Resource Consumption in Additive Manufacturing with a PSS Approach

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Abstract
Since the 1980's, additive manufacturing (AM) has gradually advanced from rapid prototyping applications towards fabricating endconsumer products. Many small companies may prefer accessing AM technologies through service providers offering production services as result-oriented Industrial Product-Service System (IPSS) rather than investing in their own production line. This study investigated potential benefits of IPSS using system dynamics modeling to study resource demands between two situations: one where an IPSS approach is used and one that is the traditional ownership of production equipment. This study concluded that AM service providers with demand-varying customers could increase service performance and maximize use of production equipment.

Keywords:
Additive Manufacturing, Industrial Product-Service Systems, Resource Consumption

1 INTRODUCTION

Product-Service Systems (PSS) have been introduced as a means to deliver value to the customer through an integrated product and service offering [1]. Broadly, PSS can be clarified into three main categories. These are product-oriented PSS, use-oriented PSS and result-oriented PSS [1]. In the first category, the product is sold traditionally and some after-sale services may be included to guarantee functionality and durability of the product. The use-oriented PSS, the producers maintain the ownership of the product, and the use, function or availability of the product is sold e.g. leasing, sharing. In the result-oriented PSS, the producers sell the capability or the result that the customers want instead of the product. The customers are charged for the provision of the agreed results, the ownership still remains with the producers [1][2]. PSS is thought to be able to provide the same or higher value to customers using equal or less materials, therefore contributing to achieving decoupling of economic growth from the environmental resources used [2]. Five strategies were proposed by Tukker and Tischner that could contribute to achieving this decoupling [2]:

- enhancing impact efficiency of production.
- enhancing the product efficiency of production.
- enhancing the intensity of use of product.
- reducing product composition of expenditure.
- enhancing quality of life per money spent.

Although the reduction of resource consumption was implied in terms of the environmental benefits, the economic gain from providing higher value to customers without increasing resources used was also obvious.

PSS in industrial applications, or Industrial Product-Service Systems (IPSS), has been proposed as a flexible solution that enables manufacturers to adapt to changing customer demands [3]. The flexibility and availability of production capacity given by an IPSS is significant since it can benefit from long-term relationships with customers [4]. 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 [5], the total cost of ownership of production equipment is removed from the customer side [4], etc. It was this potential of PSS to decouple resource consumption from the value provided to customers and the flexibility to respond to the changing customer's interests that are the focus of this paper. The paper also scoped its focus down to the PSS application in an industry using technologies known as additive manufacturing (AM).

In the AM industry the idea of service providers is not new. Such services have been with the industry almost from the beginning, i.e. providing manufacturing services to smaller users with reduced risk of investment [6]. From the manufacturer's view, it could be considered as outsourcing their manufacturing capability to the third party. In this paper, outsourcing activity of manufacturers and the services provided by these companies are viewed as a result-oriented PSS in business-to-business applications according to Tukker and Tischner's PSS classification [2].

One example of these service providers is 3Delivered, Inc, an AM service provider based in the United State of America. The study carried out in this paper was based on the information provided by 3Delivered, Inc.

This paper investigated potential benefits of a result-oriented PSS approach for a service provider in the additive manufacturing industry. This is related to work done by Wangphanich [7], which showed how 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 [2], and the further clarification made by Thompson et al. 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 [8]. 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 had a toxic substance, but hadlessmaterial or energy use, then a statement about which is "more sustainable" would have to be considered in more depth to makeanyjudgment about it.Therefore, the result-oriented PSS had potential to be a more sustainable solution than, for example, the traditional ownership approach. Based on that finding, this paper set out to explore if similar benefits could be realized in a different product category, i.e. the AM industry.

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 called an AM system. In this paper, the term 'AM device' is used to describe an AM system.

2 METHOD

This paper 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 artefact 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 produces that actual physical artefact by fabricating it with the AM devices.

The first approach (Figure 1) was the traditional ownership of production equipment. In this case, thecompany comprised a serviceunit that dealt with customer's demand and a manufacturing unit that produces the artefacts in response to the demand.This implies that the company is responsible for its own AM devices.

The second approach (Figure 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 artefact using 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.

