A Multi-part Production Planning Framework for Additive Manufacturing of Unrelated Parallel Fused Filament Fabrication 3D Printers

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A multi-part production planning framework for additive manufacturing of unrelated parallel fused filament fabrication 3D printers

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Abstract

Fostering the development of additive manufacturing (AM) in the context of mass production is a key factor to ensure its adoption in industry. It should be remembered that this technology intrinsically makes it possible to produce parts with unexpected complexities in terms of shape and structure, but this comes at a price: time. To overcome this productivity barrier, AM technology providers are currently developing 3D printing machines with high-speed performance and mass reproduction means in a single run. Although such trends can be seen as a natural evolution of this technology with respect to current consumption patterns, it still remains scientific issues on production planning strategies to be tackled. The objective of the paper is to address on-demand production planning of different AM parts in FabLabs/hubs composed of unrelated parallel 3D printers. A novel framework is then introduced to consider part orientation, path planning and part-to-printer assignment with a specific focus on fused filament fabrication technique. By targeting a minimum production time, it exhibits reasoning algorithms implemented in a Python application at the interface of computer-aided design system and process planning software. A case study with a batch of non-identical parts and 3D printers is introduced to illustrate the added value of the framework and its operational side.

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1. Introduction

Additive manufacturing (AM) is currently considered as a key technology that brings together processes and techniques to produce – in a layer-by-layer deposition mode – objects or assemblies [1]. It therefore provides more design freedom than the formative and subtractive manufacturing techniques widely accepted and mastered in industry and academia [2]. With AM, the complexity in terms of shape and structure is free, but the printing time can be significant, which breaks with current mass production rates in industry [3]. This is the reason why AM has been mainly used for rapid prototyping purposes and for the manufacturing of very complex parts with high added value. Today a part of the concerns is devoted to increasing productivity so as to meet the industrial needs for mass customisation/personalisation. In such a context, efforts are currently being made to produce batch of parts, while maintaining the same AM technique and machine, therefore leading to the development of machines with better performances and higher printing volumes [4].

In addition, the development of AM has also led to the emergence of FabLabs and 3D printing hubs/platforms [5–7] by providing flexible/efficient means and tools to foster ideation, learning, concept validation and even the realisation of parts/products on demand. In short, these manufacturing platforms – dedicated to heterogeneous demands – make it possible to stimulate creativity and innovation while removing barriers over departments/services of the company. In this case, new methods and tools – similar to the existing ones for structuring production systems – must be investigated now to increase their productivity.

Among the available processes and techniques from ISO/ASTM 52900 standard [8] that could potentially be available in FabLabs or hubs, material extrusion and its leading technique – fused filament fabrication (FFF) – has the advantage of being supported by a strong open source community while being subject to continuous improvement since the triggering RepRap project in 2005 [9]. Such advances have enabled a gradual shift from rapid prototyping towards mass customization with production capabilities of small batches of plastic parts [10]. However to reach an industrial threshold, this technique – that is mainly used for plastic parts – must face its current limitations in terms of weak mechanical performances and low production rate [11]. Compared to other subtractive or formative manufacturing processes, FFF technique does not require any fixture or tooling, which significantly reduces the production cost. However, a post-treatment step is often necessary to both support material removal and surface finishing of the parts. Augmenting FFF technique via an industry-like production logic calls into question or requires the evolution of pre-established models and methods, especially at the production planning and supply chain stages [12, 13]. In its actual shape, FFF technique demands beforehand the analysis of a part geometric definition for process parameters selection and path planning specifications in consistency with machine capabilities [14, 15]. The part can be scaled, positioned and orientated on the printer bed. The last parameter is critical as it influences the manufacturing time with potentially support structures and also the mechanical performances of the part due to the intrinsic anisotropy induced by the process [16–19]. Once that all parameters have been set up, instructions – in G-code format – are sent to the 3D printer.

