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# Order acceptance and scheduling in direct digital manufacturing with additive manufacturing

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Abstract: Additive manufacturing (AM), particularly powder bed fusion (PBF), technologies have been utilized as a direct digital manufacturing (DDM) approach in the production of parts for end users. It has been predicted that, in 2030, a significant amount of small and medium enterprises will share industry-specific AM production resources to achieve higher machine utilization and local production near customers enabled by AM will increase significantly across all industries. By then, the decision making on the order acceptance and scheduling (OAS) in production with PBF systems will play a crucial role in dealing with on-demand production orders. This paper introduces the OAS problem in a competitive environment where on-demand production service providers with multiple PBF systems compete for orders dynamically released on the market. A principle decision making process as well as the decision strategies for service providers and customers are proposed based on the characteristics of production with PBF systems.



*Keywords:* Decision Support System; Production planning and scheduling; Operations Research, Direct Digital Manufacturing

## 1. INTRODUCTION

Additive Manufacturing (AM), a process of joining materials to make objects from 3D model data usually layer upon layer, has been utilized as a direct digital manufacturing (DDM) approach in the production of parts for end users where can be found nowadays in aerospace and defence, biomedical, and automotive industries (Attaran, 2017; Ngo et al., 2018; Sing et al., 2016). The importance of AM technologies has been recognized in various businesses (Attaran, 2017; Bogers et al., 2016; R. Jiang et al., 2017; Khorram Niaki and Nonino, 2017; Mellor et al., 2014; Rayna and Striukova, 2016) and the AM has been considered as one of the key supporting technologies for smart design and manufacturing in Industry 4.0 (Wang et al., 2017; Zheng et al., 2018). The characteristics of the AM, particularly in enabling direct production of physical objects from digital design data with shortened process flow and enabling mass customization at low cost, made it a disruptive technology which will allow new business models, new products and new supply chains to flourish (R. Jiang et al., 2017). It has been predicted that, in 2030, distribution of final products will move significantly (>25%) to selling digital files for direct manufacturing through local production near customers enabled by additive manufacturing (R. Jiang et al., 2017). Recently, more and more manufacturers provide online 3D printing services, such as 3D Hubs, PROTOLABS, i.materialise, etc., where the customers upload their designs and place orders if they satisfied with the quote and printability feedback from the service providers.

Two of the most representative AM processes, Selective Laser Melting (SLM) and Electron Beam Melting (EBM), are Powder Bed Fusion (PBF) processes in which thermal energy source either a laser or electron beam is used to melt and fuse selectively regions of a powder bed (ASTM:F2790-12a). Both SLM and EBM have received significant attention in the research and have been widely used in various industries for advanced applications due to their advantages of fine resolution and high quality of printing near-full density parts (Ngo et al., 2018; Sing et al., 2016). The general production process with a PBF system is illustrated in Fig. 1, though the energy source and materials used in a particular PFB system might be different (Li et al., 2017).

The whole process is usually carried out in an inert gas environment where the thin powder layers with a typical thickness of between 20 μm and 60 μm are deposited on a metallic building platform and the selectively regions of the powder layer then to be melted and fused according to the digital model data. When the selective melting of one layer is completed, the building platform is lowered by a distance of the thickness of one powder layer and a next layer of powder is deposited on the platform. The process of powder layer deposition and selective melting will be alternate repeated until the required parts are completely built.

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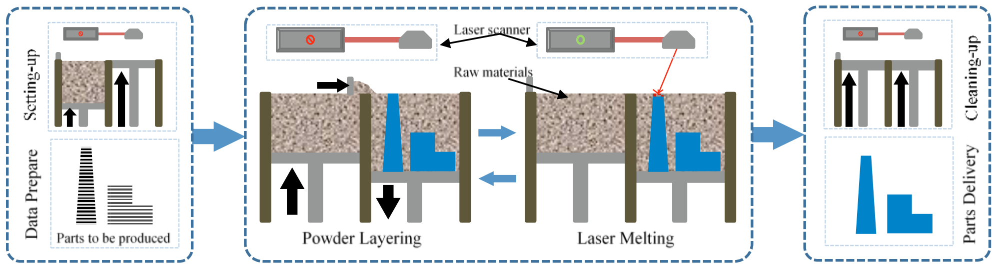


Fig. 1. Illustration of the general production process with a powder bed fusion system

