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Simulation based method considering design for additive manufacturing and supply chain: An empirical study of lamp industry

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Simulation based method considering design for additive manufacturing and supply chain

An empirical study of lamp industry

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Abstract
Purpose – The purpose of this paper is to develop a decision support tool to use with design for additive manufacturing (DfAM) and design for supply chain (DfSC) such that the Supply Chain (SC) configuration for a personalized product can be optimized under various demand uncertainties.
Design/methodology/approach – A simulation-based methodology is proposed in this industry-university cooperative research. Through identifying the company requirements with interview, an application programming interface (API) and simulation model were developed to solve the DfAM and DfSC problems of case company. Based on customer preference, the SC configuration is analyzed and suggestions are developed according to simulation results at the product design.
Findings – Results show the supplementary capacity of the additive manufacturing (AM) process improves the SC performance in terms of lead time and total cost. This work identifies the research gap between AM and SC, and gives a comprehensive investigation of different performance indicators, such as order fulfill rate and waste rate.
Research limitations/implications – Metal AM technology was not in the mass production stage at the time of this study. Thus, this research mainly emphasizes a nonmetal AM process.
Practical implications – AM technology can improve SC performance through its supplementary capacity and help the SC to be more flexible, robust and resilient in terms of lead time and total cost. This research implements an API to assist decision making. The findings of this research provide case company a valuable reference while branching its business.
Originality/value – This is the first study that considers both DfAM and DfSC with the integration of an API. It also addresses the demand fluctuation level and stochastic demand of a personalized product in a unique approach.

Keywords Simulation, Design for additive manufacturing, Decision support system, Design for supply chain
Paper type Research paper

1. Introduction
Additive manufacturing (AM) is a rapid prototyping (RP) technology that produces a 3D part by laying shapes of material layers. It first appeared in the 1980's (Campbell *et al.*, 2012), and was utilized to generate mold models for manufacturing. More recently, AM has become widely known as the trigger of the third industrial revolution. This evolution is from the patent of the main AM technology, fused deposition modeling, expired in early 2014. This consequently resulted an obvious progression for AM-related products, such as the emergence of consumer 3D printers and assistant software for consumers.

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AM has the potential to influence the supply chain (SC) from the manufacturing perspective since it is the opposite of most traditional manufacturing processes (which are subtractive). Researches presented that AM can be adopted to achieve agile SC (Vinodh *et al.*, 2009) as well as reduce the cost by up to 75 percent (D'Aveni, 2015) for manufacturing companies, and further influence the current SC (Cotteleer and Joyce, 2014), such as aerospace and automotive (Manners-Bell and Lyon, 2012; Thymianidis *et al.*, 2012). AM allows the direct production of parts without molding, making it especially capable for personalization, which is a market with better profit (Petrick and Simpson, 2013). Table I shows the comparison of AM and traditional manufacturing.

This research aims to solve the problem that enterprises are facing with academic knowledge and solutions using a case study. With the proposed methodology, the disturbances of case company are identified and solved through integrating the idea of design for additive manufacturing (DfAM) design for supply chain (DfSC). An application programming interface (API) is implemented for the customers to help eliminate any barriers to design their personalized products. Pursuing the goal of DfSC, the SC is optimized during the product design process with the data collected from API. Finally, the capacity allocation between AM and traditional machines using supporting ratio is investigated in this research. Results show that SC performance is improved with AM process in terms of lead time and total cost. The research gaps on AM and SC are identified, and a comprehensive analysis is given in terms of order fulfill rate and waste rate. This is the first work that considers both DfAM and DfSC. In addition, the demand fluctuation levels of a personalized product are addressed.

In Section 2, the literature related to AM/SC's and design techniques is reviewed. Section 3 introduces the proposed methodology. Section 4 provides information about the case study and the implementation of DfAM and DfSC. Section 5 reviews the case study results and analysis. Finally, a brief summary and conclusion is provided.

	Compared object	
Compared item	Additive manufacturing	Traditional manufacturing
Fundamental principle	Compose product by material layers	Remove unnecessary parts
Applied phase	Design phase	Manufacture phase
Product variation	Mass customization/personalization	Mass production
Total output	Low production	High production
Manufacturing speed	Slow	Fast
Price of unit product	High	Low
Diversity of utilized material	Depends on AM technology	Almost everything
Advantage	1. Less material required 2. More environmental friendly 3. Ease of design improvement 4. High degree of customization 5. No need of tool and jig	1. Less Cost 2. Higher produce speed 3. Mature technique 4. Almost no limitation of product types
Weakness	1. Higher cost 2. Slower produce speed 3. Technique is not mature enough 4. Limited type of product by the utilized material	1. More material wasted 2. Less environment friendly 3. Hard to change design 4. Lack of ease of customization 5. Need of tool and jig

Sources: Atzeni and Salmi (2012); Huang *et al.* (2013); Petrovic *et al.* (2011)

Table I. Comparison between AM and traditional manufacturing

2. Literature review

2.1 AM

Compared to traditional manufacturing, AM is capable to build a part with varying mechanical properties, which means the functionality of parts will not be sacrificed for ease of manufacturing. Additional benefits, such as lead time reduction as well as cost reduction from eliminating jig and tooling allow manufacturer to produce small batches economically and to change design quickly (Atzeni and Salmi, 2012; Huang *et al.*, 2013). Some other researches claimed that AM is capable to produce usable parts with high quality and reduce environmental cost (Kreiger and Pearce, 2013; Marya *et al.*, 2015). Huang *et al.* (2015) conducted a case study in aerospace industry, and the results showed that AM can potentially reserve energy consumption on automotive, tooling, medical and other industries. Consequently, AM is expected to act as a promoter of mass personalization and emerging field of academic because of these possibility of its manufacturing capability. The progress of information technology and 3D printing will progressively catalyze personalized service and price optimization (Piotrowicz and Cuthbertson, 2014).

Although AM has an impact on production, only a few researches regarding design and evaluation of additive manufacturing supply chain (AMSC) have been conducted. Berman (2012) noticed the potential of AM and estimated that 3D printing SC will be significantly developed within five years. Gress and Kalafsky (2015) presented that AM has the potential to transform the SC through "spatial leapfrogging," which means new commercial activities and innovations happen in new places. Khajavi *et al.* (2014) proposed AM machine technology and SC configuration as two analytic dimensions. The implementation cost of an AM machine is considered, but the annual demand is assumed to be fixed in the research. Liu *et al.* (2014) evaluated the performance of different SC configurations based on the required amount of safety inventory and built their simulation model based on the structure of a supply chain operation reference considering AM technology. These researches investigated the changes of AMSC without optimization, which is an important issue for enterprises.

2.2 Design for excellence (DfX)

The "X" in DfX was for "Excellence," inferring that a product could become perfect through continuous improvements. Scholars posited that "X" could be anything; this in turn implied that a designer considered a specific factor when designing the product to improve its performance, or brought out the implicitness of the factor (Lee and Sasser, 1995). Chiu and Kremer (2011) reviewed a significant body of literature addressing challenges that DfX faced and clustered the DfX thematically. DfX can be applied to achieve three kinds of purpose. First, to present a strategy or framework to implement DfX, such as DfSC for the enterprise SC configuration at product design stage (e.g. O'Driscoll, 2002; Swift and Brown, 2003). Second, to accomplish different goals, such as to decrease product life cost through design for manufacturing or design for recycling (Kriwet *et al.*, 1995; Curran *et al.*, 2007). The third is to engage two or more DfX simultaneously with multi purposes (Boothroyd, 1994; Chiu and Teng, 2013). Other research further integrated multi-criteria decision making and DfX. Holt and Barnes (2010) categorized DfX into life phase and virtue phase to remind the designers the impact of product in the given product life time.

van Hoek and Chapman (2006) presented that the impact to SC of new product design should be considered to ensure the efficiency of SC, which was the concept of DfSC. The coverage of a SC is very wide, incorporating decision making about the supplier, the manufacturing facility, the storage facility, the transport vehicle, the distribution center, and the retailer. Since SC is an aggregation of various stakeholders that gather to fulfill customer needs, the way to run a SC efficiently is a pivotal consideration point in its design. Chopra and Meindl (2004) considered a SC design problem as a series of decisions about production facility locations to improve the performance of SC. Ho *et al.* (2010) integrated the existing individual approaches into a technique for SC evaluation and suppliers selection.