Production planning and scheduling combined with AM technology has already received attention from researchers in recent years. Research work has been mainly focused on nesting, 2D packing and 3D packing problems with powder-based processes [20]. For this specific AM process, research efforts have attempted to regroup multiple parts and to optimise their position for a given batch [21–23]. Li et al. [12] have introduced two heuristics – namely best fit and adaptive fit – for part-to-printer assignment to reduce the cost per volume by maximising the number of parts in a single batch. Although such initiatives seem to be promising, the developed reasoning procedures are not enough suitable for FFF technique. In a context of on-demand production, FFF 3D printers do not need to be overloaded of multiple parts for a single run. To prevent manufacturing defect, it is better to organise production according to one part to one machine strategy. As a consequence, nesting algorithms will not be addressed in the present paper. Arroyo et al. [24] have presented a heuristic in the context of production planning with a set of unrelated parallel FFF 3D printers that enable the realization of different sized jobs. Based on a greedy algorithm, their heuristic exhibits better performances than other works related to discrete differential evolution, ant colony optimisation and simulated annealing. Similarly, Ransikanbum et al. [25] have optimised the load balance between FFF 3D printers in a way to reduce the total cost of the parts and the total completion time. Recently, Li et al. [26] have analysed different approaches to the production of multiple parts in an industrial context. They compared centralised and decentralised production systems in terms of cost and response time. More recently, Zhang et al. [27] have solved the part-to-printer assignment and part placement for stereolithography (SLA) technique. To do so, they have introduced a combination of an heuristic and a genetic algorithm that can be applied and adapted to FFF technique. Despite the current research efforts – which are mainly focused on the nesting of multiple parts in a single printing run – there is still a lack of methods and tools to bring multiple unoriented geometric models to single run production. This is typically an issue with FFF technique where multi-part production does not provide any efficiency and productivity gain. In such a context, it is important to consider as a whole parts orientation, path planning and part-to-printer assignment. As a consequence, the objective of the paper is to address on-demand production planning of different (non-identical) and unoriented AM parts in FabLabs/hubs composed of unrelated parallel 3D printers with a specific focus on FFF technique.

The paper is organised as follows. Section 2 presents the multi-part production planning framework for AM, in which part orientation, path planning and part-to-printer assignment are jointly processed with a greedy algorithm. Next, in Section 3, a tool implementation of the framework is proposed to demonstrate its applicability, and a case study is introduced. Last, discussion and conclusion are given in Section 4.

2. Multi-part production framework for AM

2.1. Methodology

On-demand production of multiple non-identical parts with AM technology requires to address three important steps, namely part orientation, path planning and part-to-printer assignment. Figure 1 shows a flowchart describing the aforementioned steps and input/output information starting from a heterogeneous demand in terms of geometric models to appropriate machine instructions for the hubs. The part orientation step consists in finding best orientation by minimising whether the support volume, the building time or maximising the mechanical properties of the part. This step is processed as many times as there are components. In a more detailed way, the reasoning algorithm evaluates the printability of the geometric models of the parts for a given orientation according to relevant parameters, such as the overhang area and the bed adhesion surface. Here the latter are essential to hold the part during the FFF 3D printing process.

