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Optimization Model to Extend Existing Production Planning and Control Systems for the Use of Additive Manufacturing Technologies in the Industrial Production

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Abstract

The use of additive manufacturing technologies for industrial production is constantly growing. This technology differs from the known production procedures. The areas of scheduling, detailed and sequence planning are particularly important for additive production due to the long print times and flexible use of the production area. Therefore, production-relevant variables are considered and used for the production planning and control (PPC) of additive manufacturing machines. For this purpose, an optimization model is presented which shows a time-oriented build space utilization. In the implementation, a nesting algorithm is used to check the combinability of different models for each individual print job.

Keywords: Additive manufacturing; 3d printing; Production Planning and Control (PPC); scheduling; optimization

1. Introduction

The Additive Manufacturing (AM), also known as 3D printing, is a group of manufacturing technologies that automatically applies material in layers until a three-dimensional object is created. Compared to traditional

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manufacturing, AM offers the advantage that parts can be produced directly and without special tools with a variety of materials such as plastic, metal or ceramics [1]. The integration of AM into the existing production process promises great advantages for component geometry and for the production of customer-specific products [2; 3]. With the use of multiple AM machines, companies face new challenges. The manufacturing data for the production of a part must be combined with scheduled operational process data, such as the working times of the machine operators. The operational process data is part of the production system and can be found in production planning and control systems (PPC). The core task of the PPC is the scheduling, capacity- and quantity-related production program planning, the demand planning of production and assembly processes as well as the planning and control of external procurement and in-house production [4]. Within the scope of capacity and schedule planning, the time schedule for planning and coordination of orders is calculated on the basis of quantity planning, taking into account available capacities [5]. Planning and modifying the production orders, calculating their completion times and locations, and taking into account machine and personnel availability are crucial in additive production in the areas of detailed scheduling and sequence planning. Problems, breakdowns or unforeseen order situations can be taken into account dynamically and immediately in planning with AM for all subsequent production orders without having to prepare specific tool parts, as in traditional manufacturing. To produce cost-efficiently two- or three-dimensional nesting algorithms can be used to optimize the space utilization of AM systems [6]. If components cannot be placed on top of each other due to supporting structures, a two-dimensional nesting algorithm is applied. If a superimposed part placement is possible, a three-dimensional algorithm is used [7]. While a comprehensive overview of the specific optimization problems has already been done by e.g., Scheithauer in his book "Introduction to Cutting and Packing Optimization" [8], the consideration of the maximum space utilization by means of nesting algorithms alone is not sufficient for an economical AM production due to downtimes in the case of personnel absence. The first paper published on the topic PPC and AM focuses on costs and highlights the need to plan additive manufacturing machines to reduce process costs [9]. In contrast, this paper examines the working times of human resources professionals for scheduling additive manufacturing processes in PPC. Accordingly, the aim of this work is to extend the earlier works on space utilization optimization by the temporal aspect, whereby a synchronization with the shift plans of workers can be achieved.

2. Model for time-based planning of print jobs

For the industrial use of additive manufacturing plants, print jobs must be scheduled to be terminated and started within staff working times to carry out withdrawal from and material provision to AM equipment. A solution may be such, that instead of assigning individual print jobs with a certain number of objects to a printer, the workload of individual printers is dynamically scaled according to the requirements and working hours of the operators. This implies the capability of PPC system to distribute the objects to be printed among different printers.

2.1. Optimization model

Nesting algorithms enable industrial AM production architecture with multiple printers that can dynamically share objects for print jobs. Models from different production orders are filtered according to their production parameters and combined with each other for optimal utilization. Industrial use of additive production plants requires additional data, such as the working hours of machine operators. For print jobs to be completed and started within working hours, it is necessary to dynamically allocate the objects to be printed between available printers. This means that print jobs are not permanently assigned to printers with a predefined number of objects, instead the corresponding objects are grouped together according to the current demand and availability. The model (see Fig. 1) contains three triggers that cause different process areas to start. These three triggers are associated with: 1) the sales order, 2) the change in production resources, and 3) the availability of AM production machines.