Khan *et al.* (2012) addressed that the alignment of product design with the SC will strongly improve resilience and responsiveness of SC, showing the importance of DfSC. DfSC has been applied in numerous case studies and commonly utilized key performance indicators (KPIs), such as cost, lead time and inventory level (Beamon, 1999; Gunasekaran *et al.*, 2004; Ismail and Sharifi, 2006) should be considered during the product design stage. Scholars have proposed different methodologies for DfSC analysis, based on different goals of their researches. To minimize total cost, ElMaraghy and Mahmoudi (2009) proposed an integer linear decision-making model considering product modularity and the SC configuration but product demand, transportation lead time were assumed to be fixed. In order to solve the product platform design and SC design problem, Huang *et al.* (2005) utilized a genetic algorithm for optimizing sourcing, manufacturing and product delivery configuration, evaluating the SC performance with SC cost. A mixed integer linear programming model that considered product family design and optimized the operating cost of SC was presented by Lamothe *et al.* (2006). Gokhan *et al.* (2010) developed a mixed integer planning model to simultaneously consider product design and SC performance in terms of profit, time-to-market. Chiu and Okudan (2014) investigated the impact of the modularity level to the cost and lead time performance of SC at product design stage. Additional research combined fuzzy set theory, analytic hierarchy process and the Taguchi loss function to optimize the green SC of a product under uncertainty using a motor bike case study (Chiu and Teng, 2013).

From these researches, it is noticed that most of the DfSC researches focus on mature product, but there's a new personalized market with potential waiting to be investigated.

2.3 SC Simulation as decision support

The decision making of SC is sophisticated since a SC problem covers extensively from supplier, manufacturer, storage facility, distribution center to retailer. Relationships and interactivities between each SC member will influence the SC performance. Simulation has been applied in the SC decision-making problems that are too complicated for mathematical models. Persson and Olhager (2002) applied simulation to model the complex relationship of a mobile communications manufacturing system and observed the system activities which were too complicated using mathematical model. Discrete-event simulation (DES) was employed as an appropriate tool for manufacturing performance analysis problems (Ball, 1998). Holst and Bolmsjö (2001) created different scenarios and analyze the manufacturing performance to accomplish maximum productivity from aspect of cost with DES. Labarthe *et al.* (2007) conducted simulation of SC methodological framework to achieve mass customization. In Wu (2009), a simulation-based approach was applied to simulate SC performance under uncertainty and suggestions were provided to select suppliers from economic perspective. Considering shrinkage, cost and out-of-stock percentage, simulation can be utilized to achieve quality controlled logistics in food SC problems (van der Vorst *et al.*, 2005, 2009). Furthermore, some researches utilized simulation to test the robustness of their mathematical solutions from the Pareto optimal frontier, such as Claypool *et al.* (2014) and Chen *et al.* (2012) presented in their works. Nikolopoulou and Ierapetritou

(2012) presented a hybrid simulation approach, which integrated mathematical functions and simulation model to optimize the SC. Beyond these applications, Lee and Billington (1993) applied a simulation model to find the best SC material flow and optimize the service level. From the above literature review, it can be noted that simulation is widely applied to solve SC-related problems.

2.4 Summary

According to the reviewed literature, it can be concluded that the impact of AM on the manufacturing industry is sufficient. AM provides increased possibilities to the manufacturing industry. Although AM has numerous advantages, there are two barriers need to be solved. First, AM is beneficial to innovation and personalization, but there are not sufficient case studies that probed into SC optimization issue, which is important for the enterprises. Next, researches about DfSC are plenty, but the existing issues mostly put effort on mature products, such as office chair and automobile SC. It is clear that the potential of personalized product market has not been investigated in existing researches. Enterprises have been searching for proper way to locate their expensive investment**s** but still few researches address the design of an AMSC, not to mention the optimal way to operate an AMSC remains uncertain. Therefore, the aim of this paper is to achieve DfAM through simulation and an implemented API. In conjunction with the API, the AMSC will be optimized in both planning and simulating to achieve a joint DfAMSC.

3. Methodology

This paper aims to eliminate the barriers that case company encountered. A simulation based methodology was proposed in this research. This project was initiated in the summer of 2014 and currently under second review of the case company in the summer of 2015. The flow of the proposed method is shown in Figure 1. The steps of proposed methodology is on the left, and the executed actions are on the right. From the interview with the manager of case company, it is confirmed that the case company has confronted several challenges when they endeavor to provide personalized service. The first one is that the customers are not capable to design their desired product with existing CAD tool. The second challenge is that the case company has to deal with the demand uncertainty from the personalized service, which they have never met. Third, new AM machines should be procured since it is time-consuming and cost-consuming to manufacture personalized product with traditional manufacturing process. However, the case company is not certain about this decision. Lastly, this service is different from the case company's previous business model. There is a need to reconfigure the SC and estimate the implementation cost again. Thus, this case study pays attention on supporting the case company to best locate their expensive equipment investments and choosing appropriate supplier and distributor.

This research proposed a methodology to solve the problems of the case company. For the first barrier, an API was implemented to simplify the design process. This research developed an API according to the information gained from interview. The implemented API is capable to access the volume information of the designed product. The API will be reviewed and revised by the case company to confirm if the provided features are usable. The accessed product data will be utilized to calculate the material consumption and time consumption of corresponded personalized product. As a result, the second barrier can be conquered with the data. DES is chosen

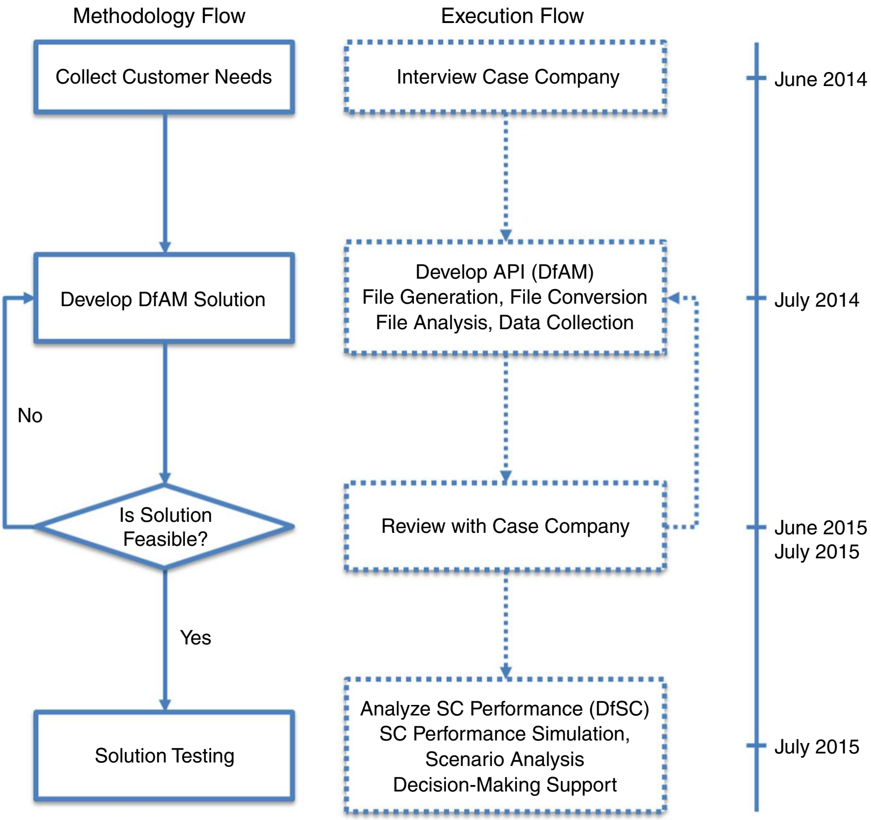

Figure 1.
Flow of proposed methodology

to solve the third and last barrier. The performance of new machines and new manufacturing process are unidentified. Moreover, the activities of different SC members are stochastic and obey different distributions. Therefore, this research considers simulation as the appropriate tool to estimate the SC performance of the case company with different combinations of supplier and distributor. Lastly, the simulation results and implemented API will be reviewed again by the case company to see if the outputs are reasonable and applicable. More details of the proposed method will be explained in the following sections.