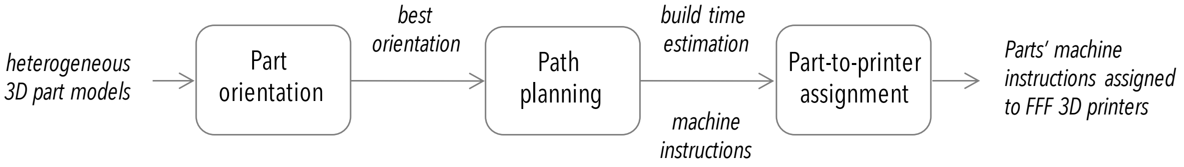

Figure 1: Proposed multi-part production planning framework for AM

Once the best orientations have been identified for all input parts, a path planning step is then processed. FFF technique uses a layered material deposition model, to which extrusion paths can be specified at each layer. This steps aims at slicing the part geometric model with a fixed layer height along the normal axis of the printer bed. The parameters' values will depend on the optimum settings for each machine. At each layer, the contour of the part is extracted to determine both the surface to print and the infill strategy (i.e. geometric pattern and density). This step also considers additional features (temporary) to ensure the part adhesion of the printer bed and supports when there is overhang surfaces. The latter are determined according to the angle after which a surface cannot be printed smoothly. This angle value is defined based on the machine parameters (nozzle diameter, fan speed, layer height, etc.). Once all parameters have been determined, build time – that includes the printer's head travel, its acceleration and maximum velocity – can be estimated and machine instructions described in G-code format can be generated. The remaining step – to which a mathematical model is developed in the following subsection – aims at assigning parts to the FFF 3D printers of the FabLab/hub.

2.2. *Mathematical model for part-to-printer assignment*

Addressing production planning issues with AM requires beforehand a formal description of the problem to be solved. The aforementioned on-demand manufacturing of heterogeneous parts with unrelated FFF 3D printers (i.e. machines) imposes assumptions to be considered in order to define the mathematical model, which can be listed as follows:

- A job refers to a single part being built on a machine. It cannot be decomposed into sub-jobs;
- There is no preemptive job;
- All the parts have the same material;
- All machines have an optimal set of parameters and are able to build any geometry with an 100 % success rate;
- All the parts can be manufactured on any machine with any orientation;
- The jobs are independent;
- All machines are parallel and unrelated, they can process the same part but with a different processing time;
- Part removal and manufacturing setup times are neglected.

Built on this, a mathematical model for part-to-printer assignment is proposed and described by using the following notations highlighting indices, sets and parameters:

Indices
$m = 1, 2, ..., m$ machines
$p = 1, 2, ..., p$ parts to be manufactured
$j = 1, 2, ..., j$ jobs

Sets
M = set of machines
J_m = set of jobs of the machines m
P = set of parts
P_m = set of parts to be manufactured by the machine m

Parameters
$t_{p,m}$ = processing time of the part p on the machine m
$J_{p,m}$ = realisation of the part p on the machine m
T_m = completion time of the machine m
T_{max} = maximum completion time among the machines

$$T_m = \sum_{i=1}^{m} t_{p,m} \qquad \forall m \in M, \quad \forall p \in P_m \tag{1}$$

$$T_{max} = max(T_m) \qquad \forall m \in M \tag{2}$$

$$min(T_{max}) = min(max(\sum_{i=1}^{m}(t_{p,i}))) \tag{3}$$

In order to produce a set of parts P with a set of machines M, they need beforehand to be oriented in a proper build direction in order to reduce the manufacturing time of each part. The orientation is critical to avoid overhang surfaces and therefore to minimise additional support required to print them. Although multiple parts can be printed on the same job, there is no advantage with the FFF technique to realise multiple parts at once unlike the powder-based processes. With powder-based processes, gathering multiple parts allows to reduce the production time. With FFF technique, the approach is totally different, if multiple parts are printed in a single run and one fails due to warping or another issue, it will lead to a failure of the entire job. In the present case, a print job $J_{p,m}$ will consist in a single part printing operation p on a machine m. Once the part is oriented, the path planning can be generated for a given machine and then the processing time $t_{p,m}$ of the job for a machine can be determined from the set of instructions. With the build time $t_{p,m}$ of each part for each available printer, an part-to-printer assignment needs to be made. The completion time of a machine is the sum of the production time of all the jobs as expressed in Equation (1). This step is called the part-to-printer assignment and consists in minimising the maximum processing time T_{max}, such as described in Equation (2) of the longest time-consuming machine (Equation (3)) and shown in Figure 2.

