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**ADDITIVE MANUFACTURING TECHNOLOGY POTENTIAL: A CLEANER
MANUFACTURING ALTERNATIVE**

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ABSTRACT

This paper focuses on an emerging manufacturing technology called Additive Manufacturing (AM) and its potential to become a more efficient and cleaner manufacturing alternative. This work is built around selected case companies, where the benefit of AM compared to other more traditional technologies is studied through the comparison of resource consumption. The resource consumption is defined as raw materials and energy input. The scope of this work is the application of AM in the scale model kit industry. The method used is the life cycle inventory study, which is a subtype of life cycle assessment (LCA). The result of the paper is the quantification of raw materials and energy consumption. The outcomes shows that AM has higher efficiency in terms of materials usage, as a higher proportion of materials ending up in the final product. Injection Molding (IM), on the other hand, wastes a significant proportion of raw materials 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. However, AM has higher energy consumption in comparison to the injection molding technique (IM). In terms of energy consumption, AM only has an advantage in this area when working with a very low production volume. The analysis of the energy consumption 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 materials usage efficiency of AM, which reduce the waste of materials and the energy, embedded in them. These two factors are likely to position AM as cleaner manufacturing alternative.

INTRODUCTION

Additive Manufacturing Technology (AM) is a relatively new manufacturing method, which originally came into practice in late 1980's. AM fabricates 3D tangible objects by solidifying raw materials layer upon layer. The raw materials used are showing great deal of variety, including various sorts of polymers, metal and ceramics

materials mostly in powder or liquid form. Depending on technologies and applications of AM, the fabrication mechanism ranges from exposure of the materials to various light sources, to electron beam bombardment, to spraying of liquid chemical binder [1]. This paper focuses on and analyzes the stereolithography (SL) method. SL is an AM method, which utilizes a beam of UV laser light to cure liquid photopolymeric resin [2]. As manufacturing technologies, it is believed that AM is having an increasing role in many industries and AM capabilities cover various ranges of applications. But, according to the recent survey by Wohlers Associates, companies benefit from using AM technology to fabricate functional parts more than other applications. The second most popular application is prototypes for fit and assembly. This indicates that the main advantage of using AM is in fostering product development processes by, improving product quality, reduce cost (less assembly and tooling etc.), reduce time to market etc. The use of AM to fabricate part production has also shown a continuous increase since 2003. In 2003 it had the value of only 3.9% of the total product-service revenues from AM, while this value in 2013 was 34.7%. Besides this, the market grow in the part production segment was 65.4% in 2013 worldwide [3].

As it has been discussed so far, the use of AM to fabricate part production increases and AM production parts have become competitive in many industries, and they penetrate many niche markets. For example, in the hearing aids industries about 90 % of custom-in-the-air hearing aids plastic shells is produced by AM technologies. Another example is in aerospace industry. Tens of thousands fabricated parts by laser-sintered are installed on both eight types of commercial and eight types of military aircraft from Boeing. Moreover, AM has been linked to the third industrial revolution by taking into consideration some factors such as: the AM capability to democratize manufacturing; the ability of AM to foster innovation (by removing barriers to entry within the product development and manufacturing industry); the AM capacity to reduce the delivery cost by simply being closer to the customer; and fostering mass customization [3]. 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 paper aims to answer this question.

By quantifying the input of raw materials and energy resources, it is expected that a comparative view of the manufacturing technologies could show their contribution to the sustainable development.

Lean manufacturing is a set of approaches, management philosophies and tools that focuses on the elimination of 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 [4]. Therefore, lean thinking focuses on the sources that become values, and the activities that consume time, materials, energy, man-power or space are considered a waste of resources. 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 [4] [5]. 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 is not limited to; the excessive inventory, poor product forecasts, insufficient or excessive capacities, poor customer service, and high costs for corrections [6]. The term used to describe this phenomenon 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 [6].

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 [6].

One part of this paper 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.

The rest of the paper is as follow. Section 2 provides a literature review of research on AM technical aspect, and its resource consumption. Section 3 first introduces the research question and then specifies the method, which is life cycle inventory (LCI) study, and also briefly describes the case companies. Section 4 provides the result in two sequences of LCI study initial results and the results with final product consumption data. Section 5 provides the discussion in four categories of raw material consumption, energy consumption, end customer's consumption and production of raw materials discussion. Section 5 concludes and points out suggestions for future research.

LITERATURE REVIEW

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 paper. 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 three main types of AM technology, including stereolithography (SL), laser sintering (LS), and fused deposit modeling (FDM) [2]. Other

researches focused on the comparison between AM and other manufacturing techniques. One of them is a comparative study 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 crossover production volume, was found to range from a few hundred to thousands, depending on part size and geometry [7]. 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 crossover volume between AM and IM, the point where both technologies has equal cost per unit produced, was estimated at 14000 units [8]. 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 overhead cost can be reduced and result in overall cost reduction [9]. Apart from benefits gained directly from different manufacturing method, the possibilities of on-demand production to indirectly reduce up-front investment in materials and storage of spare parts had been investigated by Directspare, an EU-sponsored project under Seventh Framework Program [10]. 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.

