# Mass Customization Capability Planning with Additive Manufacturing

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**Abstract.** Mass customization aims to manufacture large quantities of customized products at low costs comparable to that in mass production. However, the two operational objectives of mass customization, production flexibility and cost-efficiency, conflict with each other. In this circumstance, one of the famous prototyping technologies, additive manufacturing (AM), began to draw attention with its multiple function in the production system, which enables mass customizers to achieve the two contradictive objectives. This study defines mass customization capability planning (MCCP) as a production planning process which balances between production flexibility and cost-effectiveness. Also, the mathematical planning model of MCCP is developed to support it. Since the MCCP model includes stochastic parameters, a heuristic method is applied to the solution searching process. After, the MCCP model was validated by the experiment analysis.

**Keywords:** Mass Customization Capability Planning, Mass Customization, Additive Manufacturing.

## 1 Introduction

The term mass customization was firstly mentioned as a process to provide product variety and customization with flexibility and quick responsiveness [1]. Among the various definitions, the predominant features of mass customization include product variety, flexibility, and cost-efficiency [2]. Early papers on mass customization try to classify mass customization into several levels [3,4] and more recently, the optimal location of customer involvement in the production system [5,6].

However, as the product variety increases, the mass customizer confronts the difficulty to balance two contrasting operational goals: production flexibility and cost-efficiency. From this viewpoint, operational capability of mass customization is understood as balancing trade-offs between the two operational goals [7]. Production flexibility, the ability to respond effectively to changing circumstances, enables mass customizer to change production setups in a short time, with a little effort. The second objective, cost-efficiency, of the mass customization comes from the mass production strategy. In the view of economy of scale, homogeneous items require less attention to managing them. In contrast, mass customization requires a much higher number of production set-ups and more diverse resources to produce various kinds of products.

Regarding this, this study deals with one of the most flexible manufacturing technology, additive manufacturing (AM). Adding materials enables to produce objects with a much more complex design so the technology is expected to play a crucial role to provide the manufacturing flexibility to the production system [8]. Initially AM was used to create prototypes before the products were developed [9]. However, AM processes recently broaden its functional boundary to the rapid tooling (RT) area to create tools which are necessary for the traditional fabrication procedure, injection molding, and to the rapid manufacturing (RM) area to manufacture end-use products right away. Most of the previous papers focused on figuring out which, among the three functions, could be the optimal choice for the production system. On the other hand, this study puts more weight of its ability to switch between the three functions freely, which can contribute to increasing the production system's flexibility.

In the previous research, most of the studies with mass customization capability focused on defining the term and investigating its relationship with other managerial factors such as with product modularity [10], organizational flatness, coordination, and product modularity [11], absorptive capacity [12], and quality management [13]. Instead of adopting qualitative manner, this study understands mass customization capability planning (MCCP) as a production planning issue. With this approach, the mathematical model is developed to support it. Also, a simple experimental analysis was carried out to validate the mathematical model.

## 2 Mass Customization Capability Planning

The concept of mass customization has emerged from the convergence of the two contrasting strategies: mass production and one-of-kind production (OKP). The first strategy, mass production, focuses on achieving cost-effectiveness with a few types of standard products. Since the number of product types is somewhat limited, it is able to forecast demands for the standard products with proper forecasting techniques. Under the OKP circumstance, however, there can exist an infinite number of product types. In addition, the customization level of each product may vary depending on the customer's requests and the firm's capability to produce customized products.

As a combination of the two strategies, mass customization produces both types of products. On the one hand, mass customizer must forecast the future demands of the standard products and establish a proper production plan for the products and the parts. On the other hand, the mass customizer must prepare its capability to deal with the customized demands since the customers' specific requirements are unknown until the actual demand occurs. This gives rise to the necessity for the mass customizer to include the customization capability planning as a new production planning step.

In this respect, MCCP aims to give a guideline so as to support the mass customizer's decision-making on its customization capability. As the nature of custom order bears uncertainty, the customization capability planning does not suggest an exact solution for the mass customizer. Instead, it offers a range of customization capability levels which helps to understand the impact of the custom demands and its proper capability levels to deal with it.