In the context of FabLabs/hubs, the machines (FFF 3D printers) ensure a continuous production by using ejection solutions to remove automatically printed parts without human intervention. As an example, with the black belt 3D

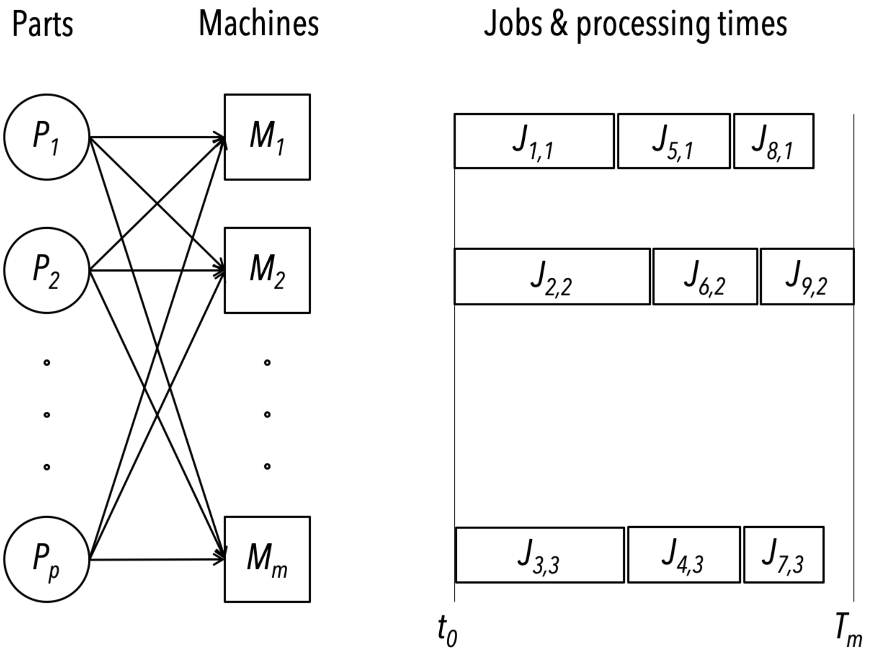

Figure 2: Illustration of the part-to-printer assignment (the width of the jobs are proportional to their processing times).

printers or the Quinly accessories [28, 29], it is then possible to eject 3D printed parts from FFF 3D printers. Without such a solution, delays could occur between two consecutive jobs, which would significantly increase production times. Here the FabLab/hub is composed of unrelated parallel machines that are able to perform the same function but have different capabilities or capacities [30]. In addition, they exhibit the same printing volume but offer different production times. This is due to the performances of the machines' hardwares (e.g. nozzle's diameter, stepper motors drivers, etc.) and the adapted process planning software's parameters like printing speed, layer height, etc. It should be noticed that a job in AM oriented production cannot be decomposed into sub-jobs in order to balance the production. Indeed, splitting a job consists in partitioning the part into several bodies, which will later require assembly operations. Such considerations are not addressed in this paper but are potentially an interesting avenue to balance the production. Last, in this proposed model, it is assumed that parts to be produced have the same material and all FFF 3D printers will always have sufficient material to perform jobs.

3. Implementation and case study

The proposed framework and its underlying components can be implemented through a set of tool and applications in order to process heterogeneous 3D STL files in a way to be rightly assigned to FFF 3D printers of the FabLab/hub.

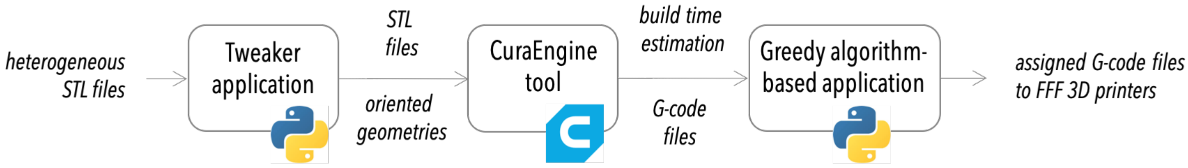

Figure 3: Implementation of the framework through Tweaker, CuraEngine and a greedy algorithm-based application