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 [7] [8] [11] [9]. 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 [7]. Depending on what factors are taken into consideration, a comparative study of energy consumption of SLS and IM has shown that the energy-based crossover volume can be as low as 50 units of 130 mm-sized products when compared against IM with recycled steel mold. The energy-based crossover 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 crossover point, the energy consumption per unit produced of the two method reverses. This crossover volume rose to around 300 units if compared to IM that used either virgin steel mold or recycled aluminum mold [7]. When part size was reduced to 45 mm, the energy-based crossover 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 crossover volume varied greatly according to factors taken into consideration. An AM manufactured product of 35 mm size is estimated to have the crossover volume of 14000 units against IM [8]. It dropped to 9000 units when the operation overhead cost of AM was considered [11].

METHOD

Research Design

The paper uses a combination of qualitative and quantitative research approaches. The initial approach to the formulation of research question follows the qualitative research design guideline, suggested by Maxwell [12]. The research question explores the potential benefits of AM technology in comparison to injection molding (IM) technique. The method used to answer the research question is based on the qualitative research approach. The representative case companies within AM industry are selected to provide quantitative data for analysis. This work 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. The following research question then designed:

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

The research question above explores AM as a means to enhance the efficiency of production according to Tukker and Tischner's proposed decoupling strategies [13]. 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 [6]. 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 [9]. 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.

Description of Companies

This work received cooperation from 3Delivered, 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 are located in the United States. Since this paper 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.

Method

In this paper the main method is life cycle inventory (LCI) study, which is a sub-type of environmental management technique, called life cycle assessment (LCA). LCI study is used to understand the resource consumption and its environmental impact from a life cycle perspective of a product, within a defined boundary [14]. In this work LCI study is used in an attempt to quantify and compare the resource consumption of AM and IM in the research question. The scope of this LCI study is based on the quantitative data provided by 3Delivered, Inc., and Click2detail. Click2detail provides product dimensional data, and 3Delivered provides production performance and technical data. The product and its physical characteristics described in this study is a scale model kit.

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 further on in the result section.

In this paper, 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 1.

Figure 1. THE ILLUSTRATION OF AN IM PRODUCT, THE FINAL PRODUCT SHOWN IN THE MIDDLE AND THE RUNNER SYSTEM IS SHOWN AS FRAME SURROUNDING THE MODEL (COURTESY OF [HTTP://WWW.BRITMODELLER.COM](http://www.britmodeller.com)).

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 2. The product was selected for two reasons. Firstly, 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.

The boundary of the LCI study includes the manufacturing and the distribution of components in the scale model 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.

Figure 2. AN EXAMPLE OF AM FINAL PRODUCT, THE T-1A JAYHAWK AIR FORCE TRAINER IN 1:72 SCALES (COURTESY OF CLICK2DETAIL).

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, which 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.

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 4.

Figure 3. THE INPUT AND OUTPUT OF MATERIALS AND ENERGY OF THE FOCUSED AM SYSTEM.

Figure 4. THE INPUT AND OUTPUT OF MATERIALS AND ENERGY OF THE FOCUSED IM SYSTEM.

Since the partner companies that provided data for this work only comprise an AM technology user and a scale model kit distributor, much of the up-stream data is not available and not included in the study. Specifically, this work 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 [15], 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 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, which is a stereolithography (SL) 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) [2].

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) [16]. The energy consumed during the production of the mold and the energy consumption of the IM process is obtained from a study by Dahmus and Gutowski (2004) [17]. The energy consumption of the steel production is from Inventory of Carbon and Energy version 1.6a (Hammond and Jones 2008) [18].

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 raw material input per functional unit (i.e. one final product of the T-1 Jayhawk scale model kit) was determined to be 35 g of VisiJet® SR 200 photopolymer. This material is a chemical mixture of triethylene glycol dimethacrylate ester and urethane acrylate polymer of unspecified type [19].

AM energy input is taken from a study of Luo et al (1999) [2]. 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 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 cm³, equal to 84g of polystyrene (PS) materials at PS density of 1.05 g/cm³.

Data of the IM energy consumption is based on a study by Thiriez and Gutowski [20]. In this paper, 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 [21]. The steel type is AISI P20 nickel chrome alloy steel [16], selected based on a SPI class 103 medium production mold [22]. The volume of two plates of steel is 5290 cm³. The volume of steel that has to be removed to produce the cavity insert is calculated to be 1262 cm³. The energy required to produce the steel plates is 558 kWh [18]. The energy required to machine the steel into the cavity inserts is 21 kWh [17]. 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. Click2detail calculates the amount of runner system required by the representative product. Each final product has a runner system made up of 1270 mm in length and 5 mm in diameter, or equal to 50 cm³ of PS material.

