

# Production Planning with AM in Mass Customization Environment

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# 1. Introduction

***We're in the middle of the transition from Mass production to Mass customization.***

- The concept of 'Mass customization' has emerged since late 1980s.
- However, the research area of mass customization has been depressed recently due to the lack of the researches which link the strategy with the operational (or tactical) insights.
- Therefore, it is necessary to investigate how to achieve mass customization in terms of the operational level.

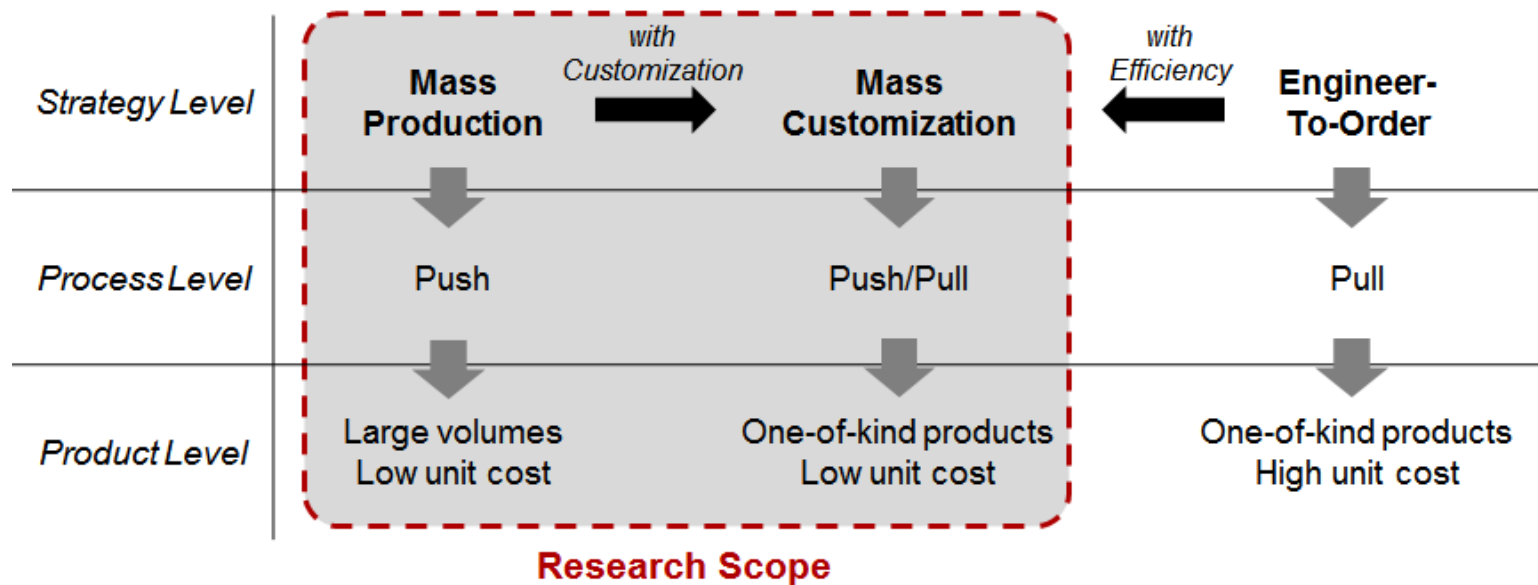
# 1. Introduction

***Additive manufacturing (AM) technology can be a solution to overcome the inherent contradictions within mass customization.***

- Mass customization is a convergence strategy of mass production and one-of-kind production (OKP).
- It results in the unavoidable contradictions within mass customization.
- With technology advances, additive manufacturing has become not only a prototyping tool but also a machine to manufacture final item.
- Therefore, AM can be used to overcome the obstacles to achieve mass customization.

# 1. Introduction

## Research Scope



# 1. Introduction

## ■ Research Objective

- This paper aims to analyze inherent contradictions within mass customization in terms of products and suggest a novel production planning framework for mass customizer.
- The production planning with AM aims for customized parts having optimal manufacturing options with consideration of the status of the production system.

## 2. Literature Review

### ■ Definition of Mass Customization

- The concept has emerged in the late 1980s as a natural follow up to increasingly flexible processes with optimized quality and costs.
- Mass customization appears as an alternative to differentiate companies in a highly competitive and segmented market.