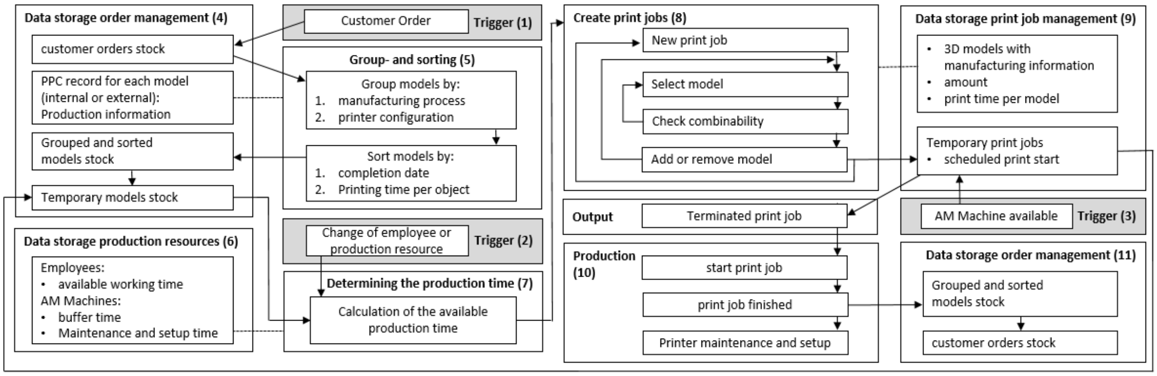

Fig. 1. Optimization model for time-based planning of print jobs

The first trigger (see Fig. 1 – Trigger 1) is an event in the customer order. The event can be a newly received sales order, a change to an existing sales order, or the complete removal of a sales order. When a new sales order is received, it is first added to the sales order list and a new process start is initiated. Subsequently, a grouping and sorting process is triggered (see Fig. 1 - section group- and sorting (5)). This first reads the information from the PPC record such as the 3D model, the number of pieces required from the parts list, the production time per model, the type of manufacturing process and, if necessary, the special configuration for printing (see Fig. 1 - section data storage order management (4)). The grouping is carried out according to the manufacturing process and the special configurations. From this process stage onwards, each grouping runs through the process independently of the other groups. Within the groupings, the models are sorted according to their completion date. Within this sorting, a further sorting is carried out according to the printing time per model. The result is a grouped and sorted list of the models to be printed, which are then copied to the temporary model list.

For the calculation of possible production times, additional data such as the available employee times is required (see Fig. 1 - section data storage production resources (6)). These employee operating times include the time required for removal, material supply or maintenance and are dependent on the number of production machines to be controlled and the manufacturing technologies used. These activities must be defined and planned as variables on the basis of their character and the machinery used. In addition, the buffer times as well as the maintenance times of the various AM production facilities must be taken into account when calculating the available production time. Note that the available production time represents the completion of a print job up to the next available employee working hours. The buffer time is a defined period that is scheduled as a buffer to the completion of a print job. This calculation takes forward and backward scheduling into account (see Fig. 1 - section determining the production time (7)). In forward scheduling, the production time is calculated from the start of an individual work slot, while in backward scheduling the production time is taken into account or counted back from the latest work slot to completion. Depending on the duration and nature of the activity, several production facilities, sequentially or jointly, may carry out different types of activities within a work time slot. To calculate the print jobs, all available production times must first be transmitted (see Fig. 1 - section data storage print job management (9)). These represent the time span up to one or more working hours, in the course of which work time slots can be skipped. In order to make the best possible economic use of additive manufacturing facilities, the longest possible time frame up to a work time slot must be found (see Fig. 1 - section create print jobs (8)). Consequently, the production time has to be calculated first, taking into account the sorting and combinability of the individual models added per printer, at maximum space utilization. Based on the maximum print time, the print time to the nearest possible work time slot must be reached. The combinations of potential objects must be used to iterate and check with which models combinability is possible. To do this, a new print job is first created for a grouping. The model with the longest printing time and the next completion date is then selected on the basis of the sorting. The model is then checked to determine if it fits into the construction space and further models can be added by means of the compatibility check according to the same sorting.

