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Increasing the utilisation of additive manufacturing and 3D printing machines considering order delivery times

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Abstract

Additive manufacturing (or 3D printing), which refers to a direct fabrication of end-use products layer-by-layer, is a new and emerging technology. It enables the manufacture of complex parts or components in low to medium volume. Although this technology has been applied in conjunction with the construction of illustrative and functional prototypes (called rapid prototyping) for years, it is now being used increasingly in producing parts directly. Some leading companies, such as Boeing and General Electric, had additively manufactured vast number of components which have less weight but more strength than those manufactured using conventional techniques. NASA has already trialled additive manufacturing on the International Space Station, which allows astronauts to print tools and parts in space exactly when needed.

The additive manufacturing machines require high utilisation and processing costs. However, maximising the utilisation of such machines may play a crucial role in reducing such costs and enabling this technology widely accessible. This research introduces the production planning problem of additive manufacturing machines in such a way that resource utilisation is maximised and the delivery times of parts produced on the machines are satisfied. Different from classical machine scheduling problem, a complex nesting problem needs to be solved to group tasks into different jobs to be processed on various types of additive manufacturing machines. The sophisticated structure of the problem is defined and a numerical example is provided. A possible solution approach is also proposed for solving the problem.

Keywords: additive manufacturing, 3D printing, production planning, machine utilisation, operations research, optimisation.

1. Introduction

Additive manufacturing (AM) is defined as the process of joining materials to make objects from 3D model data. It is also known as 3D printing (3DP) and usually applied layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining. Different AM processes (such as fused deposition modelling, laminated object manufacturing, stereo lithography and selective laser sintering) have been developed since 1980s. Amongst these AM processes, laser engineered net shaping, electron beam melting and selective laser melting (SLM) are the most significant ones. Please see Coykendall et al. (2015), Huang et al. (2012) and Koff and Gustafson (2015) for detailed information on these processes (Qiang et al., 2015).

AM processes carry several significant advantages which empower AM as a unique competitor in production of small-batch products with sophisticated structures and rapidly-changing designs (Mellor et al., 2014). These advantages include material efficiency, resource efficiency, part flexibility and production flexibility (Huang et al., 2012; Mellor et al., 2014). Within this context, a growing number of companies from various industries are trying to adopt AM/3DP technologies in the production of their products. This results in a series of issues in production planning of AM/3DP, particularly with SLM facilities, due to the unique nature of this production process.

Although AM was primarily used for making prototypes, the development of material science and manufacturing technologies enabled producing parts directly using AM technology. SLM has become dominant practice for metallic AM processes thanks to its high accuracy and performance. Various industries have adopted the SLM technology for a variety of applications. Boeing, General Electric and European Aeronautic Defence and Space (EADS) used AM for producing components with various purposes. NASA used 70 additively-manufactured parts for the Mars Rover test vehicles and experimented 3D printing on the International Space Station, which allows astronauts to print tools and parts in space exactly when needed (NASA, 2014).

SLM is a job-based production process. In accordance with the capacity of the 3DP facility and produced parts, more than one part with different heights can be produced in one job. The job can be started after a set-up operation (such as data preparation, filling of powder materials, adjustment of the AM machine, and filling up protective atmosphere). Thin powder layers (20 µm – 60 µm) are released on a metallic base plate and the cross-sections of a sliced computer–aided-design file are subsequently scanned using a high power laser beam to densify the powder material (Rickenbacher et al., 2013). These two processes, namely powder layering and laser melting, alternate until all parts in the job are produced and the parts are removed from the base plate when the whole job is completed and the machine is cleaned.

The AM technology has been studied extensively by academics and practitioners. However, the mostly focused areas are the AM process itself and its applications to different industries (see, for example, Salmi (2012), Cooper et al. (2012) and Khajavi et al. (2014)) but not the utilisation of AM facilities optimally. Even there has been limited interest in discussing the calculations of cost structures in AM. An integrated cost model for SLM was proposed by Rickenbacher et al. (2013). Rickenbacher et al. (2013) showed how the manufacturing time as well as the set-up time (and therefore the total cost per component) is significantly reduced by building up multiple parts simultaneously. Several cost models proposed in the past have also been discussed in the same study. However, to the best of the authors' knowledge, no research has addressed to the planning of AM production facilities so far.