3.1 From API to DfAM and DfSC

The first challenge to the case company is that most of the customers are not capable of using CAD software. Hence, this research has implemented an API as the DfAM tool to overcome this initial barrier. The benefits of API to both manufacturers and customers are demonstrated in Figure 2. A user-friendly environment will be created, which allows customers to generate their desired personalized products. The API will also calculate the material and time consumption, and these data will be collected in the backend. The parameters and settings of the SC simulation models will be constructed based on the collected data. For the manufacturer, these data will be utilized to achieve DfSC and decision making through simulation.

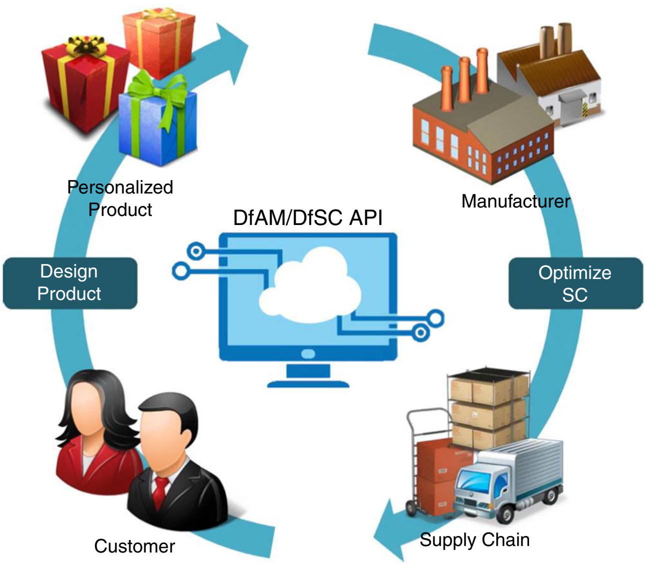

Figure 2.
The API benefits to both manufacturer and customers

3.2 SC simulation and simulation model

The purpose of the simulation models is to simulate the performance of the SC for a personalized product while considering manufacturing process planning and SC reconfiguration. In addition, the fluctuation of market needs is taken into consideration in this research. The SC consists of the customer, the material supplier, the case company and logistics. Customers will place orders after a period of time. The number of orders arriving varies each day. A material supplier provides the material needed. The manufacturer begins manufacturing after the orders have been placed. The orders which are not able to be manufactured immediately will enter the queue and wait to be fulfilled.

To investigate the different SC performance between the traditional manufacturing process and a hybrid manufacturing process under various demand fluctuation level, two models with different manufacturing processes were constructed. The difference between these models is the use of the AM machine. In the traditional manufacturing process, the AM machine is utilized to produce personalized parts while the industrial standard computer numeric control (CNC) machine is utilized to manufacture the customized and standardized parts. A hybrid process enables some customized processes for AM machines. Hence, the system variables can be described as below:

(1) Fluctuation level of demand: given the special characteristics of AM technology, it is possible that AM can support a traditional manufacturing process when needed; however, traditional machines and manufacturing processes are challenged to support the AM manufacturing process when the capacity of the traditional machine is exceeded. This study considers low, middle and high levels of demand fluctuation.

(2) Manufacturing process type: this research considers the traditional manufacturing process and the hybrid manufacturing process when producing the necessary part of the personalized product.

3.3 SC optimization

The goal of this study is to optimize the SC through simulation while considering both DfAM and DfSC. The mathematical model here is proposed to describe the SC.

Indices

I	Number of suppliers with $i=1, 2, \ldots, I$
J	Number of distribution centers with $j=1, 2, \ldots, J$
K	Number of orders with $k=1, 2, \ldots, K$
L	Number of parts with $l=1, 2, \ldots, L$
S	Number of supporting ratio with $s=1, 2, \ldots, S$

Parameters

a_S	Regression coefficient of material consumption of supporting ratio s
b_S	Residual of material consumption of supporting ratio s
c_S	Regression coefficient of process time of supporting ratio s
d_S	Residual of process time of supporting ratio s
MC_{kls}	Material consumption of part l in order k, produced with supporting ratio s
TC_j	The transportation cost of each product from distributor j to the customer
BLC_{KS}	The backlog cost generated by order k with supporting ratio s
M_S	The manufacturing cost of supporting ratio s
PT_{kls}	Process time of part l of order k, produced with supporting ratio s
STP_i	Transportation time of supplier i to case company
DTP_j	Transportation time of distributor j to the customer
V_{kl}	Volume of part l of order k
c_i	Capacity of supplier i
d_j	Capacity of distribution center j
AT_s	Assembly time of supporting ratio s

Variables

F	Number of finished orders by case company
BM_i	Quantity of material bought from supplier i
SP_j	Quantity of product sent by distributor j

$$X_i = \begin{cases} 1, & \text{if supplier } i \text{ is selected} \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

$$X_j = \begin{cases} 1, & \text{if distributor } j \text{ is selected} \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

$$X_m = \begin{cases} 1, & \text{if supporting ratio } s \text{ is selected} \\ 0, & \text{otherwise} \end{cases} \tag{3}$$

Object function:

$$\begin{aligned} \min \text{Total Cost} = & \sum_{k=1}^{F} \sum_{l} \sum_{s} MC_{kls} X_s + \sum_{j} TC_j SP_j \\ & + \sum_{k} \sum_{s} BLC_{ks} X_s + \sum_{s} M_s X_s \end{aligned} \tag{4}$$

$$\min \text{Lead Time} = \sum_i X_i STP_i + \sum_k \sum_l \sum_s \max\{PT_{kls} X_s\} + AT_s + \sum_j DTP_j X_j \quad (5)$$

Subject to:

$$\sum_i X_i = 1, \ \forall i \quad (6)$$

$$\sum_j X_j = 1, \ \forall j \quad (7)$$

$$\sum_{\text{s}} X_s = 1, \ \forall \text{s} \quad (8)$$

$$\sum_i BM_i \leqslant c_i \quad (9)$$

$$\sum_j SP_j \leqslant d_j \quad (10)$$

$$MC_{kl\text{s}} = a_{\text{s}} V_{kl\text{s}} + b_{\text{s}} \quad (11)$$

$$PT_{kl\text{s}} = c_{\text{s}} V_{kl\text{s}} + d_{\text{s}} \quad (12)$$

There are two objectives. The first objective is to minimize the total cost of the SC in Equation (4). The second objective function in Equation (5) calculates lead time from upstream supplier, manufacturer, distributor, to final customer. Constraints (6-8) stipulate that only one supplier, one distribution center and one manufacturing process can be chosen. Constraints (9) and (10) represent the capacity limit of the supplier and the distribution center. Constraints (11) and (12) define the calculation process for the material and time consumption of supporting ratios. Material and time consumption are considered to have positive relationships with volume for AM. The regression coefficient will be calculated according to the collected data.