Authors (year)	Definitions
Pine (1993)	The low-cost production of high variety, even individually customized goods and services
Hart (1995)	The ability to provide your customers with anything they want profitably, any time they want it, anywhere they want it, any way they want it.
Silveira, <i>et al.</i> (2001)	Mass customization relates to the ability to provide customized products or service through flexible processes in high volumes and at reasonably low cost

## 2. Literature Review

### ■ Comparison between mass production and mass customization

	Mass production	Mass customization
<b>Focus</b>	Efficiency through stability and control	Variety and customization through flexibility and quick responsiveness
<b>Goal</b>	at prices low enough that nearly everyone can afford them	with enough variety and customization that nearly everyone finds exactly what they want
<b>Key features</b>	<ul style="list-style-type: none"> <li>• Stable demand</li> <li>• Large homogeneous markets</li> <li>• Low-cost, consistent quality, standardized goods and services</li> <li>• Long product development cycles</li> <li>• Long product life cycles</li> </ul>	<ul style="list-style-type: none"> <li>• Fragmented demand</li> <li>• Heterogeneous niches</li> <li>• Low-cost, high-quality, customized goods and services</li> <li>• Short product development cycles</li> <li>• Short product life cycles</li> </ul>
<b>Product</b>	Standardized products built to inventory	Standardized modules assembled based on customer needs
<b>Structure</b>	Mechanistic, bureaucratic and hierarchical	Organic, flexible, and relatively less hierarchical

Source: Adapted from Pine et al. (1993), Pine (1993), and Kotha (1995)

# 3. Production Planning Framework for Mass Customizer

## ■ Contradiction within Mass Customization: *what to produce?*

### (1) Mass Production with Standard Products

- A few types of standard products are produced.
- Standard products are composed of the common parts (also known as *product platform*) and the differentiated parts.
- Differentiated parts were already designed by the manufacturers.
- It is possible to forecast demands of the standard products with proper techniques.

# 3. Production Planning Framework for Mass Customizer

## ■ Contradiction within Mass Customization: *what to produce?*

### (2) OKP Production with Customized Products

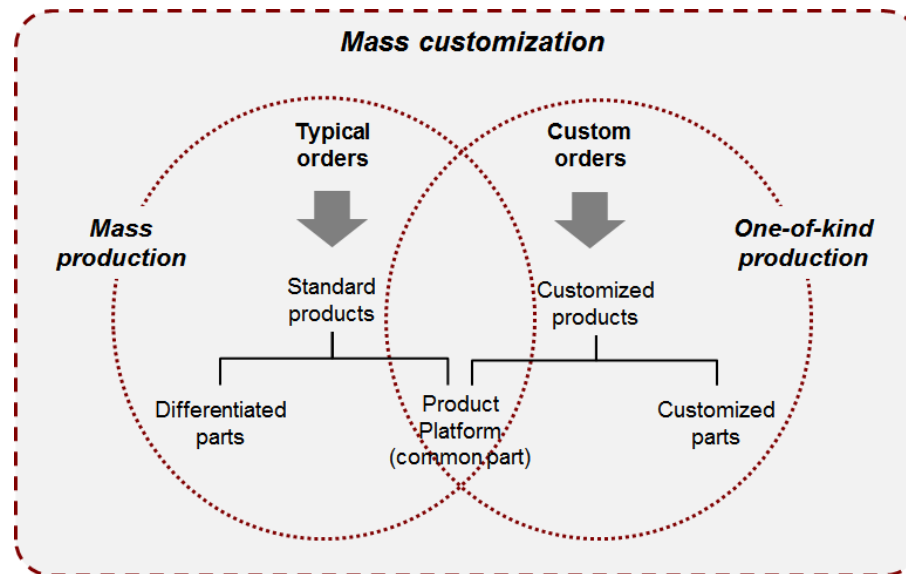
- One-of-kind production can have an infinite number of product types.
- Products are designed to meet the individual customer's requirements.
- It requires active communication with the customers at the engineering stage.
- The level of customization may vary depending on what a customer wants.

# 3. Production Planning Framework for Mass Customizer

## Contradiction within Mass Customization: *what to produce?*

### (3) Mass Customization with Standard and Customized Products

- Mass customizer must forecast the future demands of the standard products
- And also prepare its capability to deal with the customized demands.



# 3. Production Planning Framework for Mass Customizer

## ■ Re-classification of the Two Types of Demand Information

### ➤ Traditional classification:

*“**Independent demand** is any demand that originates outside the system. This includes all demand for final products and possible some demand for components (e.g., when they are sold as replacement parts). In contrast, **dependent demand** is demand for components that make up independent demand products.” (Hopp and Spearman, 2011)*

- In mass production, production plan for independent demand is carried out first, and then production plan to meet dependent demand is scheduled.
- A function of dependent demand on independent demand is used.