AM differs from other manufacturing technologies as the production cost and lead time are dynamically impacted by the combination of parts included in the same job. While some parts cannot be allocated to some machines due to the capacity and maximum supported height/area characteristics, the cost and time of a job may vary when a part with a particular height, production area and material volume is added in the job. Therefore, it is hard to determine which combination of parts will be produced on which machine. In this environment, this paper addresses to the production planning of additively manufactures components in such a way that the utilisation of AM machines are maximised and order delivery times are satisfied. The problem will be defined and the mathematical model of the problem will be presented in Section 2. A heuristic approach will be presented in Section 3. The paper will be concluded in Section 4 together with some insights for future developments.

2. Problem Definition

The distributed fabrication tasks (where each task represents a part) will be dispersed on job-by-job basis using specific height, production area and material volume of the parts in te same job. Each task will have an expected delivery time provided by the customer and all the tasks could be bided by any AM machine on the market. A reasonable expected delivery time will consider the specification of the part and a safety tolerance (3-5 days, considering that it may be fabricated together with other parts in a longer period of time or not be fabricated immediately). The distributed AM machines with particular specifications will bid for parts appeared on the market according to their capacity and production schedules. Given part delivery times, the distributed AM machines should try to get more tasks which they can deliver on time to cover their costs and make profit. A task is considered unavailable if its expected delivery time is unreasonable. If so, the task cannot be assigned to a job on a machine until its expected delivery time is expired.

A continuous cost will occur along the life time of the AM machine due to depreciation and infrastructure occupancy, no matter the machine is used or not. The AM machine could overcome these costs via undertaking profitable tasks. A dynamic cost, such as cost for set-up and operation, will added to this while the AM machine is undertaking a job. Particularly, the operation cost includes consumption of gas, electric, materials etc. and changes nonlinearly depending on the specifications of parts included in the job. Different sets or combinations of parts in a job will lead to different costs and production time as the total cost and time of performing a particular job is characterised by the total volume and maximum height of parts assigned to the job. Furthermore, this will lead to different total cost and lead time. Given a set of parts/tasks which randomly appear on the market with particular expected delivery times, the problem is how to regroup and allocate them to distributed AM machines in such a way that all parts are produced within the shortest period of time and the total profit of all AM machines is maximised.

The problem consists of a set of AM machines ($m = 1, \dots, m_n$), where each AM machine has different specifications, including operation cost, deprecation cost, set-up cost for a new job, production efficiency and capacity. There exists a set of parts ($i = 1, \dots, i_n$) with different volumes, heights and production areas as determined by the customers' demands. TO_i is the time point when task *i* is ordered by the customer and with an expected deliver time, represented by TD_i, which may be updated if the part is not fabricated before its expected delivery time. The parts will be allocated to AM machines and then grouped as different sets of jobs ($j = 1, \dots, j_n$), by considering their expected delivery times and production costs. Given that a part could not be fabricated before its expected delivery time with any AM machine, the part will be marked as delayed and will get a new expected delivery time. Each job will create some value due to the fabrication of parts included in the job and the total value could be calculated with a given value of per unit volume material VP.

2.1. Assumptions

The assumptions made are as follows:

- All parts with the same material type can be processed by any AM machine in the system.
- The position of parts related to the platform of AM machine cannot be changed arbitrarily due to the limitation of the AM process. In other words, just one specific section of the part could be placed onto the platform and it is known.
- The value of per unit volume material is an average value depending on the market condition and it is same for all AM machines in the system.

2.2. Mathematical Model

The following notation is used in the formulation of the mathematical model of the problem.

i : part index ($i = 1, \dots, i_n$ and $i \in I$)
j : job index ($j = 1, \dots, j_n$ and $j \in J$)
m : machine index ($m = 1, \dots, m_n$ and $m \in M$)
h_i : height of part i
a_i : production area of part i
v_i : material volume of part i
t_0 : initial time point
t : current time point
TO_i : time point when part i is ordered in

TD_i : time point when part i should be delivered by
TNJ_m : available time to set-up a new job on machine m
TSJ_{mj} : starting time of job j on machine m
TEJ_{mj} : ending time of job j on machine m
PPT_{mi} : production time needed if part i is fabricated on machine m individually
ST_m : time needed for machine m to set-up a new job
VT_m : time for forming per unit volume of material on machine m
HT_m : accumulated interval time per unit height for machine m
H_m : maximum height of part that machine m can process
A_m : maximum production area of part that machine m can process
TC_m : depreciation cost per unit time for machine m (no matter the machine is used or not)
OC_m : operation cost per unit time for machine m (such as gas, electric, etc. used when the machine is forming material)
SC_m : set-up cost per job for machine m
MC : cost of material per unit volume
VP : value of per unit volume material
$RV_{\Delta T}$: remaining value created by all machines during ΔT
JPT_{mj} : production time of job j on machine m
JPC_{mj} : production cost of job j on machine m

$$X_{ji} = \begin{cases} 1 & if\ part\ i\ is\ processed\ in\ job\ j \\ 0 & otherwise \end{cases}$$

$$Y_{mj} = \begin{cases} 1 & if\ job\ j\ is\ processed\ on\ machine\ m \\ 0 & otherwise \end{cases}$$