4. Case study

The case company is a lamp manufacturer located in Hsinchu, Taiwan. The business coverage of the case company is to manufacture and sell lamps. The type of lamp includes standardized and personalized. A personalized lamp is manufactured by the case company, the material of the personalized lamp is bought from ABS and lightbulb suppliers, and the finished personalized lamp will be distributed to each customer directly through distributor. There is no warehouse for finished goods since the product is make-to-order. The case company currently operates with one ABS supplier, three lightbulb suppliers and two distributors in Hsinchu. In recent years, an increasing number of customers have asked for personalized lamps. The profit which can be earned from manufacturing personalized lamps is estimated to be higher than that for standard lamps, prompting the company to consider the possibility of branch out. The case company has been concerning to procure AM machines to manufacture the personalized lampshade or not since the traditional manufacturing process is too time-consuming and cost-consuming. Therefore, to investigate the benefits that can be brought by AM, the research team discussed with the case company to plan a new manufacturing process. The throughput and time performance of new manufacturing process should be confirmed before it is applied. Since a lampshade is composed of various different materials and the mechanical limitations exist, this research has following assumptions:

(1) There are three main sizes of body: the lamp bodies are produced by cutting three different sizes of ABS material bulk, and the AM machines are able to produce them. Because the case company is a small enterprise, it lacks space to store the parts. Also, it wants to deliver highly personalized products so injection molding parts are not considered.

(2) The finished goods can be manufactured with ABS.

(3) The yield rate is 100 percent for both the CNC machine and the AM machine.

(4) The machines will not break down.

(5) The quality of finished parts from the CNC machine and the AM machine are the same.

(6) The time consumption of an AM machine made product is determined by the volume of product.

4.1 The implementation of API: lamp factory

In this research, the API ("Lamp Factory") was developed and implemented using C# programming language under Microsoft Visual Studio© 2010. Solidworks© 2010 was utilized to draw the CAD model. Figure 3 shows the interface of the API, which provides five features to accomplish DfAM.

The first feature is the forming function. With this, users can easily sketch a CAD model of the lampshade by choosing the desired shape and identifying the desired length, width and height. The second feature allows the user to shell the body of the lamp. Using this feature, the API will automatically calculate the minimum feasible thickness of the lampshade and display the results. The third feature analyzes material usage to calculate the weight and volume of the lampshade. The user can generate an approximate idea of the personalized product with the provided information. Furthermore, the manufacturer can conduct a product statistics based on this information. The fourth feature of the API is its ability to convert the CAD model to an STL file, which is required for use with a 3D printer. The forming, shelling, calculating and data converting features above are accomplished with the functions from Solidworks© 2010, including sketch function ("circle," "polygon," "rectangle" and "ellipse"), loft function, shell function, material function and save function. A 3D printing physical prototype is shown in Plate 1. The fifth feature is data collected from the product design files can also be utilized to calculate the time needed to produce the product. The "mass properties" function of Solidworks© 2010 is utilized to access the product volume and weight information. Product information will be recorded into a .txt file and these data are collected to determine the volume distribution of the customer-desired designs through the input analyzer, which is provided by Arena® Simulation Software, to further increase the reliability of simulation model.

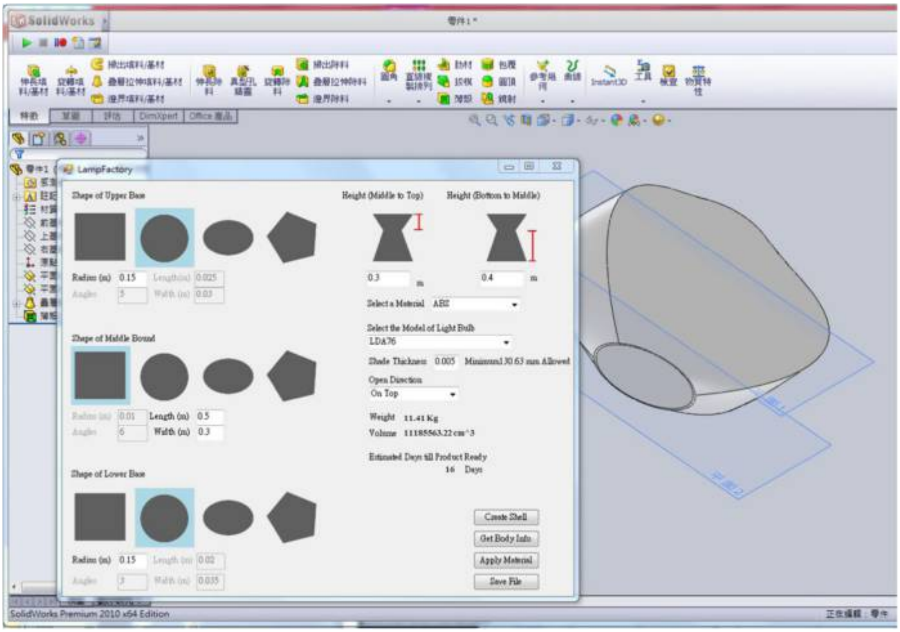

Figure 3.
Estimate product lead time after personalized design

Plate 1.
3D Printing Prototype

Moreover, the API will calculate the material consumption and time consumption based on the collected data, and these data will help the manufacturer to estimate the capacity demand, leading to the enhancement of scheduling and capacity management.

4.2 System simulation and simulation model

The case company allocates capacity based on previously collected sales data since the service has not been provided to the customers. The observation is made that the capacity of the AM machines cannot be completely utilized if the AM machines are only used to manufacture personalized lamp shades. Thus, this research considers a hybrid manufacturing process composed of both the CNC and AM machines. The three main parts of a personalized lamp are personalized lampshade, lamp body and lightbulb. Personalized lamp shade is fabricated with AM machine, lamp body is fabricated with

CNC machine, and the lightbulb is bought from the suppliers. These parts will be assembled by the worker as a finished product when all the parts are ready. The proposed new manufacturing process of a personalized lamp is shown in Figure 4. The key point of the hybrid manufacturing process is that AM machine will support the CNC machine with the production of lamp bodies when the AM machine is otherwise idle.

The scheduling rules of manufacturing process in AMSC are:

(1) the processing sequence of the placed customer orders is first in, first out (FIFO);

(2) the manufacturing priority of a personalized lamp shade is higher than that for the lamp body; and

(3) the AM machines support CNC only when there are no shade orders in queue.

Based on the given description of the system and the model, the simulation model of manufacturing process for a personalized lamp shade is as shown in Figure 5.

The highlighted decision-making module shown in the red square in Figure 6 is responsible for dispatching the lamp body orders. The first task of this module is to assign the order properly, given that the priority of the shade order is higher than that for the body order. The second task of the module is an AM capacity regulator. This research considers setting this regulator with different "supporting ratio" because the flexibility of AM capacity should be confirmed. The supporting ratio ranges from 0 to 13. Supporting ratio 0 means that no AM machine will support the CNC machine to produce lamp body, and bigger supporting ratio means more AM machines will support the CNC machine. For example, supporting ratio 6 means at most six idle AM machines will process the lamp body orders although there are much more orders waiting to be processed. This module will assign body orders to the CNC at the beginning. Otherwise, the body orders are assigned to idle AM machines. This module is critical because it takes more time for the AM machine to produce a body than for the CNC to do the same task. Thus, there should not be any body order in the processing queue of the AM machines.