# 3. Production Planning Framework for Mass Customizer

## ■ Re-classification of the Two Types of Demand Information

### ➤ Re-classification:

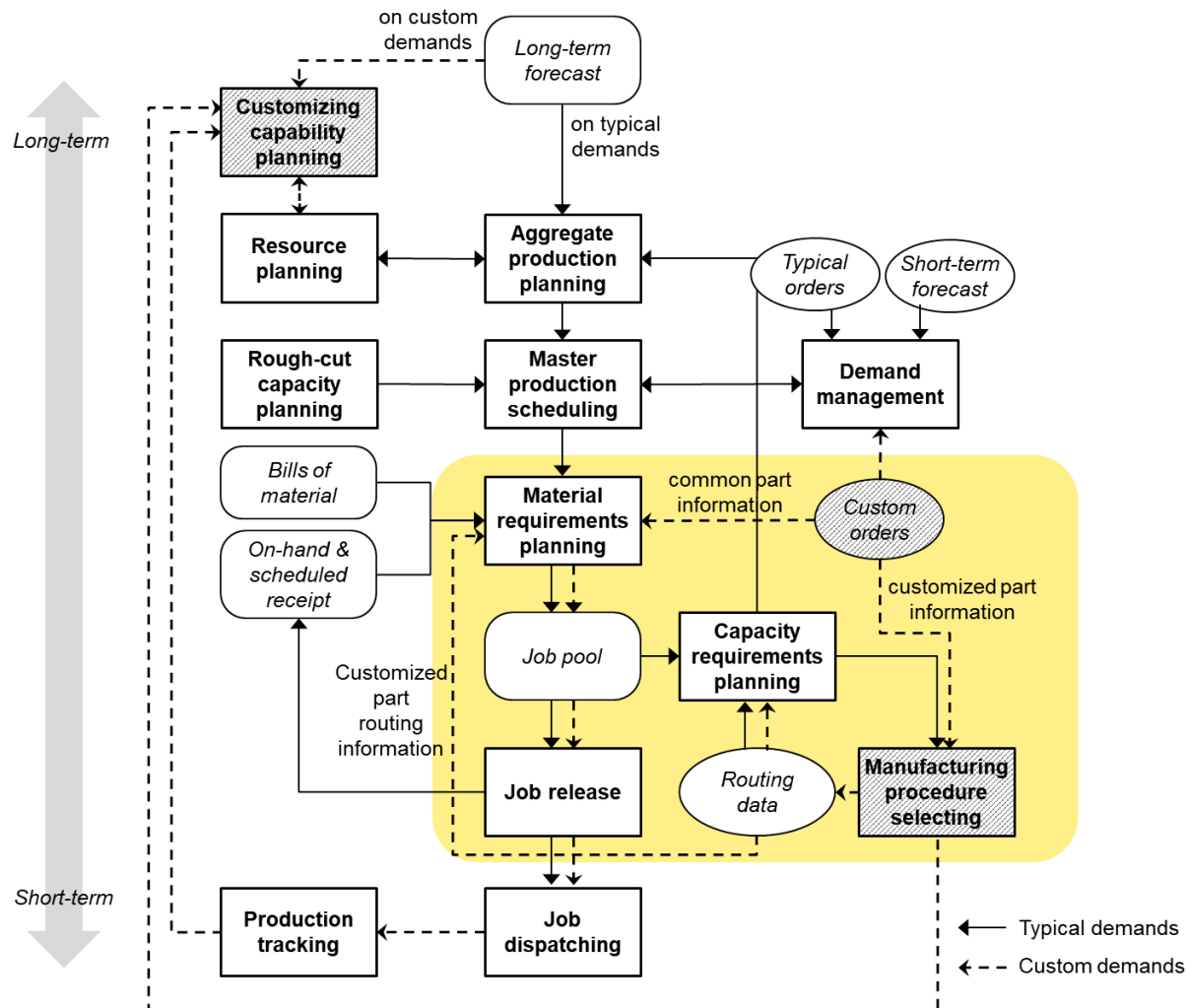
- In mass customization environment, **the scope of independent demand is enlarged due to the custom orders.**
- Custom orders include **independent demand information** not only about final products **but also about customized parts.**
- Part specifications of the custom orders are independent of the final products.
- Customers can customized their products with different shapes, colors, or materials of the parts.