Figure 3 shows, for each step of the framework, a dedicated application that has either been used or specifically developed. This is the case for the part orientation step, to which an open-source Python application called Tweaker – able to find an optimal orientation of an object on a FFF 3D printer – has been adopted [31]. Its reasoning capacities are aligned with the defined parameters (in the previous section) to be optimised for ensuring a good printability of the parts. As for the path planning step, another open-source tool has been considered and integrated, CuraEngine 4.6.3. Developed as a Cura backend from Ultimaker, it is widely used in the FFF community since it works with any kind of FFF 3D printers, and is enough suitable to analyse parts' geometries, define trajectory paths, estimate build times and generate machines' instructions. Build time estimations for all parts are important as they will be used to part-to-printer reasoning step. This last step is built upon the aforementioned mathematical model, to which a heuristic – using the longest processing time rule (LPT) [32] – has been implemented in a dedicated Python application. The algorithm 1 has been developed to control information flows between the components of the framework. More particularly, it consists in attributing the jobs – that are sorted by decreasing order of processing times – to the FFF 3D printers of the FabLab/hub in order to minimise the maximum processing time of the machines.

```
Algorithm 1: Independent parts production planning with unrelated parallel FFF 3D printers
Input: STL files with any orientation that can fit with any FFF 3D printers
Output: Allocated G-code files to be run to FFF 3D printers

Generation of the $m$ FFF 3D printers with their process parameters
foreach STL file do
    Find the best part orientation
    foreach FFF 3D printer do
        Slice the part geometry
        Determine the build time
    end
    Calculate the average building time of the part
end
Order the parts with non increasing average build time order
foreach STL file do
    Assign the parts to the FFF 3F printers which will have the minimum total processing time
end
return Allocated G-code instructions to be run to FFF 3D printers
```

To demonstrate how the implemented framework works, a batch of 6 different parts (names A to F as illustrated in Fig. 4) is introduced. The objective is to firstly analyse the related STL files in terms of part orientation, then to construct their path plans and build times so as to allocate jobs to two RepRap machines (named Machine 1 and Machine 2) with a maximum build volume of 20x20x20cm^3. By using Tweaker application and CuraEngine software, the oriented parts are subject to build time estimation (see Figure 5). Table 1 sums up the resulting build time per part per machine.

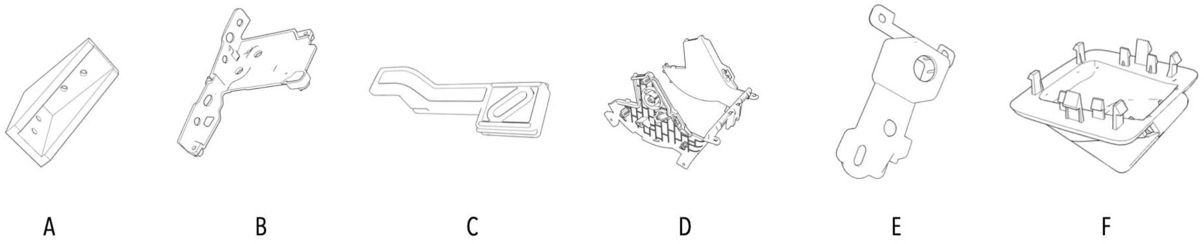

Figure 4: Set of parts to be considered for production planning

Table 1: Build time per part per machine

Part name		A	B	C	D	E	F
Time (s)	Machine 1	10 760	26 997	1 577	165 726	17 779	11 501
	Machine 2	8 918	8552	1 167	38 498	7 176	5 988
Average processing time (s)		9 839	17 775	1 372	102 112	12 478	8 745