In order to check the compatibility of the models with each other, it is verified whether the available printing time is sufficient and if the space available for the respective models is sufficient. For this purpose, there are numerous different algorithms which allow a 2-dimensional or 3-dimensional arrangement. The appropriate algorithm must be selected depending on the manufacturing process. If the compatibility check algorithm fails, the model is skipped and checked with the next model until the space is fully utilized within the production time. Afterwards, a machine code is created by means of the model combination and the print configuration, which forms the print job. The exact duration of the production process is read from this data. If this differs from the available production time, the next shorter production period is targeted as already described. If the duration of the print job matches the production period, it is saved as a temporary print job and the models are removed from the Temporary models stock. The process then restarts for the next production period or printer configuration. If "AM Machine availability" is triggered (see Fig. 1 – Trigger 3), the printer must use the first temporary print job and remove it from the list of "Temporary print jobs" (see Fig. 1 - section data storage print job management (9)). The system checks again whether the planned print start is within the defined buffer range. If this differs from a temporary print job, the entire job creation process must be restarted and then the first temporary print job must be sent to the printer and removed from the list. Production is complete after a print job has been completed and the parts removed (see Fig. 1 - section production (10)). The models are then removed from the print job list and the grouped and sorted models stock (see Fig. 1 - section data storage order management (11)). Either all models of the print job are removed completely or in case of a failed quality check only the successful models are removed from the grouped and sorted models stock. In the event of a failed quality check, the event "change of production resource" (see Fig. 1 – Trigger 2) is triggered after the models have been removed. If all models for a sales order are printed, the sales order is removed. Following the completed print job, the "maintenance" process follows, which includes all steps, depending on the printer type, until the printer is fully operational again. The trigger "AM machine available" is then activated and the process is continued for the production line using the temporary print jobs.

2.2. Implementation

The calculation requires information about the print jobs of the models, working times and available printers as shown in Table 1. On the one hand, the information on available working and printing times allows employees to plan their work, and on the other hand, they can carry out checks or maintenance of the printers at defined intervals. As soon as a change occurs in the stored data, a trigger causes a new schedule.

Table 1. Required data for planning print jobs

Type	Data	Description
Print orders	Name	Model name with path
	Count	Number of models required
	Priority	Priority within a given time frame
	Configuration	All usable printer configurations
	Material	All usable materials for the order
	Incoming date	Date and time of order receipt
	Completion date	Date and time for latest completion
Working hours Worker	Name	Worker's name or role
	Work slots	All available working times, including start and end time with date and time.
Printer	Name	Printer name
	Configuration	Usable configurations for the printer
	Workspace	Maximum usable installation space with specification of X, Y and Z
	Work slots	All available working times, including start and end time with date and time.

From the imported data, the available printing times are calculated on the basis of the operators working times and the printing time per model. The calculation of the printing time per model is done by slicing with the CuraEngine by the stored print configurations for each model. The print configurations is exported from Cura and used for planning with a written converter. Slicing divides the model from the stereolithography (STL) file format into individual layers and generates a machine code with printing time. The models are then sorted by priority and remaining time to completion. The models were automatically filtered to the printers based on the print configurations stored for the jobs. For each printer, models are then added based on the available print times until the available print time is reached. As a result, in the positive case of the combinability check, a STL file with all models is generated. Finally, slicing is performed via the newly generated STL file to check whether the available print time can be fulfilled in the given combination.