### 3. Production Planning Framework for Mass Customizer

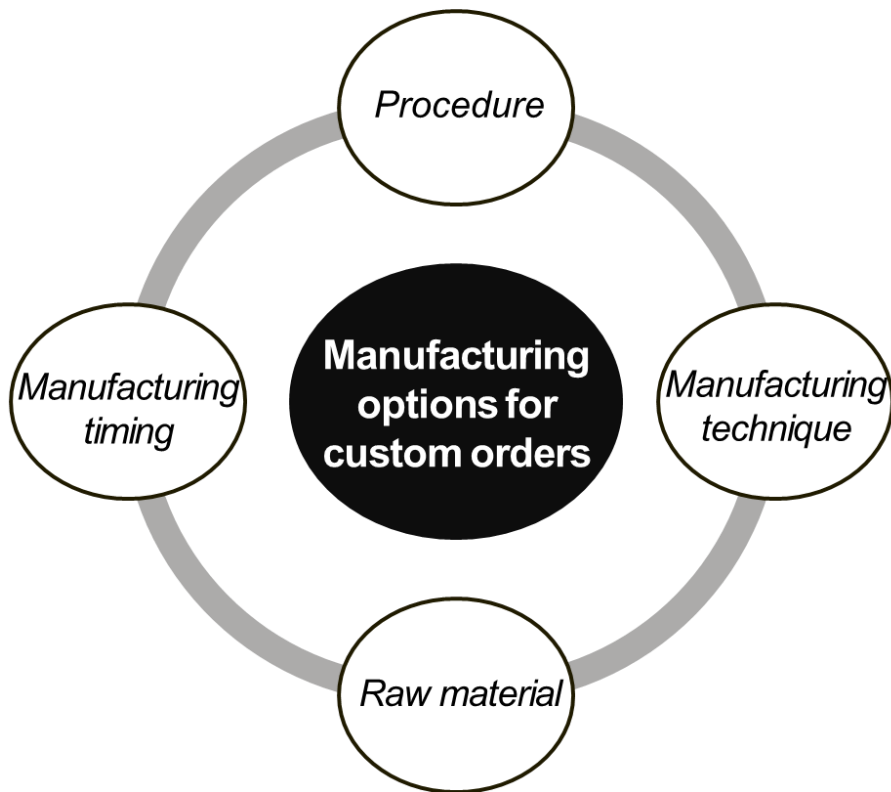
#### Re-classification of the Two Types of Demand Information

Information type	Level	Typical order	Custom order
<b>Independent demand information</b>	Product	<ul style="list-style-type: none"> <li>Number/type of final products</li> </ul>	<ul style="list-style-type: none"> <li>Number/type of final products</li> <li>Bill-of-Material</li> </ul>
	Part	<ul style="list-style-type: none"> <li>Number/type of replacement parts</li> </ul>	<ul style="list-style-type: none"> <li>Number/type of customized parts</li> <li>Number/type of replacement parts</li> <li>Part specifications</li> </ul>
<b>Dependent demand information</b>	Product	<ul style="list-style-type: none"> <li>Bill-of-Material</li> </ul>	–
	Part	<ul style="list-style-type: none"> <li>Number/type of all parts</li> <li>Part specifications</li> </ul>	<ul style="list-style-type: none"> <li>Number/type of common parts</li> </ul>

### 3. Production Planning Framework for Mass Customizer



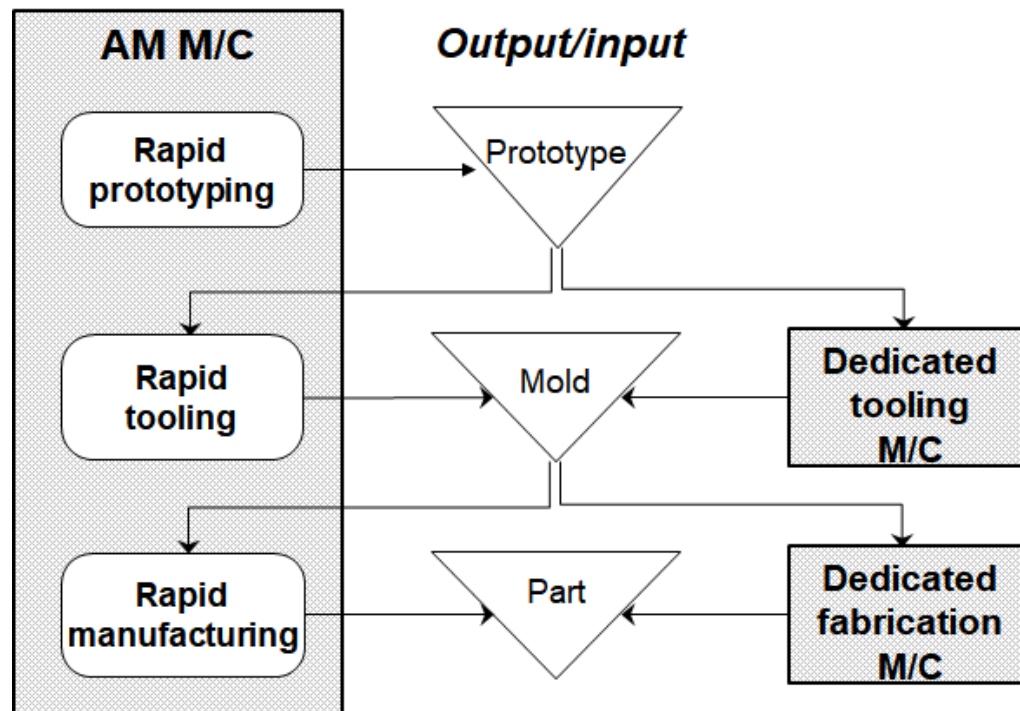
## 4. Manufacturing Options for Custom Orders



- Four types of options are considered.
- All four options are dependent with each other.
- And also affected by the status of the production system.