With the build time pert part determined from the previous step, the average build time can be calculated. Once the average processing time is determined for each part, it is then possible to sort them by applying the LPT rule. It consists in sorting the parts from the longest to process to the fastest to process as shown on Table 2. The part with the longest build time is at the left of the table (i.e. part D) and the fastest part to be processed is at the right side of the table (i.e. part C). The original set of parts, ranging from A to F is now ordered as follows: D, B, E, A, F and C. At this step, each part needs to be assigned to a FFF 3D printer in order to be produce. To assign a part, an iteration is made involving three parameters. First it is needed to determine the total processing time for each FFF 3D printer. This can be calculated by computing the sum of the build times of the parts that have been allocated to the FFF 3D printers. These parameters are shown with the columns (i) in Table 2. Secondly, it is required to know the build time of a part to a given FFF 3D printer. This has been previously determined by the CuraEngine software and is shown with the columns (ii) in Table 2. Then, the sum of the current building times in columns (i) are added to the building time of the part for every FFF 3D printer in columns (ii) to determine what will be the total processing time of a FFF 3D printer if the part is assigned to it. This value is written in columns (iii). At the end of each iteration, the part is assigned to the FFF 3D printer who will have the lowest building time. By following such steps, the maximum build time can be minimised.

The case study can be followed by using Table 2 and Figure 6. It starts with the longest part to be processed which is the part D. At the first iteration, the total build time of each FFF 3D printer is zero because no part has been assigned to any printer as shown in Table 2 column (i). Then the processing time of part D for each printer is added in column (ii) and the sum of the columns (i) and (ii) provides the column (iii). The latter represents the processing time of each machine if the part is assigned to them. At this point the lowest value is the case where the part D is allocated to the Machine 2 because it has the lowest total build time. For this first iteration, the part is attributed to the Machine 2. In Figure 6, a part assigned to Machine 1 is represented by a blue circle, whereas a part with a red circle stands for a Machine 2 assignment. In the present case, in Figure 6.(b), part D is assigned to Machine 2.

The second iteration occurs with the part B. As the part D has been assigned to the Machine 2, the current total build time for the Machine 1 is still zero. As for the Machine 2, the part D has been assigned to it, the current total build time of the Machine 2 becomes the build time of the part D. The total build time column (iii) for each machine is calculated by adding column (i) and column (ii). This time, we observe that the lowest total build time shown for the part B in column (iii) is the lowest if the part is assigned to the Machine 1. The part B is assigned to the Machine 1 as shown Figure 6.(c). The same iteration is done for all the parts until all are assigned. The result of the greedy algorithm is shown in Figure 6.(h). At the end of this reasoning step, parts D, A and F are assigned to Machine 2, and parts B, E and C are assigned to Machine 1.