2.2.1. *Objective Function*

In terms of the notations given above, the remaining value created by all machines during ΔT (from t_0 to the end of last job) can be formulated as follows:

$$RV_{\Delta T} = VP \cdot \sum_{i \in I} v_i - \Delta T \cdot \sum_{m \in M} TC_m - \sum_{m \in M} \sum_{j \in J} JPC_{mj} \ , \tag{1}$$

where

$$\Delta T = \max_{m \in M, j \in J} \{TEJ_{mj}\} - t_0 \ . \tag{2}$$

$$JPC_{mj} = SC_m + OC_m \cdot \left(VT_m \cdot \sum_{i \in I_{mj}} v_i + HT_m \cdot \max_{i \in I_{mj}} \{h_i\} \right) + MC \cdot \sum_{i \in I_{mj}} v_i \ , \tag{3}$$

where I_{mj} is the set of parts assigned to job j on machine m.

The remaining value is the total value created by all AM machines after deducting the depreciation costs during a particular duration and the additional costs due to performing all scheduled jobs. The depreciation cost of each AM machine may be different depending on their specifications. Also, the cost of a job on a machine may be different in accordance with its efficiency. The total time to complete all parts in a job depends on the parts processed in this job. In other words, the different combinations of jobs may get the same remaining value but the time to complete the last job may be different. Therefore, given a set of parts, the average remaining value per unit time should be used to evaluate the utilisation of all AM machines. The ultimate goal of the proposed model in this study is to minimise the remaining value per unit time for the whole system (including all jobs on all machines). The objective function is formulated as follows:

$$\min Z = \frac{RV_{\Delta T}}{\Delta T} = \frac{VP \cdot \sum_{i \in I} v_i - \Delta T \cdot \sum_{m \in M} TC_m - \sum_{m \in M} \sum_{j \in J} JPC_{mj}}{\Delta T} \ . \tag{4}$$

2.2.2. Constrains

Part Occurrence/Assignment Constraint:

Parts cannot be split into more than one job. Therefore, each part must be allocated to one job exactly.

$$\sum_{j=1}^{j_n} X_{ji} = 1; \quad \forall i \in I. \tag{5}$$

Job Occurrence Constraint:

Each planned job can be assigned to one machine only when there is at least one part assigned in this job. In other words, if one or more jobs are assigned in a job, this job must be assigned to exactly one machine.

$$\sum_{m=1}^{m_n} Y_{mj} - Z_j = 0; \quad \forall j \in J. \tag{6}$$

where Z_j is an indicator variable, $Z_j = \begin{cases} 1 & if \ \sum_{i \in I} X_{ji} \geq 1 \\ 0 & otherwise \end{cases}$.

Capacity Constraint:

The total area needed to produce parts assigned to each job on each machine must be smaller than the available area of that machine.

$$\sum_{i \in I} a_i \cdot X_{ji} \cdot Y_{mj} \leq A_m ; \quad \forall m \in M; \, \forall j \in J. \tag{7}$$

The maximum height of parts assigned to a job on a specific machine cannot exceed the maximum height supported by this particular machine.

$$\max_{i \in I} \{ h_i \cdot X_{ji} \cdot Y_{mj} \} \leq H_m; \quad \forall m \in M; \, \forall j \in J. \tag{8}$$

Job Utilisation Constraint:

Jobs will be utilised incrementally, starting from the first job ($j = 1, 2$, and so on). In other words, a new job can be utilised by a machine if all of jobs numbered priorly have been utilised.

$$\max_{i \in I_j} \{ X_{ji} \} \geq \max_{i \in I_j} \{ X_{(j+1)i} \} ; \quad \forall j \in J. \tag{9}$$

where I_j is the set of tasks assigned to job j.