RESULTS

Life Cycle Inventory Study Results

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 the waste. 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 up to 500000 cycles. Figure 5.1 illustrates the materials composition percentage 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 PRECENT OF MATERIALS IN THE PRODUCTS FROM AM AND IM (1000 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 crossover 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 6 illustrate the energy consumption per unit produced 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% of PS for final product and 62.5% of PS for the runner system, result in just over a third of production energy that result in the final product. This can be seen in Figure 7 below.

Figure 5.2. THE PRECENT OF MATERIALS IN THE PRODUCTS FROM AM AND IM (500000 UNITS).

Figure 6. ENERGY-BASED CROSSOVER PRODUCTION VOLUME OF AM AND IM.

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 7. ENERGY-BASED CROSSOVER PRODUCTION VOLUME OF AM AND IM. IM IS SHOWN WITH FINAL PRODUCT ONLY, AND FINAL PRODUCT WITH WASTE.

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 paper 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

8, 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.

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 9.

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 10 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 crossover production volume. The crossover volume is 530 units when considering only the final product from IM without the wasted materials. It is to 585 units when the waste is also considered. For an IM product that has a 17% surplus quantity, the crossover volume is 600 units. At 34% surplus, it becomes 615 units. With the highest wasted surplus product of 85%, IM has the crossover volume of 675 units.

DISCUSSION

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 cm³. 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.

Figure 8. THE MONTHLY INVENTORY LEVELS FOR 2011 OF A SCALE MODEL KIT DISTRIBUTOR'S INVENTORY LEVEL. THERE ARE 3 HIGH DEMAND PRODCUTS (H), 3 MEDIUM

DEMAND PRODUCTS (M) AND 1 LOW DEMAND PRODUCT (L).

Figure 9. THE PERCENT OF MATERIALS IN THE PRODUCT OF AM AND IM AT DIFFERENT SURPLUS QUANTITY.

Figure 10. THE ENERGY-BASED CROSSOVER PRODUCTION VOLUME SHIFT OF IM AT DIFFERENT WASTE COMPOSITION.

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 work, 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 design 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 fabricated 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 materials used by 3Delivered, Inc. is known to be a type of hydroxylase wax, called VisiJet® S100 support materials [23]. However, due to the fact that the detail classifications of the materials and its related energy consumption are not disclosed, it is not included in this work.

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 [24]. PS is known to be relatively safe in its polymer form. However, its styrene monomer is found to be possibly carcinogenic for humans [25]. 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.

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 paper, accounting for 20-40 kWh/kg [2], the figure for IM amounts to 1.8 kWh/kg [16] [17] [18]. 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 paper, it is assumed that AM product does not require any further energy input, as described in method and result sections (section 3 and 4). 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 [17]. 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 crossover 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 crossover 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 crossover 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 used to produce the materials that become waste. This change in crossover 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 paper 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.

End Customer's Consumption

Most work 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 paper 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 supply chain 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 [26]. The data from the scale model kit distributor, provided by Winner Hobby C. Ltd., Shows that number 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 customers any more, these products will become waste of both materials and energy used to produce them and also the loss of investment. When this leftover product is added as waste to IM, the material usage efficiency decreases the energy-based crossover production volume increase 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 product in fabricated, as AM is able to produce exactly the quantity needed by the customers. The difference in 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 crossover 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 use less energy overall than AM. However, this study 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 customer's demand more closely and reduce the waste of resources.

It has to be noted that the figures of left over inventory is this paper are used for the purpose of pointing out the possibility of 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 [27]. 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.

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 [18]. 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 11 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.

From figure 11, 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.

Figure 11. THE ESTIMATED ENERGY CONSUMPTION OF AM AND IM, IF THE RAW MATERIALS PRODCUTION PHASE IS INCLUDED.

CONCLUSION AND FUTURE WORK

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 a higher 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 crossover 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.

It is important to acknowledge the nature of the case study presented in this paper, and also the specific scenario under study. This study focuses on a niche market, scale model kit industry, and a specific AM technology (stereolithography). Hence the results interpretation and generalization should be handled with caution.

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. AM technologies are also so broad, thus make a radical claim about AM requires investigation also on other AM methods (e.g. SLS, FDM). This paper, as an initial study toward that path, only studied stereolithography (SL) hence its results generalization is limited to that (SL) AM particular method.

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 where up-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.

As pointed out in the discussion, 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, and also in order to complete the understanding of energy consumption of AM technology, an investigation on energy consumption of different AM post-processing methods is also needed. Future work may look to compare the gas emissions and other environmental impacts between AM and IM. However, as it is mentioned in method section (page 4), due to lack of data access, this study excluded those comparison.

The paper 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 requires further 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 work. 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 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.

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