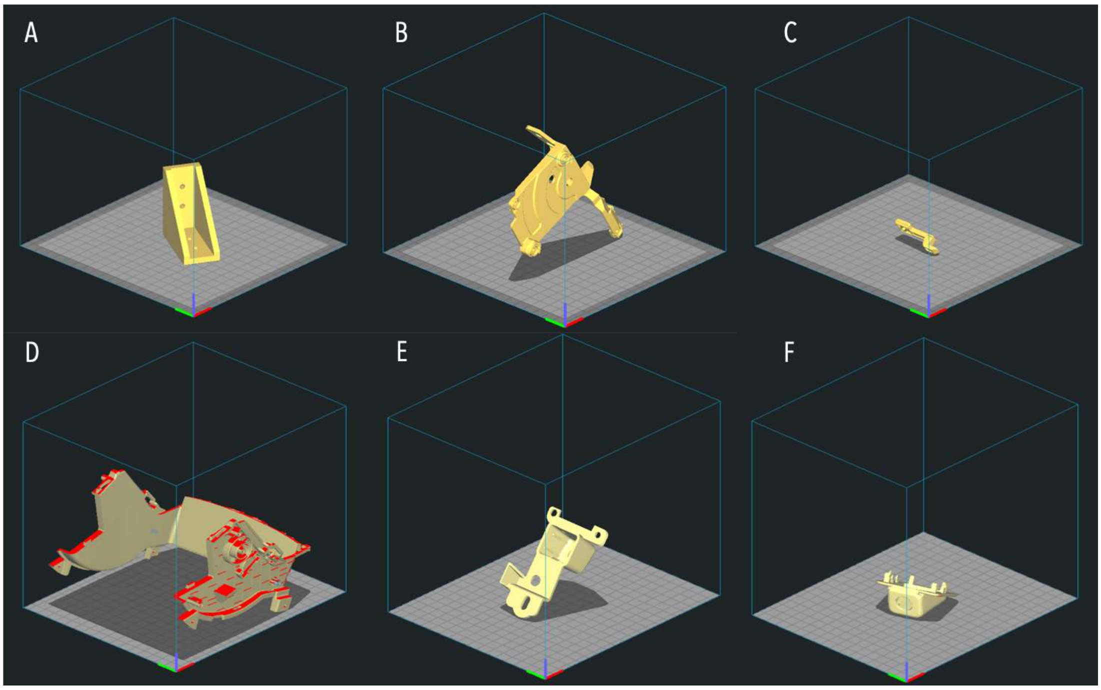

Figure 5: Parts with their optimised orientations in Cura software using Tweaker application

Table 2: (i) printer's built time before attributing the current part, (ii) build time of the current part, and (iii) total build time

Part name	D			B			E			A			F			C		
Build time (s)	(i)	(ii)	(iii)	(i)	(ii)	(iii)	(i)	(ii)	(iii)	(i)	(ii)	(iii)	(i)	(ii)	(iii)	(i)	(ii)	(iii)
Machine 1	0	165726	165726	0	26997	26997	26997	17779	44776	44776	10760	55536	44776	11501	56277	44776	1577	46353
Machine 2	0	38498	38498	38498	8522	47020	38498	7176	45674	38498	8918	47416	47416	5988	53404	53404	1167	54571

4. Discussion and conclusion

In this paper, a multi-part production planning framework for AM in the context of unrelated parallel FFF 3D printers in FabLabs/hubs has been proposed and implemented through a set of applications and illustrated via a case study. It includes, as main pillars, part orientation, path planning with build time estimation and part-to-printer components in a way to analyse heterogeneous part geometric models (STL files) towards the assignment of machine instructions (G-code files) to the available FFF 3D printers. The implementation strategy has been to consider and gather existing independent functional applications (such as Tweaker and CuraEngine) and also to develop a new one (greedy algorithm-based application) to fully cover the main components of the framework in a seamless manner. As a result, the framework implementation is suitable to be reused in any FabLabs or hubs, to which demands and 3D printing machines are different. By following such a tool's architecture, each step of the AM production planning can be addressed independently and then can be tuned or even replaced in order to improve the final output.