## 4. Manufacturing Options for Custom Orders

### 1) Manufacturing Procedure of the Customized Part



## 4. Manufacturing Options for Custom Orders

### 1) Manufacturing Procedure of the Customized Part

Starting process	Manufacturing step		
	Prototyping	Tooling	Fabrication
Prototyping	AM machine	Dedicated machine; or AM machine	Dedicated machine; or AM machine
Tooling	—	AM machine	Dedicated machine; or AM machine
Fabrication	—	—	AM machine

# 4. Manufacturing Options for Custom Orders

## 2) Manufacturing Technique for the Customized Part

Building method	Technique	Acronym	Raw material	Energy consumed	Other properties
<b>Powder-based system</b>	Selective laser sintering	SLS	Nylon, metal, ceramic, paraffin wax	High power laser beam	Rough surface; long material changeover time; requiring surfacing finishing process and coloring process
	Direct metal tooling	DMT		High power laser beam	Rough surface; long material changeover time; requiring surfacing finishing process and coloring process
	Color jet printing	CJP	Binder, ink	High power laser beam	Rough surface; long material changeover time; requiring surfacing finishing process
<b>Molten material system</b>	Fused deposition modeling	FDM	Nylon, ABS, ceramic, investment casting wax, alloy	Heat	Mainly used in home; suitable for small size part; long building time; often occurs delamination;
<b>Photopolymer-based system</b>	Stereolithography	SLA	Liquid photopolymer	UV laser beam	Limited types of material;

## 4. Manufacturing Options for Custom Orders

### ■ 3) Raw Material of the Customized Part

- The raw material types are limited to the machines' property.
  - For example, some of the AM machines can't manufacture with metals.
  - Dedicated machines have less diverse materials than the AM machines.
- The basic materials for the process are fixed.
  - Especially prototyping and molding process require certain kinds of material.
  - What if a customer wants its product manufactured with unusual material?
- The required types of raw material affects the manufacturing sequence of the customized part.

## 4. Manufacturing Options for Custom Orders

### ■ 4) Manufacturing Timing of the Customized Part

- Considering all previous options, it may or may not be able to meet the due date.
- The manufacturing timing of the customized parts must be decided according to both manufacturing options and the status of the production system.
- If the production system is busy at a certain date, the manufacturing timing of the customized part can be delayed.
- However, tardy schedule results in a penalty cost on the part.

# 5. Production Planning Model with AM

## Decision variables

### Manufacturing options for customized parts

- Manufacturing procedure of each customized part
- Manufacturing techniques of each customized part
- Manufacturing timing of each customized part

### Manufacturing plan for all parts

- Number of non-customized and customized parts manufactured each period

### Raw material requirement plan

- Amount of raw materials to manufacture parts

# 5.1 Assumptions

1. In this model, detail information on the custom orders is already known to the planner.
2. Parts can be customized in terms of their design and the raw material used to produce the final output.
3. This model focuses on the part manufacturing level in the entire production planning framework.
4. Both typical and custom demands have due dates. Typical demands can be stored as inventories or back-ordered while custom demands must be manufactured at the due date.
5. AM machines can simultaneously take more than a function in the production system.
6. From the previous assumption, the manufacturing options for the customized parts can be chosen especially in terms of their manufacturing procedures, techniques, timing, and raw materials.
7. Support processes such as machine maintenance and repair are not considered.

## 5.2 Notations

### ➤ Indices

$i$	Index of non-customized part ( $i = 1, 2, \dots, I$ )
$j$	Index of customized part ( $j = 1, 2, \dots, J$ )
$k$	Index of building technique of AM ( $k = 1, 2, \dots, K$ )
$m$	Index of manufacturing step ( $m = 1, 2, \dots, M$ ) (1 for prototyping, 2 for tooling, 3 for fabrication)
$r$	Index of raw material ( $r = 1, 2, \dots, R$ )
$t$	Time periods ( $t = 1, 2, \dots, T$ )

## 5.2 Notations

### ➤ Parameters

$net_{it}^{NC}$	Net requirement of non-customized part $i$ at period $t$
$net_{jt}^C$	Number of customized part $j$ with due date of period $t$
$vol_i^{NC}$	Volume of non-customized part $i$ at period $t$
$vol_j^{NC}$	Volume of customized part $j$ at period $t$
$t_{im}^{NC}$	Processing time of non-customized part $i$ at manufacturing step $m$
$t_{jm}^{C\_DM}$	Processing time of customized part $j$ of dedicated machine at manufacturing step $m$
$t_{jk}^{C\_AM}$	Processing time of customized part $j$ of AM machine with building technique $k$
$t_m^{Set\_DM}$	Setup time of dedicated machine at manufacturing step $m$
$t_k^{Set\_AM}$	Setup time of AM with building technique $k$
$t_k^{Post\_AM}$	Post processing time of AM with building technique $k$