Time Constraint:

The start time of a job cannot be earlier than that part emerged on the market.

$$Y_{mj} \cdot TSJ_{mj} \geq \max_{i \in I} \{ TO_i \cdot X_{ji} \cdot Y_{mj} \} ; \ \forall m \in M; \, \forall j \in J. \tag{10}$$

Jobs planed on the same machine will be utilised incrementally and the start time of the job cannot be earlier than the end time of previous job.

$$\max_{j \in J} \{ Y_{m(j+1)} \cdot TSJ_{m(j+1)} \} \geq \max_{j \in J} \{ Y_{mj} \cdot TEJ_{mj} \} ; \ \forall m \in M. \tag{11}$$

3. Heuristic Procedures

As the parts sequentially appear on the market, each AM machine evaluates the accessible parts and put suitable parts into its wish list. An accessible part means this part has appeared by current time ($TO_i \leq t$) and the part has not been assigned to any started job yet. The parts in the wish list of an AM machine are regrouped into jobs by considering the production costs and the remaining value. The objective of an AM machine is to maximise the average remaining value per unit time from the beginning of the system to the end of the new job. Furthermore, before starting a new job, the machines are able to adjust the combination of parts which will be included in this job. Once the new job is determined, the parts which will be included in this job will be removed from the machine's wish list and marked as inaccessible to all machines on the market. The average remaining value per unit time for a machine, represented by $RV_{m,\Delta T}$, can be calculated as follows:

$$RV_{m,\Delta T} = \frac{VP \cdot \sum_{i \in I_{mj}} v_i - \Delta T \cdot TC_m - JPC_{m(j+1)}}{\Delta T}, \tag{12}$$

where

$$\Delta T = TSJ_{m(j+1)} + JPT_{m(j+1)} - TEJ_{mj}, \tag{13}$$

$$JPT_{m(j+1)} = ST_m + VT_m \cdot \sum_{i \in I_{m(j+1)}} v_i + HT_m \cdot \max_{i \in I_{m(j+1)}} \{h_i\}, \tag{14}$$

$$TSJ_{m(j+1)} \geq TEJ_{mj}.$$

$TSJ_{m(j+1)}$ and TEJ_{mj} are the expected starting time of a new job and the ending time of the last scheduled job on machine m.

If a part is included in the wish list of more than one machine at the same time, the part is assigned to the job with earliest starting time. If there are more than one machine with a new job starting at the same time, the part is assigned to the job with larger average remaining value. If the jobs have the same starting times and average remaining values, then the part is assigned to a randomly determined job. Given that an AM machine is failed in a competition for a part in its wish list, the parts which have been assigned to other machines will be inaccessible for this machine and new parts need to be reselected from its wish list with the aim of improving the average remaining value of its new job.

The AM machine will consider the expected delivery time of the part when selecting a part into its new job. The parts should be fabricated before their expected delivery time to satisfy the customer demands. Therefore, the ending time of the new job planned by the machine should be earlier than any part's expected delivery time in this job. However, if a part has not been assigned to any job before the latest starting time of this part, then its expected delivery time will be ignored and a new delivery time will be determined depending on the ending time of the assigned job. The latest starting time of part i on machine m is represented by TSP_{mi} and calculated as follows:

$$TSP_{mi} = TD_i - ST_m - VT_m \cdot v_i - HT_m \cdot h_i. \tag{15}$$

The latest starting time of parts on all machines will be adopted as a decision criterion for ignoring the expected delivery time. In other words, a part's delivery time can be ignored only when it is not possible to fabricate this part on any machine in the system. This constraint can be represented as follows:

$$t \geq \max_{m \in M} (TSP_{mi}). \tag{16}$$

The parts will be assigned to jobs one-by-one according to this approach until all parts have been assigned. The duration of the system will be determined by the latest ending time of all planned jobs and thus the total cost of performing all planned jobs can be calculated. Also, the duration and total costs are used to calculate the average remaining value per unit time for the given parts.

4. Conclusions

The major reason which prevents the extensive application of SLM is its high operating costs caused by the nature of layer-upon-layer process. Distributed tasks need to be centralised to increase the utilisation of AM/3DP facilities. However, it is usually hard for individual companies to undertake the high investment and operating costs of centralisation. Furthermore, the production tasks of one company are usually far from filling the capacity of an AM/3DP machine, and the machines are mostly used for producing parts during the research and development (R&D) phase of creating new products. Therefore, it is recommended that distributed production tasks should be centralised to increase the utilisation of the AM/3DP machines. Second, the nature of the layer-upon-layer process and job-based production makes it difficult to produce an optimal production schedule of parts.

This paper addressed to the production planning of AM/3DP machines with the aim of increasing resource utilisation for the first time in the literature. Delivery times of orders from distributed customers are considered as a significant factor in the decision making process of assigning parts into machines and so the jobs. The problem is modelled mathematically and a heuristic procedure is proposed for solving the problem. The authors' ongoing research aim to experiment the proposed model and the heuristic approach on numerical problem sets and report in the near future. Also, considering the unique and sophisticated production environment of SLM, novel production-planning models and optimisation techniques are required to facilitate their application in industry.

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