As an emerging disruptive manufacturing technology, the application of PBF has increased substantially particularly in industrial sectors with small batch sizes and a high level of customization during the past years (R. Jiang et al., 2017; Li et al., 2017; Rayna and Striukova, 2016; Wang et al., 2017). It is predicted that, in 2030, a significant amount of small and medium enterprises will share industry-specific AM production resources to achieve higher machine utilization (R. Jiang et al., 2017). This development will put practical problems regarding production planning and scheduling on to the table (Kucukkoc et al., 2018, 2016, Li et al., 2018, 2017). Typically, the problem of order acceptance and scheduling (OAS), which is defined as a joint decision of which orders to accept for processing and how to schedule them (Slotnick, 2011), will play a crucial role in dealing with on-demand production orders from small and medium enterprises distributed around the world. Although the topic of OAS has attracted considerable attention from those who study scheduling and those who practice it over the last decades (D. Jiang et al., 2017; Silva et al., 2018; Slotnick, 2011), the OAS problems in production with PBF is barely discovered.

This paper aims to introduce the OAS problem in a competitive environment where on-demand production service providers with multiple PBF systems compete for orders dynamically released on the market. The characteristics of production with PBF systems are first analysed in Section 2 and then the problem of OAS in production with PBF systems is defined in Section 3. According to the problem statement, the decision-making process is discussed and the considerable decision-making strategies for both service providers and customers are proposed in Section 4. A numerical example is given in Section 5 to demonstrate the performance of different decision-making strategies, followed by conclusions and future research directions in the final section.

## 2. PRODUCTION WITH PBF SYSTEMS

### 2.1 Production capability and limitations

A PBF system is a kind of batch processing machine (BPM) in which a batch of identical or non-identical parts can be processed simultaneously according to its capacity. The producing of a batch of parts is usually called an AM job. As shown in Fig. 1, the production with PBF system usually consists of three key steps: job setup; parts building, and parts collection. Firstly, a series of operations is needed to set up a new AM job, such as process of digital model data, preparation of powder materials, and filling up protective atmosphere. Afterwards, the AM job can be started and the parts are built through repeating of powder layers deposition and selective melting. Finally, the parts in the job can be taken out from the machine for post-processing (e.g., heat treatment and removal of support structures) when all the parts have been produced.
A batch of parts can be grouped to form an AM job when they are able to fit the machine's production capacity which is generally limited by the cuboid space of the machine's building chamber. The parts assigned to an AM job are processed simultaneously and once the job is started no part can be added into or taken out from the machine. For metal PBF system like SLM and EBM, the parts are usually needed to be built onto the metallic building platform to avoid thermal induced deformation and should be properly oriented to reduce support structures (Atzeni and Salmi, 2012; Laureijs et al., 2017; Sing et al., 2016). Also, the parts are usually nested using their 2D bounding box within the area of building platform. In other words, the parts should not be overlapped each other.

### 2.2 Production time and costs

The production time as well as the costs of an AM job usually comprise of two sections: time and cost of manual operations including setup of the job and collection of produced parts; and the time and cost of producing the parts assigned to the job. The time spent on setting up of a new job and collection of produced parts usually ranges from one hour to several hours and the cost depends on the salary level. However, the processing time and cost of an AM job are usually varied according to the total material volume and the maximum height of the parts included in the job, as well as the efficiency of the PBF machine to conduct this job.

The PBF machine conducts an AM job through alternatively repeating the process of powder layer deposition and selective melting of the powder layer region. It must be pointed out that the accumulated time spent on powder layers deposition will be significant when the thickness of each layer is quite small, even longer than the time spent for melting all the required powder materials to build the parts. For example, given that the layer thickness of 20 μm and 15 seconds on deposition of each powder layer, the machine will spend more than 62 hours on generating powder layers to produce a part 300mm high. This case could be worse for particular PBF process where each layer might need additional time for powder materials pre-heating. Therefore, the production time of an AM job could be extended significantly by adding a new part not only because it increases the time for melting the powder materials but also because it might increase the time for powder layer deposition. This will make it more challengeable when considering the due date of each part because the assignment of new part to a job may cause the other already assigned parts cannot be completed on time.

Additionally, for a particular AM job, the time and cost related to the manual operations and powder layers deposition will be shared by all the parts assigned to the job. Therefore, the production cost of a particular part might be significantly different if the part is assigned to a different AM job. The difference of the production cost per volume of material could be more than 40% when the part is assigned to different jobs even the machine with the same specification (Li et al., 2017). Provided that the printing service price is based on the material volume of the parts, it is vitally important to appropriately determine how the parts should be scheduled to maximize the profit via minimizing the proportion of non-melting costs shared by all parts.