There is a significant difference in the decision variables between the MCCP model and the traditional capacity planning model. In addition to the capacity-related decision in the traditional models, the MCCP model decides the proper customization capability according to the custom demand forecast. Therefore, the important decision variables of the MCCP model are related to its customization capability: *the customization level* and *the custom order fulfillment ratio*.

A mass customizer decides its level of product variety by setting a proper customization level. By setting the customization level, the firm is able to produce customized products of which customization level locates within the customization limit. However, if there is a new order requiring a product with being more customized than the firm's customization limit, the firm faces a difficult situation where putting most of its capacity on that order. Second, the custom order fulfillment ratio depends on the number of customized products manufactured in the planning horizon.

The customization level and the custom order fulfillment ratio are related to each other. For example, a firm can either produce a large quantity of customized products with a low customization level or produce a small number of high-customized products. Therefore, it is difficult to evaluate which of the two strategies represents the higher customization capability since they are in the two different dimensions.

# 3 Mass Customization Capability Planning Model

## 3.1 Assumptions and Notations

Since the mathematical representation of MCCP does not exist before, this very first model is developed based on the detailed assumptions. First, demand information of both typical and custom order is known by long-term forecasting. However, only typical orders include detail profile of the products, such as bill-of-materials and part specifications. Long-term forecasting for custom orders is available only to predict customers' tendency to customize their products. The products are customized from the standard products. Parts can be customized, while BOM information for the final products is fixed. In addition, it is assumed that customers can customize both common parts and differentiated parts as well. Customized products are comprised of common parts, differentiated parts, and customized parts while standard products consist of common parts and differentiated parts. Regarding AM, it is assumed that all parts can be additively manufactured. The building time of AM machines is assumed to be affected by the building technique of the AM machine and the part design. Indices, parameters, and decision variables are represented in Table 1-3, respectively.

**Table 1.** Indices

| | |
|---|---|
| $i$ | Index of product ($i = 1, 2, \dots, I$) |
| $j$ | Index of part ($j = 1, 2, \dots, J$) |
| $l$ | Index of customized part originated from part $j$ ($l = 1, 2, \dots, Y_{jt}^{C}$) |
| $k$ | Index of AM machine type related to building technique($k = 1, 2, \dots, K$) |
| $m$ | Index of dedicated machines' possible function ($m = 1, 2, \dots, M$) (in this model, 1 for tooling and 2 for fabrication) |

| | |
|---|---|
| $n$ | Index of effective design factor ($n = 1, 2, \dots, N$) |
| $s$ | Index of manufacturing step ($s = 1, 2, \dots, S$) (in this model, 1 for prototyping, 2 for tooling, and 3 for fabrication) |
| $r$ | Index of raw material ($r = 1, 2, \dots, R$) |
| $t$ | Time periods ($t = 1, 2, \dots, T$) |

**Table 2.** Parameters

| | |
|---|---|
| $d_{it}^{TOTAL}$ | Forecasted total demand including the standard product *i* and customized product modified from the standard product *i* at period *t* |
| $d_{it}^{ST}$ | Forecasted demands of the standard product *i* at period *t* |
| $d_{it}^{CU}$ | Forecasted demands of the customized product *i* at period *t (stochastic value)* |
| $n_{ij}$ | The number of the part *j* to manufacture a unit of standard product *i* |
| $t_m^{Set\_DM}$ | Setup time of dedicated machine with function $m$ |
| $t_k^{Set\_AM}$ | Setup time of AM with building technique *k* |
| $t_k^{Post\_AM}$ | Post processing time of AM with building technique *k* |
| $t_{jm}^{NC}$ | Processing time of non-customized part *j* at dedicated machine $m$ |
| $t_{jlm}^{C\_DM}$ | Processing time of customized part $(j, l)$ at dedicated machine $m$ |
| $t_{jlk}^{C\_AM}$ | Processing time of customized part $(j, l)$ at AM machine with building technique *k (stochastic value)* |
| $t_i^{ASSEM}$ | Assembling time of product $i$ |
| $start_{js}$ | Binary parameter whether customized part *j* starts at manufacturing step $s$ *(stochastic value)* |
| $n^{DM}$ | Mold life made by dedicated tooling machine |
| $n_k^{AM}$ | Mold life made by AM technique *k* |
| $p_i^{ST}$ | Unit price of standard product $i$ |
| $c_j$ | Unit cost of manufacturing part *j* |
| $k_m^{DM}$ | Purchasing cost of a unit of dedicated machine $m$ |
| $k_k^{AM}$ | Purchasing cost of a unit of AM machine $k$ |
| $h$ | Holding cost of a part unit |
| $w_t$ | Available working time in period $t$ |
| $rm_{jlr}^{C}$ | Binary parameter whether customized part $(j, l)$ is supposed to be made with raw material $r$ *(stochastic value)* |
| $b_{mr}^{DM}$ | Whether dedicated machine at manufacturing step $m$ can handle raw material $r$ |
| $b_{kr}^{AM}$ | Whether AM with building technique $k$ can handle raw material $r$ |
| $\alpha_{jl}$ | Effective design vector for customized part $(j, l)$ *(stochastic value)* |
| $s_{jln}$ | Effective design subfactor $n$ of customized part $(j, l)$ |
| $M_{m,0}^{DM}$ | Initial number of dedicated machines $m$ |
| $M_{m,0}^{AM}$ | Initial number of AM machines $k$ |
| $C^{UP}$ | Upper bound of customization limit |