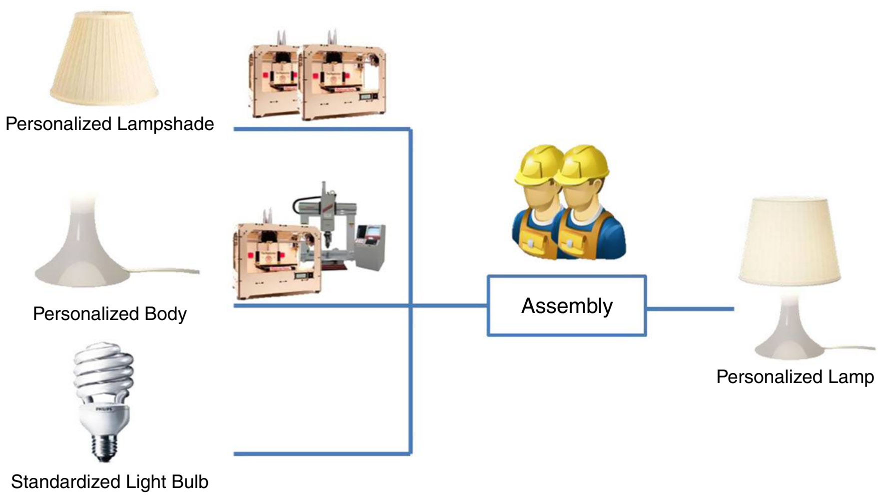

Figure 4. Manufacturing process of a personalized lamp

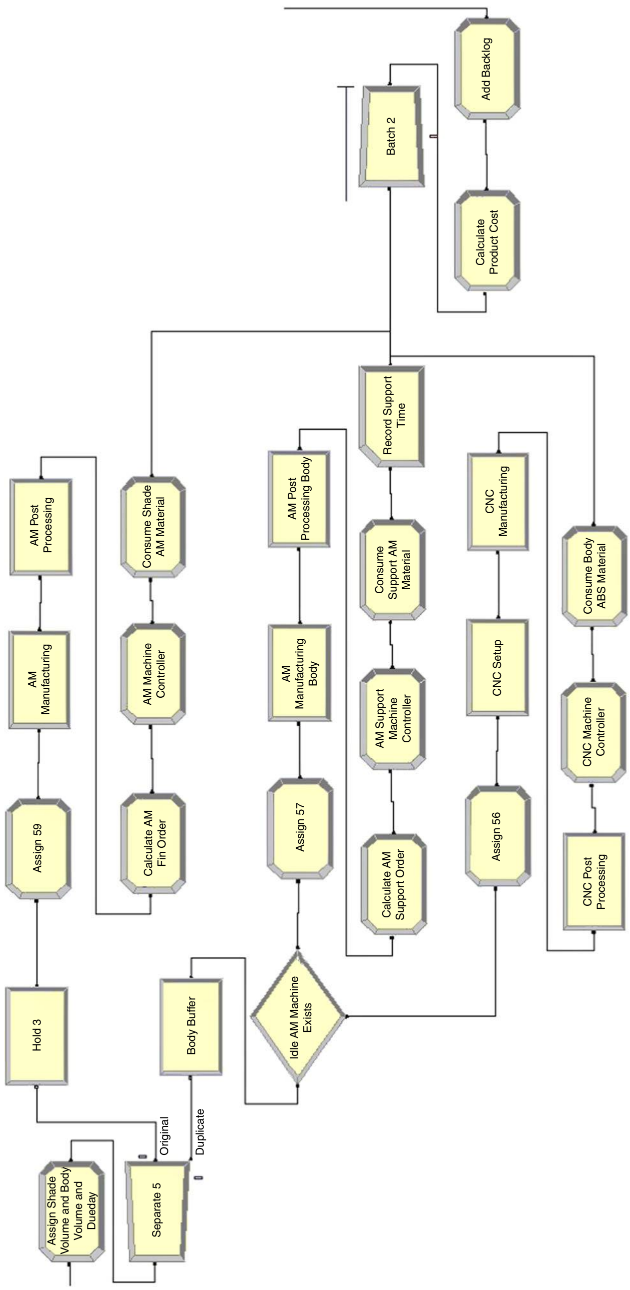

Figure 5.
Simulation model of hybrid manufacturing process

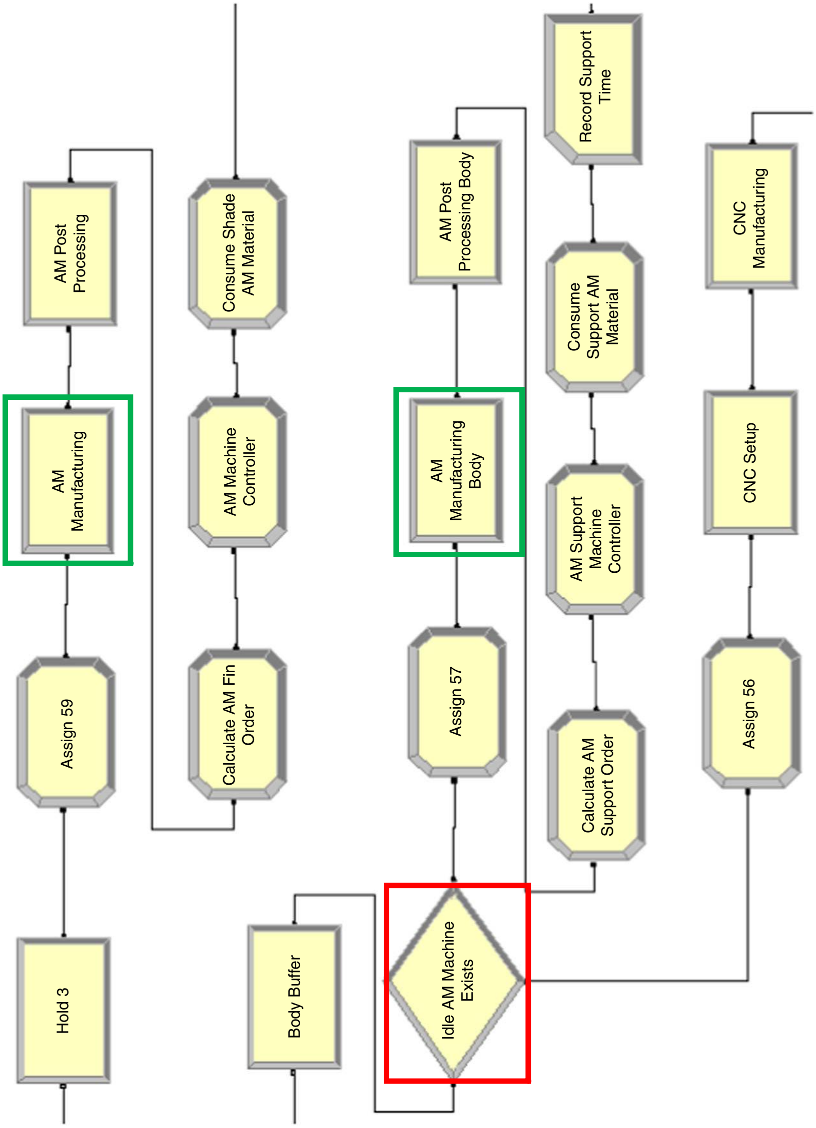

Figure 6.
The additional decision module and adjusted processes for new manufacturing process

The processes, highlighted in the green boxes, in Figure 6, will fabricate products using the same AM machines group. The upper process is for shade production, while the below process is for body production. To ensure the AM machines will process the shade order first, the priority of upper one is set higher than the one below. The decision-making logic is shown in Figure 7.

The set parameters of the model are summed up in Table II. The statistics of "AM Post Processing," "CNC Setup," "CNC Manufacturing" and "CNC Post Processing" were provided by the case company. The value of other parameters were estimated based on information provided by the case company. The "input analyzer" provided by Arena® Simulation Software was utilized to convert these statistics to the parameters and has confirmed with manager of case company.