## 3. PROBLEM STATEMENT

### 3.1 Problem definition and assumptions

This paper studies the OAS problem in DDM environment where service providers with PBF systems compete for orders released by customers through offering competitive offer specified with service price and due date. In a period of time $T$, a set of distinct orders ($N = \{1,2,3,\dots,n\}$) are released on the market one by one in time sequence and a set of PBF machines ($M = \{1,2,3,\dots,m\}$) with different specifications are available at the beginning of the planning period making decisions on which order should be competed for and how to schedule the accepted orders simultaneously to maximum the machine's average-profit-per-unit-time (APT) during the whole makespan.

To further specify the problem to be addressed in this paper, the following assumptions are made:

- The machines considered in this paper are PBF systems with SLM/EBM processes used for metal parts production which can only handle one job at a time;
- The orders from customers have been separated into individual part orders in which the parts have been properly oriented according to the requirements of SLM/EBM process and all the parts together with necessary support structures are regarded as one digital model;
- A batch of parts assigned to a machine's job is feasible only when the parts can be placed in the machine without overlapping with each other which can be measured with the boundary box of a part order's digital model, and all the parts assigned to a machine's job will be processed simultaneously;
- A part order will be scheduled for production if an offer was received and the customer accepted this offer. The service provider cannot cancel the order once the customer has accepted the offer.

### 3.2 Mathematics model

To formulate the mathematical model of the OAS problem in DDM with PFB systems, the notations and decision variables are given in Table 1.

**Table 1. Notations and decision variables**

| Notations | Descriptions |
|---|---|
| $i, j, k$ | The index used for part orders $i \in N$, AM jobs $j \in N$, and PBF machines $k \in M$ |
| $h_i, l_i, w_i, v_i, r_i$ | The boundary height, length, width, material volume, and the arrival time of part order $i$ |
| $W_k, L_k, H_k$ | The maximum width, length, and height of building space on machine $k$ |
| $ST_k, VT_k, HT_k$ | The time for setting up a new job, forming per unit volume of material, and coating per unit height of material respectively for machine $k$ |
| $HC_k$ | The cost of human work per unit time for machine $k$ |
| $TC_k$ | The operation cost per unit time for machine $k$ |
| $MC_k$ | The cost of per unit volume of material on machine $k$ |
| $R_k$ | The rate of profit expected by machine $k$ |
| $BT_K$ | The buffer time to start a new job on machine $k$ |
| $\delta_v^k, \delta_h^k$ | The estimated coefficient of material volume and maximum height of part for machine $k$ |
| $JST_{k,j}, JPT_{k,j}$ | The start and production time of the $j^{th}$ job on machine $k$ |
| $JPP_{k,j}$ | The profit obtained from the $j^{th}$ job on machine $k$ |
| $op_{k,j}^i, od_{k,j}^i$ | The price of per unit volume of material and due date offered by machine $k$ to part order $i$ |
| $P_{k,j}^i$ | The profitability coefficient of part order $i$ to the $j^{th}$ job on machine $k$ |
| $APT_k$ | The average profit per unit time obtained by machine $k$ |
| $X_{k,j,i}$ | Variable to determine if part order $i$ is accepted and assigned to the $j^{th}$ job on machine $k$ |
| $Y_{k,j}$ | Variable to determine if the $j^{th}$ job on machine $k$ is assigned with any parts |
| $t$ | The system time $t \in [0, T]$ |

The objective of the OAS problem to be addressed in this paper is to maximize the average-profit-per-unit-time obtained by a PBF machine during the whole makespan through applying a particular decision-making strategy. The average-profit-per-unit-time for PBF machine $k$, represented as $APT_k$, can be formulated as follows:

$$\max APT_k = \frac{\sum_{j\in N} JPP_{k,j}}{\max_{j\in N}\{JCT_{k,j}\} - \min_{j\in N}\{JST_{k,j}\}} \tag{1}$$

where the net profit obtained by the $j^{th}$ job on machine $k$, represented as $JPP_{k,j}$, can be calculated as follows:

$$JPP_{k,j} = \sum_{i\in N}\left(op_{k,j}^i - TC_k \cdot VT_k - MC_k\right) \cdot v_i \cdot X_{i,k,j} - TC_k \cdot HT_k \cdot \max_{i\in N}\{h_i \cdot X_{i,k,j}\} - ST_k \cdot HC_k \cdot Y_{k,j}. \tag{2}$$