3. Results

In order to check the functionality of the proposed optimization model, test objects were defined in two groups. The first group had different geometric shapes for checking the functioning of the nesting algorithm (see Fig. 2 (a)) and the second group for checking compliance with the specified print times. In the second grouping, all objects had the same base area, but with different heights (see Fig. 2 (b)). For these simulations, two scenarios with expected results were defined. In the first scenario, the available print time is sufficient to place all models in the build space, the expected result is a scheduled print job that is finished before the end of production time and offers space for further models. In the second scenario, the available printing time is not sufficient to fill the entire installation space. The expected result is that on the basis of the parameters of the individual models, such as priority and completion date, the order for the models was chosen and saved as finished print jobs, where the remaining printing time is not sufficient for any further existing models.

The implementation was evaluated by test objects and a print job for a 42-part project with a specified order of completion. All models required for the project with the number of pieces and the calculated printing time can be found in the Appendix A.1. The test objects were used to check the functionality of the nesting algorithm and compliance with print times. For the nesting algorithm, different geometric shapes were used and for maintaining the print times, objects with the same base area and different heights were chosen. For the project, the sequence and completion date for each model was determined on the basis of the bill of material (BOM) structure. For the simulation, an operator with fixed working hours for the printers was defined (see Table 2) and two printers which are available for the entire period. It was assumed that the planned removal time of the manufactured parts is always thirty minutes per printer. The results of the planned orders can be seen in Table 3. The models associated with the print jobs can be viewed in Appendix A.2. A complete schedule with forward scheduling could be calculated for prints with job IDs 1, 2 and 3. Due to the workload, the work time slots can be skipped on Tuesday and Wednesday. Forward scheduling was not possible for the job with ID 4, since the completion time exceeds the employee's availability on Friday. Therefore, the implementation has switched to backward scheduling, which takes into account all new models that arrive before the start date and can be added to the print job if applicable.

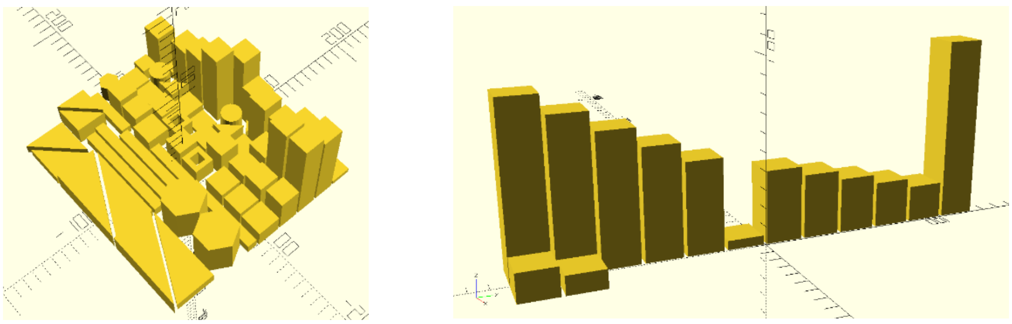

Fig. 2. (a) Geometric shapes for checking the nesting algorithm; (b) Models for testing compliance of defined print times

Different filter configurations for infill settings and colors are taken into account by the implementation for the planning, but to provide a better overview, a uniform infill setting and color was selected for all objects. As an alignment in the diagonal resulted in poor results with linear parts, the nesting algorithm was specified to be 90° for possible rotations. The reduction of the degree allows for more rotations and thus an increase in space utilization, but also for a longer calculation time of the algorithm. The tests showed that Fused Deposition Modeling (FDM) printers are prone to errors when using the maximum print area. During the maintenance of the printers, test printouts were used in addition to the replacement of the spare parts to determine the maximum usable print area and redefined in the table for printer data.