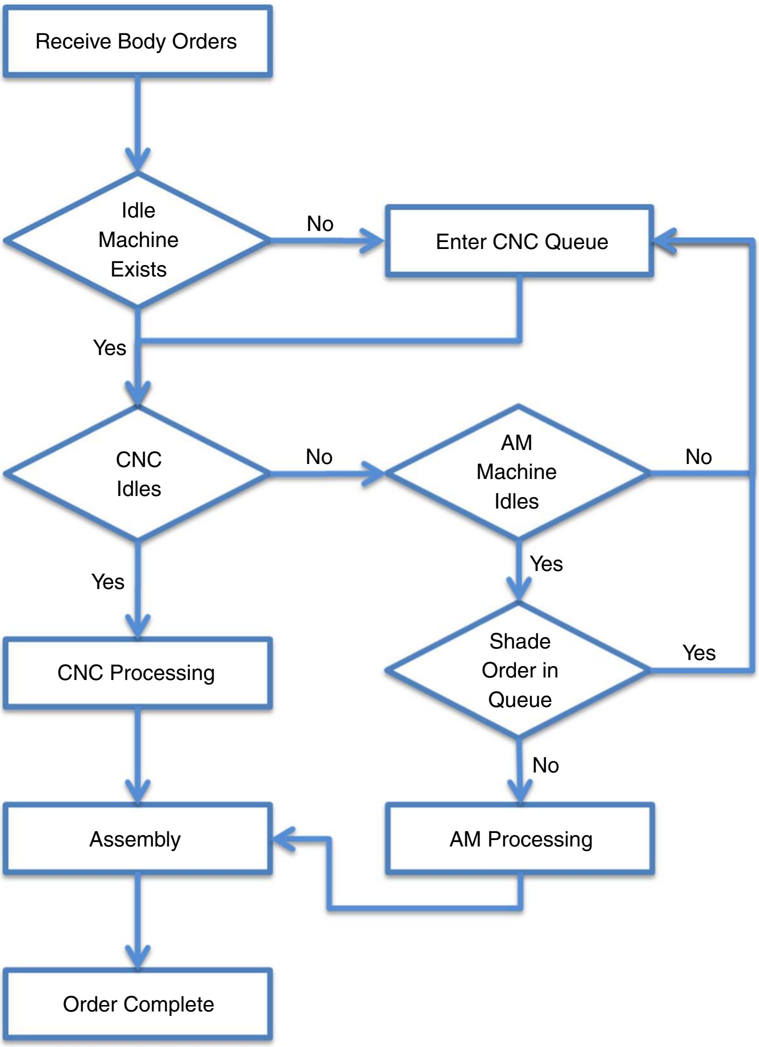

Figure 7.
Flow of body process in new manufacturing process

Number	Name of parameter	Set value in Arena
1	Time between order arrivals	Exponential (1) Days
2	Entities per arrival	Normal (4, 0.4) represents low level Normal (4, 1.2) represents middle level Normal (4, 2.0) represents high level
3	Shade volume	32,200 + Weibull (1,080,000, 0.506) cm^3
4	Body volume	$\begin{cases} 0.3, & x = 504,000 \\ 0.3, & x = 3,000,000 \\ 0.4, & x = 12,000,000 \end{cases}$ gram
5	AM manufacturing shade	Seize delay release 1 AM machine, priority (1) 0.001995 × Volume + 53.5224 min
6	AM post processing	Seize delay release 1 worker, priority (2) $\begin{cases} \frac{(x-15)}{125}, for\ 15 \leqslant x \leqslant 25 \\ \frac{2(40-x)}{375}, for\ 25 < x \leqslant 40 \end{cases}$ min
7	AM manufacturing body	Seize delay release 1 AM machine, priority (3) 0.0009977 × Volume + 53.5224 min
8	CNC setup	Seize delay release 1 worker, 1 CNC, priority (3) Uniform (10, 20) min
9	CNC manufacturing	Seize delay release 1 CNC, priority (1) $\begin{cases} \frac{(x-5)}{3}, for\ 5 \leqslant x \leqslant 7 \\ \frac{(8-x)}{3}, for\ 7 < x \leqslant 8 \end{cases}$ hours
10	CNC post processing	Seize delay release 1 worker, priority (2) $\begin{cases} \frac{(x-5)}{25}, for\ 5 \leqslant x \leqslant 10 \\ \frac{(15-x)}{25}, for\ 10 < x \leqslant 15 \end{cases}$ min

Table II.
Parameters of the simulation model

The simulation model was conducted using Arena® simulation software. The length of each simulation was two months, with a one-month warm-up period and a 24 hour-per-day run time. To observe the SC performance under different fluctuation levels, the batch size of each order arrival was divided into three levels, respectively, low, middle and high level with an average monthly demand of 120. The number of replications was set at 100 for each SC configuration and fluctuation level.

4.3 Results

The inputs of this model in the simulation are the fluctuation level, including low, middle and high level; and the support AM machines from 0 to 13. Value 0 means no AM machine will support CNC machine, and larger value means more AM machines will support CNC machine. The results of the simulation will be presented in the following sections, which will be arranged as the following order. The first is minimization of total cost, and the second is to minimize lead time. In the respective sections, the proper SC configuration will be suggested, and the SC performance of different value of supportive AM machines will be discussed based on specified performance indicators. Moreover, the total ABS material consumption will be discussed along with different AM utilization.

4.3.1 Total cost. As an important SC performance indicator, the simulation results of total cost are categorized into low, middle and high fluctuation levels. Two scenarios: AM support or not are compared. For readability, in the following sections, SC configuration^{1A} will represent that "lightbulb supplier 1" and "distributor A" is chosen. The information of lightbulb suppliers and distributors are summarized in Tables AI and AII.

For low fluctuation level, SC configuration^{1A} provides less cost, and total cost is 1,423,332 New Taiwan dollars. The AM support scenario has cost advantage but longer lead time. For middle and high fluctuation levels, SC configuration^{3B} performs better both in total cost and lead time and the best choice is SC configuration^{3B}. The detailed result information is shown in Table III. Table III compares the performance of supportive AM machines and the best supporting ratio (11, 10 and 4 for low, middle and high level) of the chosen SC configurations. The more AM machines involve, the lower the total cost.

Figure 8 shows the trends of cost of each selected SC configuration under different fluctuation levels. From right to left is high fluctuation level, middle fluctuation level and low fluctuation level. The *y*-axis is cost, and the *x*-axis is number of supportive AM machines. The blue curve represents the total cost and the red curve represents the material cost.

The total cost decreases as the material cost decreases, which resulted from larger supportive AM machines. The reason for this situation is that AM fabricates with less material than traditional machine. This implies that if the decision maker pursues lower cost, he can choose the supplier and distributor with lower cost, and has his AM capacity allocated with higher AM supportive ratio.

4.3.2 Average lead time. The average lead time is calculated when the simulations satisfy the terminated conditions. Two scenarios: total cost and lead time minimization are compared. For low fluctuation level, SC configuration^{2B} provides shorter lead time of 7.11 days. For middle fluctuation level, SC configuration^{3B} performs better, and has the lead time of 7.22 days. For high fluctuation level, the most suited supplier combination is still SC configuration^{3B}, whose lead time is 7.64 days. The detailed result information is shown in Table IV.

Figure 9 shows the trends of lead time (upper row) and order fulfill rate (lower row) of each selected SC configuration under different fluctuation level. The *y*-axis is time for the upper one (lead time) and percentage for the lower one (order fulfill rate), and the x-axis is number of support AM machines.

It is noticed that order fulfill rate increases as the lead time decreases, showing the opposite trend. The best solution exists when number of support AM machines is around four. The average lead time of high fluctuation level is longer than middle and low level, which leads to the lower order fulfill rate. This implies that if the decision

Table III. Suppliers with best performance under different fluctuation level

	Low level		Middle level		High level	
Lightbulb supplier	1		3		3	
Distributor	A		B		B	
Support AM no.	11	0	10	0	4	0
Lead time (days)	11	9.09	8.59	9.15	7.65	9.38
Total cost (NT dollars)	1,423,332	1,826,192	1,514,616	1,812,128	1,607,139	1,810,259
Order fulfill rate	0.7984	0.7486	0.7552	0.7421	0.783	0.7228