**Table 3.** Decision variables

| | |
|---|---|
| $X_{it}^{ST}$ | Number of standard product $i$ manufactured in period $t$ |
| $X_{it}^{CU}$ | Number of customized product transformed from standard product $i$ manufactured in period $t$ |
| $Y_{jt}^{NC}$ | Number of part *j* manufactured in period $t$ |
| $Y_{jt}^{C}$ | Number of customized part *j* manufactured in period $t$ |
| $Z_{jlkt}$ | Whether customized part $(j, l)$ at period $t$ is fabricated by AM machine $k$ |

| | |
|---|---|
| $W_{jt}$ | Whether part type $j$ can be customized at period $t$ or not (binary) |
| $M_{mt}^{DM}$ | Number of dedicated machine $m$ in period $t$ |
| $M_{kt}^{AM}$ | Number of AM machine with building technique $k$ in period $t$ |
| $PM_{mt}^{DM}$ | Number of dedicated machine $m$ purchased at the start of period $t$ |
| $PM_{kt}^{AM}$ | Number of AM machine $k$ purchased at the start of period $t$ |
| $I_{jt}$ | Inventory level of part $j$ at the end of period $t$ |
| $MOLD_{jt}^{NC}$ | Number of molds of non-customized part $j$ manufactured by dedicated tooling machine in period $t$ |
| $WT_{mt}^{DM}$ | Working time of dedicated machine $m$ in period $t$ |
| $WT_{kt}^{AM}$ | Working time of AM machine with building technique $k$ in period $t$ |
| $WT_{mt}^{C\_DM}$ | Working time of dedicated machine $m$ operating for customized parts in period $t$ |
| $C_{it}^{CU}$ | Customization level of product $i$ |
| $\beta_t$ | Service level (order fulfillment ratio) for custom orders at period $t$ |

### 3.2 Mathematical Model

The objective functions of MCCP model are to maximize the economic benefit during the entire planning periods as in Equation (1), at the same time to maximize the total customization level of the products as in Equation (2).

Maximize

$$f_1 = \sum_{t=1}^{T}\sum_{i=1}^{I}\left(p_i^{ST} \times X_{it}^{ST} + p_i^{CU} \times X_{it}^{CU}\right) - \sum_{t=1}^{T}\sum_{j=1}^{J} h \times I_{jt} - \sum_{t=1}^{T}\sum_{m=1}^{M} k_m^{DM} \times PM_{mt}^{DM} - \sum_{t=1}^{T}\sum_{k=1}^{K} k_k^{AM} \times PM_{kt}^{AM} - \sum_{t=1}^{T}\sum_{m=1}^{M} e_m^{DM} \times WT_{mt}^{DM} - \sum_{t=1}^{T}\sum_{k=1}^{K} e_k^{AM} \times WT_{kt}^{AM} \quad (1)$$