The start time and completion time of the $j^{th}$ job on machine $k$, represented as $JST_{k,j}$ and $JCT_{k,j}$ respectively, are determined the availability of the machine and the production time of the job which can be calculated as follows:

$$JST_{k,j} = \max\{t, JCT_{k,j-1}\} \tag{3}$$

$$JCT_{k,j} = JST_{k,j} + ST_k \cdot Y_{k,j} + VT_k \cdot \sum_{i\in N}(v_i \cdot X_{k,j,i}) + HT_k \cdot \max_{i\in N}\{h_i \cdot X_{k,j,i}\}. \tag{4}$$

### 3.3 Constraints

In the environment of production with PBF systems, several constraints have to be considered in scheduling part orders on PBF machines.

- Part orders can be assigned to a job on a PBF machine only when they can be placed on the machine's building platform without overlapping with each other, and any part order is not higher than the maximum height supported by the machine;
- A part order can only either be assigned to an exact AM job on a particular PBF machine or be rejected, and the machine can only handle one AM job at a time thus the AM jobs have to be scheduled to the machine in sequence;
- A part order is available for scheduling only after its arrival thus the start time of an AM job should be no earlier than any part order's arrival time assigned to this job.

## 4. DECISION MAKING STRATEGIES

### 4.1 Decision making process

In a competitive DDM service environment, the principle decision making process to schedule an AM job on a PBF machine is shown in Fig. 2. To schedule a new AM job, the PBF machine (service provider) selects one available part order at a time from the market and makes an offer with promised price $op_{k,j}^i$ and due date $od_{k,j}^i$ to the selected order based on applied decision-making strategies. The offer will be withdrawed if it was rejected. Alternatively, once an offer is accepted by the customer, the part order will be assigned to the AM job. The service provider will keep trying to obtain more part orders by making offers to available orders on the market until the AM job has reached conditions for assignment to the machine.

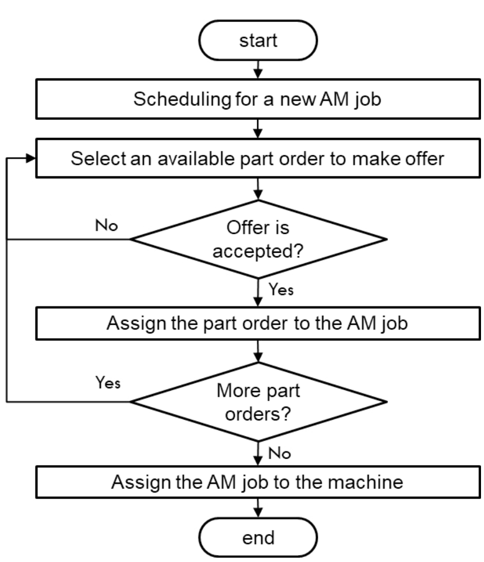


Fig. 2. The principle decision making process to schedule an AM job on a PBF machine

On the service provider side, each PBF machine aims to compete for as many orders as possible to maximize the total profit within a given period which can be evaluated with the average profitability during this period. The most important decisions made by the provider are service price and due date can be offered to a part order. As mentioned previously, the assignment of a new part to an AM job will affect the completion time of the job thus affect the due date of all parts included in this job. An order is available and can be delivered on time only when the part order can be assigned to a job which has enough capacity and the completion time of the job is not later than any promised due date of all orders included in the job.

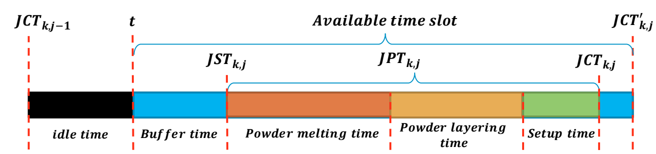


Fig. 3. Available time slot for an AM job in scheduling

An AM job is feasible only when the start time and the completion time of the job are located within its available time slot. At the time moment $t$, an example of available time slot for the $j^{th}$ job on machine $k$ is illustrated in Fig. 3. The job can be started at any time after the current time $t$ and the completion time of previous job $JCT_{k,j-1}$ has been assigned to machine $k$. The production time of an AM job comprises the time for setting up the job, powder layering and melting which respectively depends on the maximum height and total materials volume of all parts to be assigned to this job. However, the service provider has to make decision on the due date to be offered to the first part order without knowing the subsequent part orders. It is critical to estimate a properly completion time for the job. Later completion time gives more time to compete for more part orders, however, it might reduce the competitiveness of the offer due to a longer lead time. The estimated completion time of the $j^{th}$ job on machine $k$, represented as $JCT'_{k,j}$, can be formulated as follows:

$$JCT'_{k,j} = max\{JCT_{k,j-1}, t\} + BT_k + JPT'_{k,j} \tag{5}$$

where $JPT'_{k,j}$ is the estimated production time of the $j^{th}$ job on machine $k$. Considering part order $i$ as the first part order to be assigned, the estimated total material volume and maximum height of all part orders can be calculated as $V'_{k,j} = v_i \cdot \frac{W_k \cdot L_k}{w_i \cdot l_i} \cdot \delta_v^k$ and $H'_{k,j} = \max\{H_k \cdot \delta_h^k, h_i\}$ respectively. Thus, the estimated production time $JPT'_{k,j}$ and production cost per unit volume of materials $PPC'_{k,j}$ for the job can be calculated as follows:

$$JPT'_{k,j} = ST_k + VT_k \cdot V'_{k,j} + HT_k \cdot H'_{k,j} \tag{6}$$

$$PPC'_{k,j} = \frac{HC_k \cdot ST_k + (TC_k \cdot VT_k + MC_k) \cdot V'_{k,j} + TC_k \cdot HT_k \cdot H'_{k,j}}{V'_{k,j}} \tag{7}$$

Given the estimated completion time and production cost per unit volume of materials, the due date $od_{k,j}^i$ and service price per unit volume of materials $op_{k,j}^{i}$ to be offered to part order $i$ by machine $k$ can be calculated as follows:

$$od_{k,j}^{i} = JCT'_{k,j} \quad \text{and} \quad op_{k,j}^{i} = PPC'_{k,j} \cdot (1 + R_k) \qquad (8)$$

On the customer side, a part order might receive multiple offers from different PBF machines at the same time. The customer makes decision on acceptance of the received offers based on their strategies such as lowest price, shortest due date, or competitive coefficient of the offer. The competitive coefficient of the offer made by machine $k$ with its $j^{th}$ job to part order $i$, represented as $O_{k,j}^{i}$, can be formulated as follows:

$$O_{k,j}^{i} = \frac{\left(\max\{op_{k,j}^{i}\} - \min\{op_{k,j}^{i}\}\right)\cdot\left(\max\{od_{k,j}^{i}\} - od_{k,j}^{i}\right)}{\left(\max\{od_{k,j}^{i}\} - \min\{od_{k,j}^{i}\}\right)\cdot op_{k,j}^{i}} \qquad (9)$$

### 4.2 Decision variables and strategies

The service price and due date to be offered to a part order mostly depends on the service providers' anticipation and confidence for the market. The providers' attitudes toward the market can be reflected in the decision variables including buffer time $BT_k$, volume coefficient $\delta_v^k$, and height coefficient $\delta_h^k$, which are used for the estimation of the total materials volume and the maximum height of all part orders to be assigned to the AM job as well as the completion time of the job. According to the possible attitudes of service providers, three decision strategies for the generation of offers are proposed as follows:

- *CONSERVATIVE* ($BT_k = 0, V'_{k,j} = v_i, H'_{k,j} = h_i$): the service provider presumes that the current order is the only opportunity to form an AM job and the job will be started once the machine is available without waiting for other part orders.
- *OPTIMISTIC* ($BT_k = 24\ hours, \delta_v^k = 1, \delta_h^k = 0.5$): the service provider presumes that there will be enough available orders coming from market a little after (e.g., 24 hours), and their bulk density not lower than current part order which manifests as bigger $\delta_v^k$ and smaller $\delta_h^k$.
- *MODERATE* ($BT_k = 72\ hours, \delta_v^k = 0.5, \delta_h^k = 1$): the service provider presumes that there are enough available orders likely coming from market within a relative longer duration (e.g., 72 hours), and their bulk density might lower than current part order which manifests as smaller $\delta_v^k$ and bigger $\delta_h^k$.

However, given the service price and due date can be offered by a machine, the profit obtained from an AM job depends on the actual production costs per unit volume of materials which might be significant different due to the combination of part orders. The time spend to produce a part order can be divided into two parts, one profitable operations for powder melting, one non-profitable operations for powder layering and job setup. The rate of time spend on profitable operation in the total time within per unit area, termed as the profitability of part order $i$ for the $j^{th}$ job on machine $k$, represented as $P_{k,j}^{i}$, formulated as follows:

$$P_{k,j}^{i} = \frac{VT_k \cdot v_i}{(VT_k \cdot v_i + HT_k \cdot h_i)\cdot(w_i \cdot l_i)} \qquad (10)$$

In the case of there are multiple available part orders waiting for offering at the same time, a decision making strategy based on the part orders' profitability can be used for service providers on selection of part orders.