## 5.2 Notations

### ➤ Parameters

$rm_{ir}^{NC}$	Whether non-customized part $i$ supposed to be fabricated with raw material $r$ (binary)
$rm_{jr}^C$	Whether customized part $j$ supposed to be fabricated with raw material $r$ (binary)
$rm_r^{Ptype}$	Whether raw material $r$ is basic material for prototype
$rm_r^{Mold}$	Whether raw material $r$ is basic material for mold
$b_{mr}^{DM}$	Whether dedicated machine at manufacturing step $m$ can handle raw material $r$ (binary)
$b_{kr}^{AM}$	Whether AM with building technique $k$ can handle raw material $r$ (binary)
$n^{DM}$	Mold life made by dedicated tooling machine (maximum number of use in fabrication)
$n_k^{AM}$	Mold life made by AM technique $k$ (maximum number of use in fabrication)
$c_r^{material}$	Unit cost of raw material $r$
$c^{energy}$	Unit cost of raw material $r$

## 5.2 Notations

### ➤ Parameters

$p^{NC}$	Penalty cost for a unit of back-ordered part (non-customized)
$h$	Holding cost of a unit of part (non-customized)
$M_m^{DM}$	Number of dedicated machines in manufacturing step $m$
$M_k^{AM}$	Number of AM machines with building technique $k$
$w_t$	Available working time in period $t$
$e_m^{DM}$	Energy consumption of dedicated machine at manufacturing step $m$ per unit time
$e_k^{AM}$	Energy consumption of AM machine with building technique $k$ per unit time

## 5.2 Notations

### ➤ Decision Variables

$X_{it}^{NC}$	Number of non-customized part $i$ manufactured at period $t$
$X_{jt}^C$	Number of customized part $j$ manufactured at period $t$
$I_{it}^{NC}$	Inventory level of non-customized part $i$ at period $t$
$S_{it}^{NC}$	Number of back-ordered non-customized part $i$ at period $t$
$Y_{jmt}^C$	Number of customized part $j$ passed through manufacturing step $m$ at period $t$
$Z_{it}^{NC}$	Whether non-customized part $i$ is manufactured at period $t$ (binary)
$Z_{jmt}^C$	Whether customized part $j$ is passed through manufacturing step $m$ at period $t$ (binary)
$\Psi_{jmt}^{C\_DM}$	Whether customized part $j$ is proceed by dedicated machine at manufacturing step $m$ at period $t$ (binary)
$\Psi_{jmk}^{C\_AM}$	Whether customized part $j$ is proceed at manufacturing step $m$ by AM machine with building technique $k$ at period $t$ (binary)

## 5.2 Notations

### ➤ Decision Variables

$START_{jmt}^C$	Whether manufacturing procedure of customized part $j$ starts at manufacturing step $m$ at period $t$ (binary)
$\Omega_{jt}^{C\_DM}$	Number of customized part $j$ fabricated by dedicated machine at period $t$
$\Omega_{jkt}^{C\_AM}$	Number of customized part $j$ fabricated by AM machine type $k$ at period $t$
$R_{rmt}^{DM}$	Amount of raw material $r$ consumed by dedicated machine at manufacturing step $m$ in period $t$
$R_{rkt}^{AM}$	Amount of raw material $r$ consumed by AM machine with building technique $k$ in period $t$
$MOLD_{it}^{NC\_DM}$	Number of molds of non-customized part $i$ manufactured by dedicated tooling machine in period $t$
$MOLD_{jt}^{C\_DM}$	Number of molds of customized part $j$ manufactured by dedicated fabrication machine in period $t$
$MOLD_{jkt}^{C\_AM}$	Number of molds of customized part $j$ manufactured by AM machine type $k$ in period $t$
$WT_{mt}^{DM}$	Working time of dedicated machine at manufacturing step $m$ in period $t$
$WT_{kt}^{AM}$	Working time of AM machine with building technique $k$ in period $t$

## 5.3 Production Planning Model with AM

### Objectives

- Minimize **total cost** and **total setup time of machines** during the entire planning horizon.