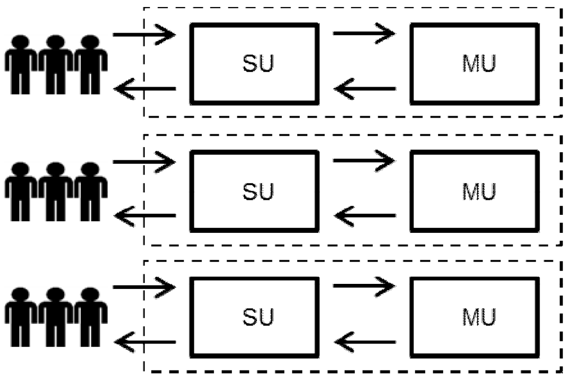

Figure 1: In traditional ownership approach, the manufacturing company functions of both Service Unit (SU) and Manufacturing Unit (MU)

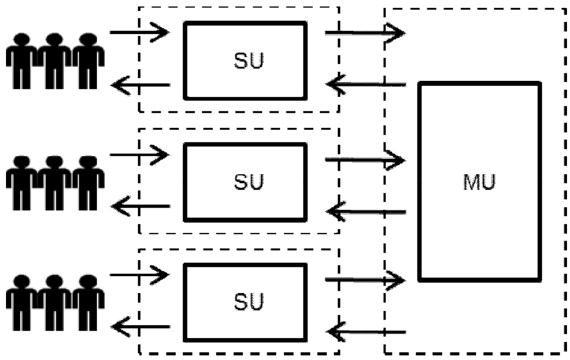

Figure 2: In result-oriented PSS approach, the function of Manufacturing Unit (MU) is provided by fabricator. The Service Unit (SU) remains with the company (manufacturer).

The proposed result-oriented PSS approach has some 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 one 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 manufacturers' responsibility in product pooling.

2.1 Modeling

In order to see the difference in the number of devices required between the two approaches, a system dynamic (SD) model was used to simulate the flow of demand at varied production capacity input. Three demand scenarios were explored in the SD model based on the characteristic of customers' demands

1. Time-critical demand was characterized by urgency of the order. If a manufacturer could not complete the order within one day, the order would be cancelled.
2. Nontime-critical demand was of less urgency. Usually the customer could afford some waiting time. In this paper the satisfactory waiting time was modeled ascompleting the order within 7 days.
3. Mixed demand represented more realistic scenario where different customers had different time demands, with the time-critical order having priority over its noncritical counterpart.

Three hypothetical manufacturers with their own sets of demands were created for each of the three scenarios and were simulated in with following assumptions:

1. The manufacturing was assumed to be on-demand production, meaning that product is built only when an order is placed.
2. Each manufacturer was expected to have a demand of around 10000 units per year. This demand represented a daily randomized range between 0 and 54 units.
3. The AM deviceand the data referred to in this simulation were based on information for stereolithography technology used by 3Delivered, Inc. One device was assumed to be inoperation 20 hours per day, 365 days per year. The other 4 hours were allocated to nonproduction activities e.g. device maintenance.
4. The products from the AM devices were assumed to have identical build time of 5 hours per unit. Therefore an AM device would have an output of 4 units per day.

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

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

2.2 Model optimization

Once the input data was fed into the SD model, the model was adjusted to yield optimal output. The optimal output has the following success criteria:

1. Cancellation oftime-critical order is less than 10%.
2. Nontime-critical demand is met within 7 days.

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

3 RESULT

3.1 Number of AM devices needed

For a manufacturing unit to be able to respond to the demand, it needed to 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 demand 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 the minimum number of AM device in all three scenarios, as shown in figure 3. 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.

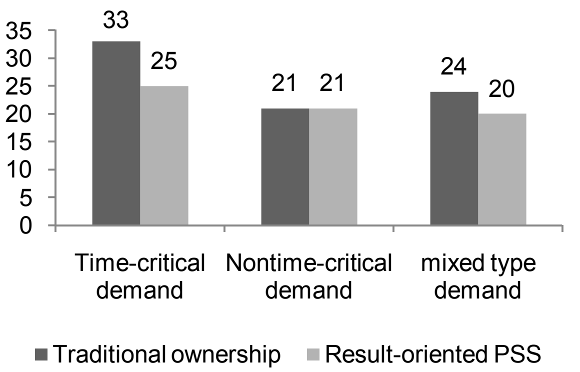

Figure 3: The optimized minimum number of AM devices required for each scenario.

3.2 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 4.

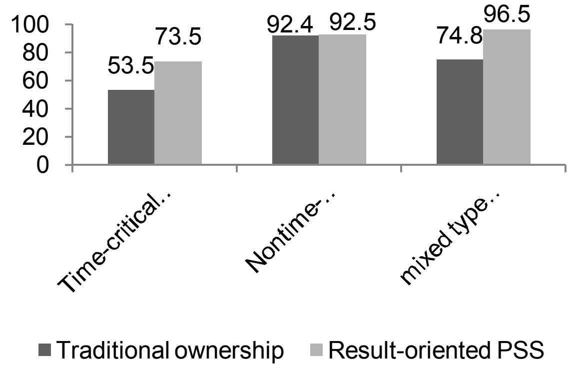

Figure 4: The production capacity utilization (% of AM device capacity that is utilized) for each scenario.