### 4.3 Numerical example

To demonstrate the variety of offers when applying with different decision strategies, a simple numerical example is calculated based on formulations (5) to (8), and the results are shown in Table 2. The example is designed to demonstrate the variety of offers generated by a PBF machine to different part orders when applying with different decision-making strategies. The specifications of PBF machine: $W_k \times L_k \times H_k$ $(25 \times 25 \times 32)$, $VT_k$ $(0.03)$, $HT_k$ $(0.7)$, $ST_k$ $(2)$, $TC_k$ $(60)$, $HC_k$ $(30)$, $MC_k$ $(2)$, and $R_k$ $(0.3)$. The units of time, volume, dimension is $hour$, $cm^3$ and $cm$ respectively. There 3 part orders are considered in the example which with the same material volume of 1200 $cm^3$ but varies in dimensions of boundary box.

It can be seen that the offered price, due dates, and average profit per unit time are varies for same part order with different strategies as well as for different part orders with same strategy. The OPTIMISTIC strategy always generates lower service prices for same part order, and part order with higher profitability presents higher $APT$.

**Table 2 Variety of offers with different decision making strategies**

| | **Part Order 1** ($w$: 10, $l$: 15, $h$: 10) | **Part Order 2** ($w$: 10, $l$: 20, $h$: 20) | **Part Order 3** ($w$: 20, $l$: 20, $h$: 30) |
|---|---|---|---|
| **CONSERVATIVE** ($BT_k$: 0, $\delta_v^k$: −, $\delta_h^k$: −) | $op$: 5.46, $od$: 45<br>$APT$: 33.60 | $op$: 5.92, $od$: 52<br>$APT$: 31.50 | $op$: 6.37, $od$: 59<br>$APT$: 29.90 |
| **OPTIMISTIC** ($BT_k$: 24, $\delta_v^k$: 1, $\delta_h^k$: 0.5) | $op$: 5.13, $od$: 187.2<br>$APT$: 31.62 | $op$: 5.25, $od$: 152.5<br>$APT$: 29.80 | $op$: 5.86, $od$: 103.3<br>$APT$: 24.54 |
| **MODERATE** ($BT_k$: 72, $\delta_v^k$: 0.5, $\delta_h^k$: 1) | $op$: 5.67, $od$: 171.4<br>$APT$: 19.09 | $op$: 5.91, $od$: 152.7<br>$APT$: 16.76 | $op$: 6.46, $od$: 132.4<br>$APT$: 13.51 |

## 5. CONCLUSIONS AND RESEARCH AGENDA

According to the projection estimated by (R. Jiang et al., 2017), by 2030, *"a significant amount of small and medium enterprises will share industry-specific additive manufacturing production resources to achieve higher machine utilization"*, and *"the AM will be used to efficiently enable customized products (mass customization) for every* *customer, moving from build-to-stock to build-to-order"*. The problem of OAS by then will play a crucial role in dealing with on-demand production orders from small and medium enterprises distributed around the world. Although the topic of AM has attracted considerable attention and the practical problems related to the production with AM technologies are rapidly emerging, the research on the OAS problems in production with PBF systems is just catching up.

This study introduced the dynamic OAS problem in a competitive environment where on-demand production service offered by service providers with multiple PBF systems. The characteristics of production with PBF systems was analysed and the challenges in dealing with OAS problem were discussed. Based on the analysis, a principle decision making process and considerable decision-making strategies have been proposed for both service providers and customers. As an attempt to address the dynamic OAS problem in AM on-demand production environment, the authors aim to open up opportunities to study the different production problems in industrial AM production field. Firstly, as the OAS in production with PBF systems is a joint decision on order acceptance and BPM scheduling problems (both of which are known to be NP-Hard), metaheuristic procedures will be developed for the generation of offers and generation of feasible schedule solutions for solving the OAS problem efficiently. Secondly, the decision-making strategies for service providers will be further investigated to maximize the profitability. Additionally, a comprehensive set of experiments will be designed and conducted to validate the heuristic algorithms. Finally, a simulation system based on the proposed decision-making process will be developed for the investigation of different decision-making strategies.

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