Maximize

$$f_2 = \sum_{t=1}^{T}\sum_{i=1}^{I} C_{it}^{CU} \quad (2)$$

*Subject to*

$$I_{jt} = I_{j,t-1} + Y_{jt}^{NC} - \sum_{i}^{I}\left\{n_{ij} \times X_{it}^{ST} + n_{ij} \times X_{it}^{CU} - Y_{jt}^{C}\right\} \quad \forall j,t \quad (3)$$

$$Y_{jt}^{C} = \sum_{i}^{I} n_{ij} \times X_{it}^{CU} \quad \forall j,t \quad (4)$$

$$X_{it}^{ST} = d_{it}^{ST} \quad \forall i,t \quad (5)$$

$$X_{it}^{CU} \le d_{it}^{CU} \quad \forall i,t \quad (6)$$

$$\sum_{i}^{I} X_{it}^{CU} = \sum_{i}^{I} d_{it}^{CU} \times \beta_t \quad \forall t \quad (7)$$

$$Y_{jt}^{C} \le W_{jt} \times big\ M \quad \forall j,t \quad (8)$$

$$C_{it}^{CU} = \frac{\sum_j \left(n_{ij} \times W_{jt}\right)}{\sum_j n_{ij}} \quad \forall i,t \quad (9)$$

$$C_{it}^{CU} \le C^{UP} \quad \forall i,t \quad (10)$$

$$MOLD_{jt}^{NC} \geq \frac{Y_{jt}^{NC}}{n^{DM}} \qquad \forall j,t \qquad (11)$$

$$\sum_{k=1}^{K} Z_{jlkt} = 1 \qquad \forall j,l,t \qquad (12)$$

$$M_{mt}^{DM} = M_{m,t-1}^{DM} + PM_{mt}^{DM} \qquad \forall m,t \qquad (13)$$

$$M_{kt}^{AM} = M_{k,t-1}^{AM} + PM_{kt}^{AM} \qquad \forall k,t \qquad (14)$$

$$WT_{mt}^{C\_DM} = \sum_{j=1}^{J}\sum_{l=1}^{Y_{jt}^{CU}}\left(t_{jlm}^{C\_DM} \times \sum_{s=1}^{m+1} start_{js}\right) \qquad \forall m,t \qquad (15)$$

$$WT_{kt}^{AM} = \sum_{j=1}^{J}\sum_{l=1}^{Y_{jt}^{CU}}\left\{\left(t_{jlk}^{C\_AM} + t_{k}^{Set\_AM} + t_{k}^{Post\_AM}\right) \times Z_{jlkt}\right\} \qquad \forall k,t \qquad (16)$$

$$WT_{mt}^{DM} = \sum_{j=1}^{J}\left(t_{jm}^{NC} MOLD_{jt}^{NC} + t_{m}^{Set\_DM}\right) + WT_{mt}^{C\_DM} \qquad \forall t,\ m = 1 \qquad (17)$$

$$WT_{mt}^{DM} = \sum_{j=1}^{J}\left(t_{jm}^{NC} Y_{jt}^{NC} + t_{m}^{Set\_DM}\right) t_{jm}^{NC} + WT_{mt}^{C\_DM} \qquad \forall t,\ m = 2 \qquad (18)$$

$$WT_{kt}^{AM} \leq w_t \times M_{kt}^{AM} \qquad \forall k,t \qquad (19)$$

$$WT_{mt}^{DM} \leq w_t \times M_{mt}^{DM} \qquad \forall k,t \qquad (20)$$

The customization level of the product $i$ at period $t$ is calculated from Equation (9). Equation (10) ensures that the value of customization level can't be over than the upper bound of the customization level. Equation (11) ensures the number of molds used to fabricate un-customizable part $j$ must be higher than the number of un-customizable part $j$ divided by the mold life $n^{DM}$. Equation (12) ensures that only one of AM techniques is selected to proceed customized part $l$ from part $j$ at the period $t$. Equations (13) and (14) represent the number of machine $m$ at period $t$ is the sum of the number of machines at the previous period $t-1$ and the number of machines purchased at the start of the period $t$. Equations from (15) to (20) are the time-related capacity constraints of the manufacturing processes.