3.3 Fulfillment of customer's demand

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 1.

4 DISCUSSION

4.1 Required number of AM devices

From the SD model, the result suggested that result-oriented PSS supports the reduction of resource use, i.e. the number of AM device in this paper. It showed that less resources (fewer devices) could be used to supply the same or even more value to customer. The reason for this could be explained with the result from the SD model.

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 any time the demand surged above the capacity of these 11 devices, the manufacturer had to cancel the orders that exceeded 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 devices 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 surge 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 source of demand. In this simulation, it was set to deny the lowest demand first, keeping the higher ones. This helped the fabricator utilizing their 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 nontime-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 customer’s satisfaction if it was shipped out within seven days.

In the third scenario, the demand was randomly mixed between time-critical demand and nontime-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 nontime-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 result-oriented PSS approach, which was a result of a 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 much lower number of order cancellations, at 0.7% of total number of order received. In addition, whenever the time-critical demand was high, the nontime-critical demand could be pushed into backlog to be produced in the later days. These two factors helped bring the production capacity utilization up from 74.8% to 96.5%, while the number of device needed was reduced from 24 devices to 20 devices.

4.2 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. Stereolithography used in this paper was just one technology among many options. Each technology has its own characteristics. The fast pace of development of the AM industry that introduces newer and higher performance AM device on almost annual basis is also a factor. For a manufacturer choosing to invest in a certain technology, it is likely that the technology would define 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 choses to use fabricator for manufacturing would be able to change to or add another fabricator with different or higher performance technologies, according to their changing customer’s demand. This follows the argument for the value of flexibility described by Richter [4].

From the fabricator side, the opportunity to capture the production demand of AM product consumer was notable. Since AM is a relatively new technology, more customers are expected to adapt this new manufacturing technique, resulting in more demand in the future [6]. The fabricator would be in a very good position to offer these new comers a choice of producing their creations without upfront investment in manufacturing equipment. The same offer was actually also available from other manufacturing technique e.g. injection molding. However, the competitive edge of AM lay in its distinct characteristic of having no tooling required. This means that there is practically a very low minimum production volume, as opposed to very large production volume required to cover the injection molding tool. The fabricatoris also able to provide the same production capacity to multiple companies at a lower investment, in the form of lower number of device required, than would be the case of those companies were to invest in their own production line.

	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

Table 1: The demand fulfillment performance of each scenario.

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 nontime-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 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 filecould mean the loss of intellectual property topotential competitors.

4.3 Endcustomer value discussion

From an endcustomer's perspective, whatever happened behind the shopfront of a manufacturer was largely unknown or irrelevant to them. Whether the manufacturer was doing in-house production, or outsourcing it to a fabricator, the route that provider most reliable and satisfactory result would then be more preferred. These benefits could be found in fabricator.

4.4 Sustainability discussion

From sustainability standpoint, if there is an alternative to provide the same value to a customer at a lower resource input, then that alternative could probably 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 service 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 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 can not go beyond 100%, as utilization approaches that threshold, additional devices must be added to meet demand, thus the number of devices remains coupled with product output.

The higher intensity of use of the product achieved by result-oriented approach still had another potential environmental benefit. As discussed by Wongphanich, the higher intensity of use could result in the product using up its life capacity sooner. Thereafter it was expected to be replaced be a newer, higher performance and 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 life length of the system was speculated by the company to be independent of the intensity of use. The life limiting factor was the printhead 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 printhead was a consumable part and can be replaced. The replacement would not result in any improvement in its environmental performance.

That the environmental benefit would be incrementally increased each time the product was replaced also relied on an assumption that the subsequentAM decviceswould be improved environmentally as well. The washing machine studied by Wangphanch 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 [6]. Although the performance in building speed and resolution have constantly improved, it might not be the case with the energy consumption.

5 CONCLUSION

This works suggest that the result-oriented PSS in general achieved intensification of 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. However, it is acknowledged that the simplified scenarios discussed in this works do not completely reflect the reality. Further works should be conducted to study the more complicated scenarios with complexity and constraints being taken into consideration.

When intensity of use of a product increases, and the demand for the function of the product remains relatively constant, a reduction in the number of productsrequired to provide the function is achieved. 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 desired decoupling.

Increased intensity of use of product could result in earlier replacement of the product, only when the life length 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 increase the flexibility in production capacity allocation and support maximizing the use of production equipment.

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