$$\begin{aligned}
 \text{Minimize } g_1 = & \sum_{t=1}^T \sum_{r=1}^R \sum_{m=1}^M c_r^{material} \times R_{rmt}^{DM} + \sum_{t=1}^T \sum_{i=1}^I h \times I_{it}^{NC} + \sum_{t=1}^T \sum_{i=1}^I p^{NC} \times S_{it}^{NC} \\
 & + \sum_{t=1}^T \sum_{m=1}^M e_m^{DM} \times WT_{mt}^{DM} + \sum_{t=1}^T \sum_{k=1}^K e_k^{AM} \times WT_{kt}^{AM}
 \end{aligned} \tag{5-1}$$

$$\text{Minimize } g_2 = \sum_{m=1}^M t_m^{SETUP} \left( \sum_{j=1}^J Z_{jt}^{NC} + \sum_{i=1}^m \sum_{k=1}^K Z_{kit}^C \right) \tag{5-2}$$

$$\text{Minimize } g = \lambda g_1 + (1 - \lambda) g_2 \tag{5-3}$$

## 5.3 Production Planning Model with AM

subject to

$$I_{it}^{NC} - S_{it}^{NC} = I_{i,t-1}^{NC} - S_{i,t-1}^{NC} + X_{it}^{NC} - net_{it}^{NC} \quad \forall i, t \quad (5-5)$$

$$X_{it}^C \geq net_{it}^C \quad \forall j, t \quad (5-6)$$

$$\sum_{m=1}^M \sum_{t=1}^T START_{jmt}^C = 1 \quad \forall j \quad (5-7)$$

$$Z_{jmt}^C \geq START_{jmt}^C \quad \forall j, m, t \quad (5-8)$$

$$START_{jmt}^C + \sum_{m'=1}^m \sum_{t'=1}^t Z_{j,m',t'}^C \geq Z_{jmt}^C \quad \forall j, m, t \quad (5-9)$$

$$\sum_{t=1}^T Z_{jmt}^C \geq 1 \quad \forall j, m = 3 \quad (5-10)$$

## 5.3 Production Planning Model with AM

subject to

$$Z_{jmt}^C \leq \Psi_{jmt}^{C\_DM} + \sum_{k=1}^K \Psi_{jmkt}^{C\_AM} \quad \forall j, m, t \quad (5-11)$$

$$\Psi_{jmt}^{C\_DM} = 0 \quad \forall j, t, m = 1 \quad (5-12)$$

$$X_{it}^{NC} \leq Z_{it}^{NC} \times big\_M \quad \forall i, t \quad (5-13)$$

$$Y_{jmt}^C \leq Z_{jmt}^C \times big\_M \quad \forall j, m, t \quad (5-14)$$

$$MOLD_{jt}^{C\_DM} \leq \Psi_{jmt}^{C\_DM} \times big\_M \quad \forall j, t, m = 2 \quad (5-15)$$

$$MOLD_{jkt}^{C\_AM} \leq \Psi_{jmkt}^{C\_AM} \times big\_M \quad \forall j, k, t, m = 2 \quad (5-16)$$

$$\Omega_{jt}^{C\_DM} \leq \Psi_{jmt}^{C\_DM} \times big\_M \quad \forall j, t, m = 3 \quad (5-17)$$

$$\Omega_{jkt}^{C\_AM} \leq \Psi_{jmkt}^{C\_AM} \times big\_M \quad \forall j, k, t, m = 3 \quad (5-18)$$

## 5.3 Production Planning Model with AM

subject to

$$\Omega_{jt}^{C\_DM} + \sum_{k=1}^K \Omega_{jkt}^{C\_AM} = X_{jt}^C \quad \forall j, t \quad (5-19)$$

$$MOLD_{it}^{NC\_DM} \geq \frac{X_{it}^{NC}}{n^{DM}} \quad \forall i, t \quad (5-20)$$

$$\sum_{t=1}^T \left\{ n^{DM} \times MOLD_{jt}^{C\_DM} + \sum_{k=1}^K n_k^{AM} \times MOLD_{jkt}^{C\_AM} \right\} \geq \sum_{t=1}^T \Omega_{jt}^{C\_DM} \quad \forall j \quad (5-21)$$

$$Z_{j,m-1,t}^C \geq \Psi_{jmt}^{C\_DM} \quad \forall j, t, m = 2 \quad (5-22)$$

$$rm_{jr}^C \times \Psi_{jmt}^{C\_DM} \leq b_{mr}^{DM} \quad \forall j, r, t, m = 3 \quad (5-23)$$

$$rm_{jr}^C \times \Psi_{jmnt}^{C\_AM} \leq b_{kr}^{AM} \quad \forall j, k, r, t, m = 3 \quad (5-24)$$

$$rm_r^{Mold} \times MOLD_{jkt}^{C\_AM} \leq b_{kr}^{AM} \times big \ M \quad \forall j, k, r, t \quad (5-25)$$