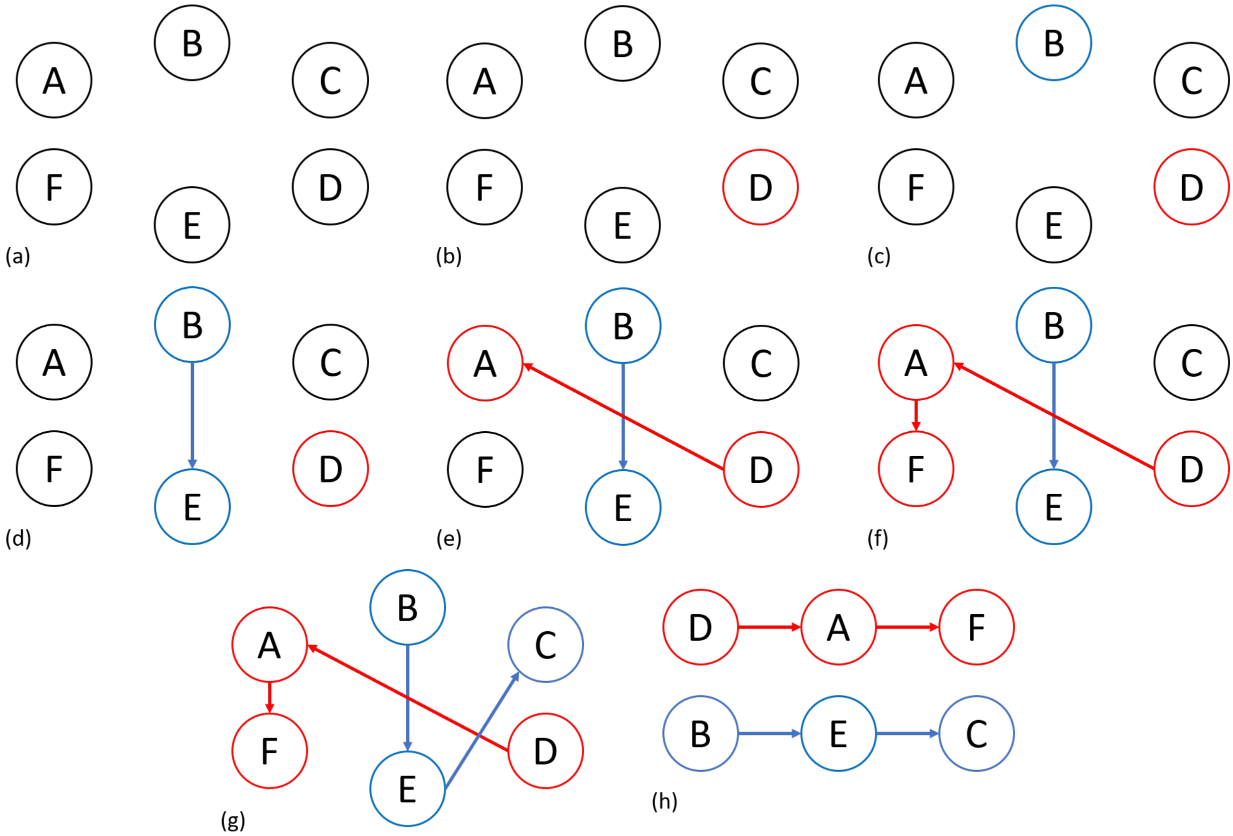

Figure 6: Part-to-printer assignment iterations. Black circles represent the remaining parts to be assigned, blue circles represent the parts allocated to Machine 1 and red circles to Machine 2. (a) initial state (b) iteration 1 (c) iteration 2 (d) iteration 3 (e) iteration 4 (f) iteration 5 (g) iteration 6 (h) results

The work done can be applied in FabLabs/hubs with 3D printing machines equipped with automatic ejection systems or just on a simple offline hubs of machines. In the first case, the G-code files listed per machine can be added straight away on the printing list of each machine. In the second case, parts to be printing can require a manual intervention whether at the beginning of the job or at its end. If additional parts are introduced into the initial batch or if a machine is stopped for technical reasons during the production process, the proposed framework will be able to consider these new parameters. To do so, a new calculation for the remaining parts to be printed with the working FFF 3D printers can be done.

Furthermore, some of assumptions made in the paper needs to be discussed in order to open perspectives. as for FabLab/hub of FFF 3D printers, the opportunity of splitting a job by partitioning a part into sub-parts has not been considered. However, such an approach will let the authors to address later on two different important scientific issues. Indeed, by considering part partitioning can be seen as a strategic action to balance the production through the set of FFF 3D printers. This may also result in a decrease of the maximum processing time by removing some of the workload on the machine with the longest processing time on another machine. Another key issue related to part partitioning concerns large-scale parts to which the question of splitting is of interest and will be addressed later.

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Declarations

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Conflicts of interest/Competing interests

The authors have no conflicts of interest to declare that are relevant to the content of this article.

Code availability (software application or custom code)

No available code. The algorithm-based reasoning procedure is described in the paper.

Ethics approval

Not applicable for that section.

Consent to participate

The authors are consent to participate.

Consent for publication

The authors are consent for publication.

Availability of data and material

Not available.

Authors' contributions

Thibaut Cadiou: Conceptualization; Methodology; Software; Writing original draft. Frédéric Demoly: Conceptualization; Methodology; Writing - review & editing; Supervision. Samuel Gomes: Funding acquisition; Supervision.

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