Table 2. Staff available working time for printers

Weekday	**Time**
Monday	08:00 – 09:00
Tuesday	08:00 – 09:00
Wednesday	08:00 – 09:00
Thursday	10:00 – 11:00
Friday	13:00 – 14:00
Saturday	-
Sunday	-
Monday	08:00 – 09:00

Table 3. Planed and scheduled print jobs

Job-ID:	1	2	3	4
Printer-ID:	1	2	1	2
Start:	Monday 08:30:00	Monday 09:00:00	Thursday 10:30:00	Saturday 09:39:29
Finish:	Thursday 09:19:59	Thursday 09:14:03	Friday 12:18:10	Monday 07:30:00
Sliced print time:	72:49:59 h	72:14:03 h	25:48:10 h	45:50:31 h
Time of removal:	Thursday 10:00 – 10:30	Thursday 10:30 – 11:00	Friday 13:00 – 13:30	Monday 08:00 – 08:30

4. Conclusion

This paper presents and analyses an optimization model for the planning of AM systems using nesting algorithms for time-oriented work space utilization. Production-relevant variables for the production planning and control of additive manufacturing machines are identified and tested experimentally during implementation. The maximum use of space was combined with the focus on synchronizing workers shift schedules. The optimization model was divided into the areas grouping and sorting, calculation of production times and creation of print jobs. The calculated production time takes into account the sorting and combinability of the individual parts by applying an nesting algorithm for maximum space utilization while observing the specified production time. Certain triggers represent the external influencing factors and cause either a partial area or the entire process to be executed. With the presented evaluation example, the feasibility of the optimization model was demonstrated, in which the downtimes were minimized by a time-oriented space utilization. In the test printouts it has been noticed that the calculated printing time does not exactly correspond to the actual printing time. This problem was solved by adjusting the buffer time. However, further research is required for accurate planning to ensure that the calculated print time corresponds to the real one. Further research could take into account the material stock on the AM machines in the optimization model and use it for selecting the operator slot.

Appendix A. Project parts and planned jobs

A.1. Project parts

Table 4. Required components for the project with quantity and printing time per part

Quantity	**Name**	**Calculated print time per model**
4	IE_Foot_Bottom.stl	04:27:00
2	Bottom_CornerF2.stl	04:29:54
2	BottomM_CornerF2.stl	04:27:03
2	Lock_CornerF2.stl	02:53:22

2	LockM_CornerF2.stl	02:54:05
2	F-Roller.stl	11:19:56
2	F-RollerM.stl	11:17:43
4	F-RollerPlate.stl	00:30:17
4	Spacer_CornerF2.stl	00:39:57
2	Top_CornerF2.stl	03:50:38
2	TopM_CornerF2.stl	03:52:18
2	F-Nut_Trap.stl	02:22:20
1	F-ToolMount.stl	08:55:49
1	F-Z-Lower.stl	04:52:16
1	F-Z-Motor.stl	04:38:59
2	F-XYZ_T8.stl	09:42:18
2	F-XY.stl	22:55:59
1	F-Spacer.stl	01:29:19
4	F-RollerMount.stl	06:25:09

A.2. Planned jobs

Table 5. Parts with quantity to the planned jobs

Job-ID	Parts with Quantity
1	F-RollerM.stl * 2; F-RollerPlate.stl * 1; Spacer_CornerF2.stl * 4; Top_CornerF2.stl * 2; TopM_CornerF2.stl * 2 F-Nut_Trap.stl * 2; F-ToolMount.stl * 1; F-Z-Lower.stl * 1; F-Z-Motor.stl * 1; F-Spacer.stl * 1; F-RollerMount.stl * 1
2	IE_Foot_Bottom.stl * 4; Bottom_CornerF2.stl * 2; BottomM_CornerF2.stl * 2; Lock_CornerF2.stl * 2 LockM_CornerF2.stl * 2; F-Roller.stl * 2; F-RollerPlate.stl * 3
3	F-XYZ_T8.stl * 2; F-RollerMount.stl * 1
4	F-XY.stl * 2

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