## 5.3 Production Planning Model with AM

subject to

$$R_{rkt}^{AM} \geq \sum_{j=1}^J (rm_r^{Ptype} \times vol_j^C \times Z_{j1t}^C) + \sum_{j=1}^J (rm_r^{Mold} \times vol_j^C \times MOLD_{jt}^{C-AM}) \\ + \sum_{j=1}^J (rm_{jr}^C \times vol_j^C \times \Omega_{jkt}^{C-AM}) \quad \forall r, k, t \quad (5-26)$$

$$R_{rmt}^{DM} \geq \sum_{k=1}^K R_{rkt}^{AM} \quad \forall r, t \quad m = 1 \quad (5-27)$$

$$R_{rmt}^{DM} \geq rm_r^{Mold} \times \left\{ \sum_{i=1}^I (vol_i^{NC} \times MOLD_{it}^{NC-DM}) + \sum_{j=1}^J (vol_j^C \times MOLD_{jt}^{C-DM}) \right\} \quad \forall r, t \quad m = 2 \quad (5-28)$$

$$R_{rmt}^{DM} \geq \sum_{i=1}^I (rm_{ir}^{NC} \times vol_i^{NC} \times X_{it}^{NC}) + \sum_{j=1}^J (rm_{jr}^C \times vol_j^C \times \Omega_{jt}^{C-DM}) \quad \forall r, t \quad m = 3 \quad (5-29)$$

## 5.3 Production Planning Model with AM

subject to

$$\begin{aligned}
 WT_{kt}^{AM} = & \sum_{j=1}^J \{ t_{jk}^{C\_AM} \times (\Psi_{j1kt}^{C\_AM} + MOLD_{jkt}^{C\_AM} + \Omega_{jkt}^{C\_AM}) \} \\
 & + \sum_{j=1}^J \sum_{m=1}^M (t_k^{Set\_AM} + t_k^{Post\_AM}) \times \Psi_{jmkt}^{C\_AM}
 \end{aligned}
 \quad \forall k, t \quad (5-30)$$

$$\begin{aligned}
 WT_{mt}^{DM} = & \sum_{i=1}^I (t_{im}^{NC} \times MOLD_{it}^{NC\_DM}) + \sum_{j=1}^J (t_{jm}^{C\_DM} \times MOLD_{jt}^{C\_DM}) \\
 & + t_m^{Set\_DM} \times \left( \sum_{i=1}^I Z_{it}^{NC} + \sum_{j=1}^J \Psi_{jmt}^{C\_DM} \right)
 \end{aligned}
 \quad \begin{array}{l} \forall t \\ m = 2 \end{array} \quad (5-31)$$

$$\begin{aligned}
 WT_{mt}^{DM} = & \sum_{i=1}^I (t_{im}^{NC} \times X_{it}^{NC}) + \sum_{j=1}^J (t_{jm}^{C\_DM} \times \Omega_{jt}^{C\_DM}) \\
 & + t_m^{Set\_DM} \times \left( \sum_{i=1}^I Z_{it}^{NC} + \sum_{j=1}^J \Psi_{jmt}^{C\_DM} \right)
 \end{aligned}
 \quad \begin{array}{l} \forall t \\ m = 3 \end{array} \quad (5-32)$$

## 5.3 Production Planning Model with AM

subject to

$$WT_{kt}^{AM} \leq w_t \times M_k^{AM} \quad \forall k, t \quad (5-33)$$

$$WT_{mt}^{DM} \leq w_t \times M_m^{DM} \quad \forall t, m \neq 1 \quad (5-34)$$

$$WT_{mt}^{DM} = 0 \quad \forall t, m = 1 \quad (5-35)$$

$$I_{i0}^{NC} = 0 \quad \forall i, j \quad (5-36)$$

$$S_{it}^{NC} = 0 \quad \forall i, j, t = T \quad (5-37)$$

$$\begin{aligned} &X_{it}^{NC}, X_{jt}^C, I_{it}^{NC}, S_{it}^{NC}, Y_{kmt}^C, \Omega_{jt}^{C\_DM}, \Omega_{jkt}^{C\_AM}, MOLD_{it}^{NC\_DM}, \\ &MOLD_{jt}^{C\_DM}, MOLD_{jkt}^{C\_AM} \text{ are non-negative integers.} \\ &R_{rmt}^{DM}, R_{rkt}^{AM}, WT_{mt}^{DM}, WT_{kt}^{AM} \text{ are non-negative.} \\ &Z_{it}^{NC}, Z_{jmt}^C, \Psi_{jmt}^{C\_DM}, \Psi_{jmnt}^{C\_AM}, START_{jmt}^C \in \{0, 1\} \end{aligned} \quad \forall i, j, k, r, m, t \quad (5-38)$$

## 6. Conclusion

- This research analyzes the contradiction within mass customization and suggests a suitable production planning framework for mass customizer.
- Also, the possible manufacturing options for custom orders are addressed.
- Based on the framework and the possible manufacturing options, the production planning model with AM is developed.
- This mathematical model can help mass producers who want to change their production strategy to mass customization.
  
- Later, the production planning model with AM will be verified with a numerical experiment.
- In addition, the case analysis will be carried out to find out the influence of the custom demand change and the technological advance of AM.