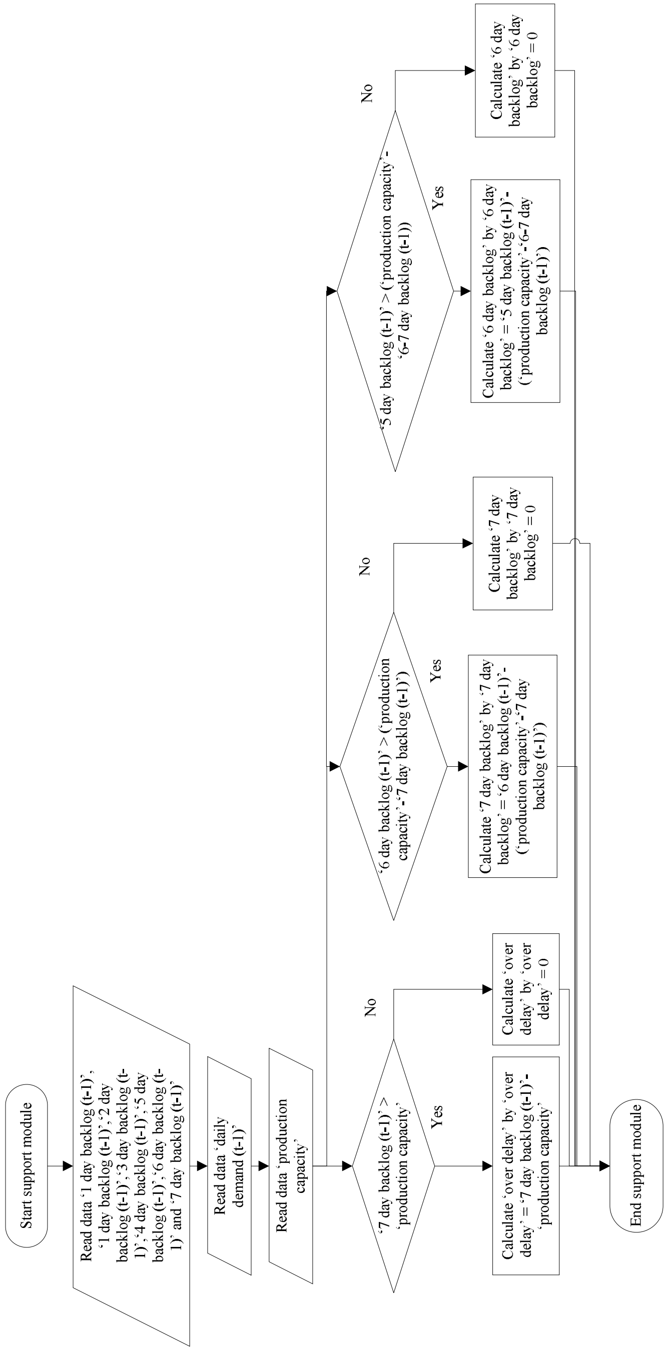
Wohlers, Terry. 2011. *Wohlers report 2011: additive manufacturing and 3D printing state of the industry*. Fort Collins: Wohlers associates, Inc.

Appendices

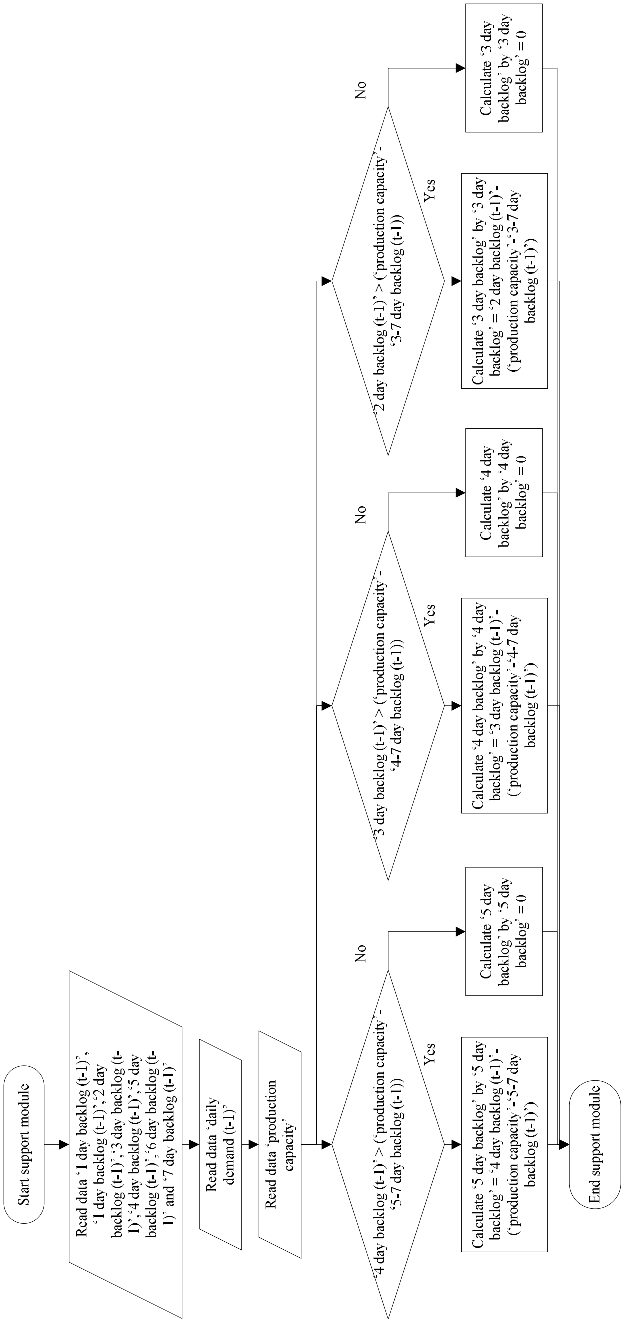
Appendix A: Flow diagram of backlog module



Appendix B: Flow diagram of support module, section 1.



Appendix B: Flow diagram of support module, section 2.



Appendix B: Flow diagram of support module, section 3.