### 3.3 Solution Algorithm

The MCCP model requires a specific solution searching procedure since it includes probabilistic parameters and multi objectives, and the range of index $l$ (index of customized part) is decided by the decision variable $Y_{jt}^{C}$. The solution searching procedure is divided into two parts: (1) to decide optimal MCCP plan and (2) to check the time-related capacity constraints of machines (Fig. 1). In terms of solving multi-objective problem, the algorithm controls the upper limit of the second objective (total customization level), finds optimal plan satisfying feasibility condition with the given value of the second objective, and relaxes the boundary of the second objective if the resulting solution is infeasible. To address the solution algorithm, an index $p$ is defined as the iteration number.

One of the key elements of this algorithm is $C^{UP}$, the upper bound of customization level. The value of $C^{UP}$ is renewed at every iteration $p$. The solution searching algorithm starts with $p = 0$. The first stage focuses on deciding optimal customization level which satisfies $C_p^{UP}$. In this stage, the mathematical model is applied except the equations which include index $l$ such as Equations (12), (15), and (16). The second stage checks feasibility of the result of the first stage. If the solution can't satisfy the time-related capacity constraints, it must pass through another iteration with the iteration number $p + 1$. With the increased iteration number, the upper bound of customization level $C_{p+1}^{UP}$ has a value of $C_p^{UP} - \Delta C^{UP}$, which lowers the previous upper bound of customization level with $\Delta C^{UP}$.

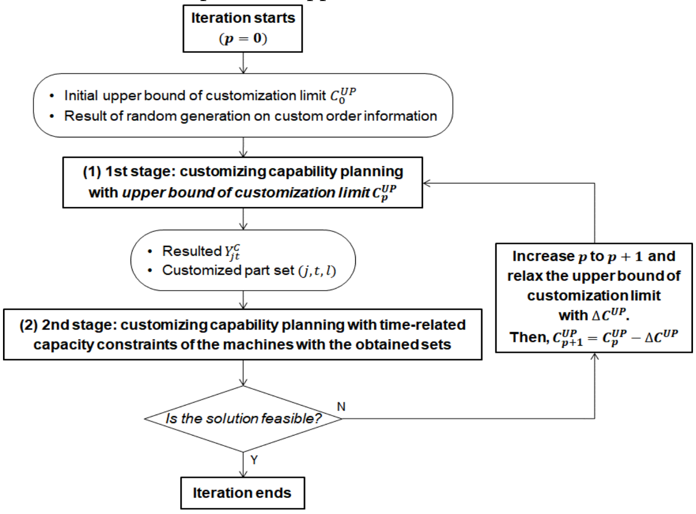


**Fig. 1.** Solution algorithm of the MCCP model

## 4 Experimental Analysis

To validate the MCCP model, a simple experimental analysis was carried out. It reflected the situation where the custom demand increased with linearly. Also, three manufacturing steps were considered: prototyping, tooling, and fabrication with consideration of the AM's possible function in production system. It was assumed that dedicated manufacturing technology corresponds to a certain manufacturing step. In this case, injection molding was assigned to fabrication, and machining was assigned to tooling. Meanwhile, AM processes were assumed to be capable of operating in all manufacturing steps. And, the five different AM processes included selective laser sintering, electron beam melting, laser metal deposition, fused deposition modeling, and stereolithography apparatus. The lengths of processing time, setup time, and post-processing time were assumed based on the characteristics of the processes. There were two types of products which consisted of two common parts and the other differentiated part. The demand of each product was randomly generated from normal distribution with its mean and standard deviation (which was set as 10).

The result showed that the customization level stayed same due to the lower demand increasing rate (0.2% per period). Meanwhile, the ratio of the number of customized products to the total number of products increased as the custom demand increases. In terms of the machines, three AM machines with SLS process were purchased to correspond to the increasing trend of custom demand.

## 5 Conclusion

To implement mass customization successfully, the mass customizer should balance between the two contrasting objectives: production flexibility and cost-efficiency. This study argues that the mass customization capability, defined as the ability to balance between the two objectives, must be planned as a long-term planning step. Based on the argument, the MCCP model is developed to support the mass customizer's decision-making process on its appropriate level of production flexibility, as well as the resulting profits. Also, heuristic method is used to search optimal boundary of the decision variables, especially the customization level and order fulfillment ratio.

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