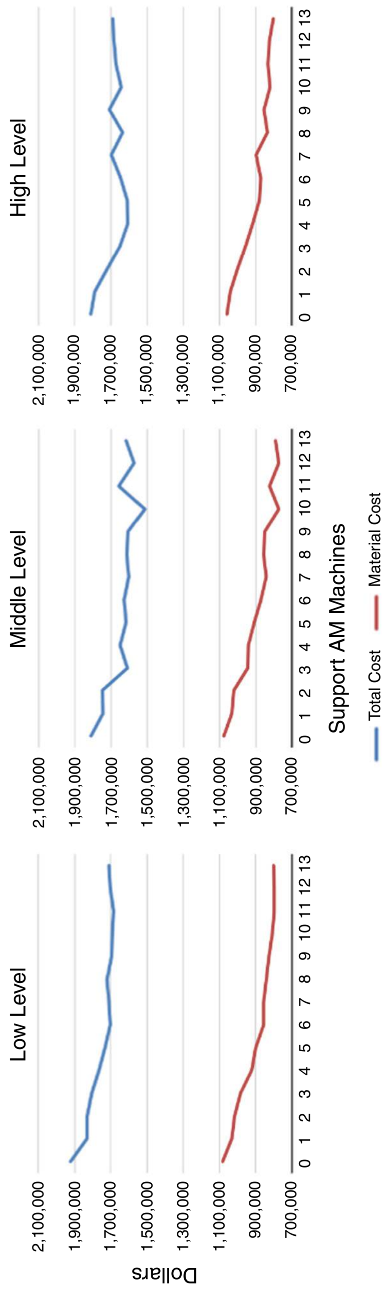

Figure 8.
Trend of total cost (blue) along with material cost (red)

maker aims at shorter lead time, smaller supporting ratio can be chosen, and the order fulfill rate can be sufficiently increased with shortened lead time. However, there is a trade-off between shortest lead time and least total cost, and this research will be summarized in Section 4.3.5.

It is observed that AM can reduce lead time obviously, but the rule cannot be applied for every supporting ratio. Generally, supporting ratio 3 to 5 can provide better performance from the aspect of average lead time, but supporting ratio 9 to 13 are not proper for decreasing average lead time. The reason for this situation might be that AM machines spend more time than CNC machine, and it becomes flexible capacity for the body manufacturing process.

4.3.3 Lead time variation. From the aspect of lead time variation, it is observed that standard deviation decreases as the supporting ratio becomes larger. Figure 10 shows the standard deviation of time with different supporting ratio under each fluctuation level.

In Figure 10, the standard deviation fluctuates more intensely when the demand fluctuation becomes larger. By controlling the supporting ratio, the variation can be migrated. The standard deviation shows a decreased trend as the supporting ratio

Table IV. Suppliers with best performance under different fluctuation level

Purpose	Low level Minimize Lead time	 Minimize Total cost	Middle level Minimize Lead time	 Minimize Total cost	High level Minimize Lead time	 Minimize Total cost
Lightbulb supplier	2	1	3	3	3	3
Distributor	B	A	B	B	B	B
Support AM no.	4	11	3	10	3	4
Lead time (Days)	7.11	11	7.22	8.59	7.64	7.65
Total cost (NT dollars)	1,575,551	1,423,332	1,608,401	1,514,616	1,650,411	1,607,139
Order fulfill rate	0.7984	0.6784	0.7952	0.7552	0.7832	0.783

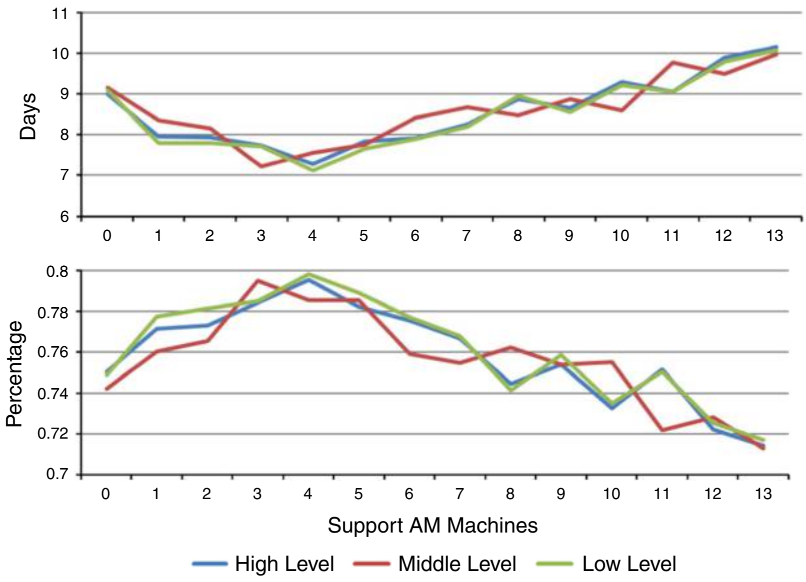

Figure 9. Trends of lead time (upper row) and order fulfill rate (lower row) of each selected SC configuration under different fluctuation level

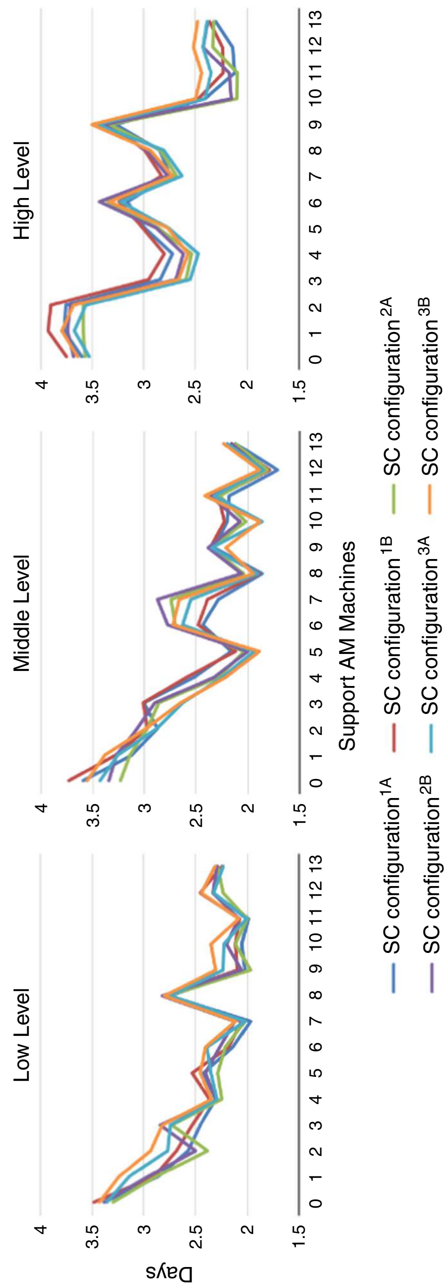

Figure 10.
Trend of lead time variation under different fluctuation level

increased. AM machines serve as flexible capacity to regulate the capacity utilization and smoothen the production line of the case company. As a result, the average lead time reduces. Although the standard deviation of lead time even becomes less with larger supporting ratio, it is not recommended to allocate so much AM capacity to support CNC machine because AM consumes more time to produce body parts than CNC machine. This implies that allocating too much AM capacity will idle CNC machine and increase the cycle time of body parts. By choosing proper supporting ratio, SC configuration adequately has better performance.

4.3.4 Material consumption. Since the green consciousness rose in recent years, many countries have established policies of waste and recycling. These policies force enterprises to review environmental impact of their SCs and products on. While producing the same part, AM manufacturing process consumed only 25 percent material as traditional manufacturing process does and the material utilization of AM is up to 98 percent while traditional processes can only be down to 10 percent at most (Dougherty, 2015).

The material consumption is recorded after each simulation, and it is plotted with the utilization of AM machine in Figure 11. It shows that the material saving ratio

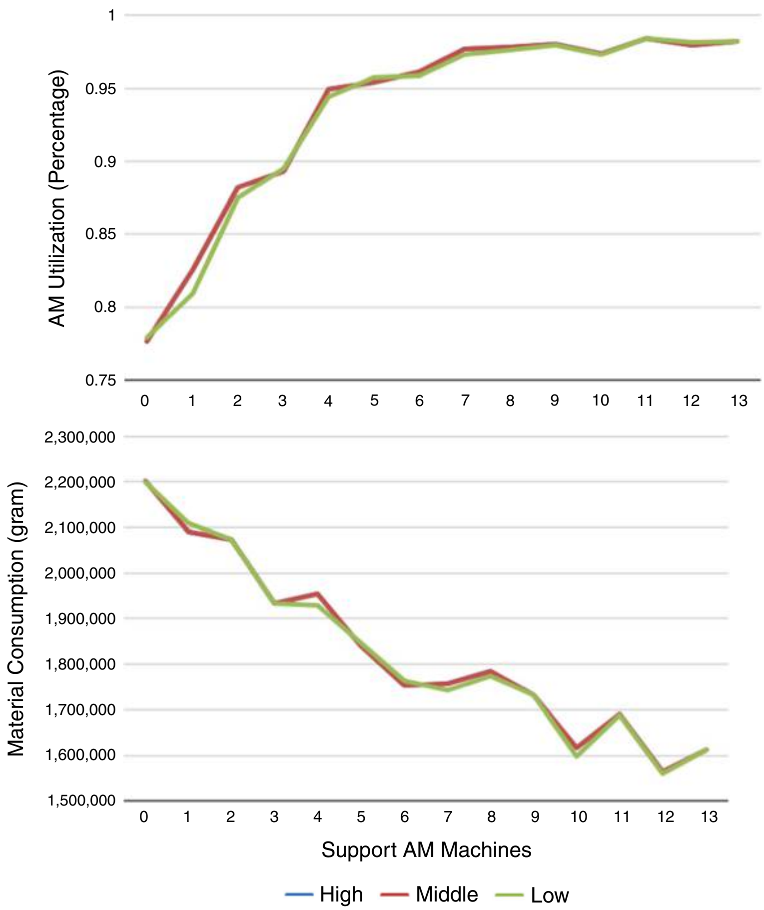

Figure 11.
AM utilization (upper row) and material consumption (lower row) under different demand fluctuation levels

grows as the utilization of AM machine grows. It can be concluded that higher supporting ratio would bring higher material saving ratio. It is noticed that the curve of AM utilization reaches 95 percent of its whole capacity, and the curve go smoothly after value of support AM machines arrives 6 for all fluctuation levels. After observing total cost (Figure 8) and average lead time (Figure 9), we found that although higher supporting ratio could save around 10 percent of material, it increases more than 10 percent of average lead time and saves no money because of the rising backlog cost and holding cost. Hence, AM could be beneficial to the production system and SC from many aspects when the capacity is allocated properly.

4.3.5 Brief summary of decision support. Based on the results of simulation, three suggestions for decision making: total cost, lead time and order fulfill rate under each fluctuation level can be accomplished. The proper SC configuration along with proper AM support ratio to achieve different aims have been summarized in Table IV.

According to Table IV, the trade-offs can be concluded as follows. For low fluctuation level, 10 percent total cost can be reduced through minimizing total cost, but the lead time will be increased by 35 percent and the order fulfill rate will decrease 12 percent. For middle fluctuation level, if least total cost is aimed to be achieved, then 6 percent total cost will be reserved while 14 percent lead time is increased and 4 percent order fulfill rate is decreased. For high fluctuation level, the benefit of minimizing total cost and lead time is very close. Minimizing total cost can reserve 3 percent of total cost, but nearly 0 percent of lead time will increase and nearly 0 percent order fulfill rate will be decreased.

The difference of performances between minimizing total cost and minimizing lead time are very small for high fluctuation level. When the fluctuation becomes smaller, the difference between different aims will lead to sufficient influence to SC performance indicators. By changing the supporting ratio, the SC performance can be adjusted to achieve different kinds of decision making. It can also be concluded that AM machines enhance the flexibility and resilience of SC.

4.4 Discussion

This research cuts into a practical issue from the aspect of personalized product market along with AM technology, which is an emerging one with higher potential benefits. For personalized and innovative product, SC needs to be more responsive to catch up with the fast and changeable customer demands. As a decision support system, this research considers the stochastic demand, which shapes the research closer to the reality. Hence, the decision maker can receive recommendations under various demand fluctuation levels. In addition, the KPIs of SC in this research are lead time, total cost and order fulfill rate, which the case company pays attention and cares about.

According to the US Department of Energy, AM saves 50 percent energy consumption and material costs (up to 90 percent) than traditional manufacturing (Chu, 2012). Moreover, Gebler *et al.* (2014) addressed that AM is capable to add 1.2-4.5 percent CO2/GDP-intensity in total, which is a considerable number. Additionally, the potential influence of AM on sustainability is more significant than on market. This means AM has the capability to save various kinds of resource during manufacturing period, and increases the sustainability of SC.

Numerous of researches have highlighted the importance of early customer involvement at the product design stage. The proposed API addresses this question with personalized product which can conceivably improve the customer satisfaction. In addition, product level decisions and SC-level decisions are coordinated in this study.

The advantage of AM technology break the barrier of integral and modular product architectures so that the efficiency of production can be further upgraded. Another insight is that AM reshapes the SC structure to become flat due to the simplicity of manufacturing process. This reduces the complexity of management and increase the flexibility as well as resilience of SC operation. Finally, DfSC can investigate potential issues such as supplier involvement and risks at the product design stage so that the decision makers can solve or mitigate these problems in a longer time period. As a result, enterprises obtain competitive advantage from the synergy of DfAM and DfSC.

However, there are some limitations that should be acknowledged in this research. The first is the utilized material of AM. Most of the material utilized is powder or liquid, and the material will be heated to form the final part. The parts which are produced with AM will slightly rougher than the traditional one. Although the appearances of final parts are highly the same, the molecular structure has been destroyed, which will lead to the quality variation. Quality is not simply the fineness or appearance, but the life cycle of an AM product may be shorter than one processed by traditional manufacturing process. The length of product life time and the product quality are key issues to case company. Since only a few practical data can be referred in this industry, this research did not consider these factors. Accordingly, yield rate is also a limitation for this research. AM parts are more possible to fail in the forming process than traditional parts, but there is merely no practical data to refer. This research believes that these limitations will be conquered in the future as AM progresses. Once these limitations are conquered, the market will be opened up with high profit.

5. Conclusion

This is the first paper that considers both DfAM and DfSC in conjunction with an API. SC configuration is analyzed and suggested according to simulation results at the product design stage. In addition, this research considers demand fluctuation level and stochastic demand of a personalized product, which have not yet been considered in other AMSC papers. The lead time, total cost and order fulfill rate were investigated and utilized as the KPIs of the SC performance. According to the case study, the average lead time can be shortened about 35 percent with proper supporting ratio. The total cost of recommended manufacturing process with suitable supporting ratio can reduce total cost by up to 10 percent for low fluctuation level, around 6 percent for middle level and 3 percent for high fluctuation level averagely.

AM is a technology that can produce parts directly through laying material layers one on another. This technology is influencing both industry and the academy. To further probe the manufacturing capability of AM, the future research should concern more factors such as yield rate. Further, the material recycling process can be involved as a way to enhance the material reservation advantage of AM. The AM technology that is capable to process multiple materials can also be taken into consideration. Finally, the future works can aim at developing a sustainable SC optimization decision support system. Through calculating and concerning the emission produced and power consumed, the manufacturing process can be adjusted at product design stage. AM strongly improves the SC performance in terms of decreasing average lead time and total cost. Therefore, we believe the findings of this research can become the starting point of industrial AM applications.

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Appendix

Table AI. List of lightbulb supplier

Supplier	KOTAS	Phillips	Panasonic
Lightbulb cost	54	95	80
Transportation cost	If the order size is less than 37, the cost is 80. Otherwise, the product is shipped for free	If the order size is less than 32, the transportation cost is 100. Otherwise, the product is shipped for free	If the order size is less than 88, the transportation cost is 80. Otherwise, the product is shipped for free
Lead time	Within 7 Days	2-5 days	2-4 days

Table AII. List of distributor

Distributor	Chunghwa post	Black cat
Transportation cost	145 NT dollars for each product	200 NT dollars for each product
Lead time	2-3 days	1-2 days

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