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# To kit or not to kit: Analysing the value of model-based kitting for additive manufacturing

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ABSTRACT

The use of additive manufacturing (AM) for the production of functional parts is increasing. Thus, AM based practices that can reduce supply chain costs gain in importance. We take a forward-looking approach and study how AM can be used more effectively in the production of multi-part products in low to medium quantities. The impact of introducing kitting in AM on supply chain cost is investigated. Kitting approaches are traditionally devised to feed all components belonging to an assembly into individual containers. Where conventional manufacturing approaches are used for kitting, the produced parts pass through inventory and kit preparation steps before being forwarded to the assembly line/station. However, by taking advantage of the object-oriented information handling inherent in the AM process, kitting information can be embedded directly within the digital design data and parts produced in a common build. This model-based kitting practice reduces – even eliminates – the need for a manual kit preparation step and promises additional supply chain benefits. Eight experiments were conducted using laser sintering (LS) to investigate the impact of model-based component kitting on production cost and supply chain cost. The results show that with current state-of-the-art volume packing software, production costs increase with the adoption of kitting. The increased production cost was off-set to different extents by kitting supply chain benefits, including simplified production planning, reduced work-in-progress inventory and elimination of parts fetching prior to assembly. Findings of this research are of interest for manufacturers, service bureaus and practitioners who use AM for low quantity production, as well as developers of AM volume packing and production planning software.


## 1. Introduction

In manufacturing, the practice of kitting [6] to supply the required parts for a single assembly in pre-set containers provides an alternative to the currently dominant practice of continuous supply line-stocking. Kitting reduces operator learning requirements [25] and improves the assembly quality and efficiency [5,6,18,19]. Up to this point, however, kitting has not challenged continuous line-stocking as the dominant approach even in low to medium volume production except in a few specific industries (e.g.: electronics). Parts are typically produced in large batches. In this setting, the preparation of kits constitutes an additional process step that requires stocking and fetching of individual parts before the grouping of the components into kits. These often require manual kitting which creates a range of problems, such as missing parts and incorrectly composed kits.

Additive Manufacturing (AM) represents an opportunity to produce kits directly on the basis of a design model [28]. By utilising approaches such as the composite design pattern [12], the digital design model used in producing the part can encompass additional information that defines how the parts are related, for example, as components in an assembly kit. While currently AM is only used for the production of individual functional parts in mainly aerospace and medical products, the emergence of significantly cheaper polymer laser sintering machines is likely to expand the use of AM to many – even all – parts of an assembly

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[39]. Therefore, it is important to begin investigating how the new AM enabled practice of model-based kitting impacts costs and performance in the supply chain.

Build volume packing is one of the factors that influence the manufacturing cost of AM, and consequently, its competitiveness with conventional processes. The production unit cost can be decreased by optimising the arrangement of the parts in the chamber [3]. However, in more realistic settings, such as an AM service bureau's supply chain, a number of additional elements must be considered. These elements include the order delivery schedule (which may result in stockouts or carrying inventory), the product assembly process (for multi-part, hybrid products, which may result in delivery delay and additional manual work) and durability of the produced parts (to achieve certain engineering requirements, the orientation of parts may need to be fixed). Therefore, it is important to minimize the total cost by considering the entire supply chain rather than focusing on the build volume packing in isolation. Addressing this question, this research sheds light on the value of model-based kitting in AM for the production of multi-process (AM and conventional), multi-part products. Two case-assisted investigations are conducted to illustrate the advantages and disadvantages of utilising pre-set kits in the supply chain context.

The remainder of this paper is organized as follows. Section 2 presents a literature review, Section 3 explains the research methodology, Section 4 presents the findings and results of our analysis and Section 5 is dedicated to the discussion of the results. This paper ends with conclusions summarizing the research outcomes and suggestions for future investigations.

## 2. Literature review

This section reviews the existing literature in the fields of AM and pre-set kitting.

### 2.1. Additive manufacturing

AM, also known as three-dimensional printing, is a manufacturing process that differs from conventional manufacturing in terms of its operating principle [21]. Instead of removing material to generate the intended shape, AM adds material layer by layer to produce objects. There are multiple AM processes which are capable of generating end-use objects and each process variant utilises one or more build materials. The range of build materials for AM is growing and currently includes various metals, metallic alloys, polymers, ceramics and composites [17].

Additive manufacturing has a number of characteristics that make it attractive for various industries [26,27]. The possibility of toolless production, enables the economic production of very small quantities, down to a single unit. The layer by layer nature of the process makes it possible to produce complex geometries (as well as assemblies) that are difficult to manufacture with traditional manufacturing processes [22]. This allows designers to design for performance and pay less attention to design for manufacturing [35]. Moreover, in metal AM, layer-wise production significantly reduces the amount of waste raw material as a large percentage of the unused raw material can be reused. The resulting savings can be significant when a product requires the use of valuable metals, such as titanium [14].

Polymer powder bed fusion, also known as laser sintering (LS), which is a common powder-based AM process used to produce functional polymer parts, has been used in high-value applications, such as those found in the aerospace industry (air cooling ducts on Boeing's F-18 Super Hornets and 787 commercial airliners according to Freedman, [15]). The LS process begins with a computer-aided design (CAD) file, which is created or acquired from a source. Then, the three-dimensional design is converted into .stl format and analysed using special software for additive manufacturability. This step is concerned with the object wall thickness and other problems, such as the inappropriate collision of triangles, which determine the actual surfaces in the .stl format. The LS method is performed without a support structure for the overhangs as the unsintered powder acts as the support, obviating the need for software-generated support structures. The next step involves feeding the error-checked design file to the software supplied by the LS machine manufacturer, for slicing and creation of the print layers. The output of this step is a file that contains all the production layers, which can be loaded into other software for packing of the print job in the production chamber and final touches, such as shrinkage value setup. To avoid thermal shock on the parts, blank layers of powder are included during this step at the beginning and the end of the job. The output of this step is sent directly to the LS machine controller computer, upon which the operator releases the build process (for details on AM technology variants, see Gibson et al. [17] or Hopkinson et al. [23]).

It takes approximately two hours for the machine to heat the powder, prepare the chamber nitrogen atmosphere and start the production process. A laser is used to selectively sinter the pre-heated powder on each layer until all of the parts have been formed. When the LS completes the build process, the parts are placed in an oven to gradually cool. This step can take up to one day. Then, the secondary processes are started, including recovery of the parts from the powder, blasting, and washing, which are highly manual tasks. After these processes, the parts are ready for assembly and delivery to customers (for the time required for the LS process steps, see Baumers et al., [3]).

When AM is used in final part production applications, the .stl file format illustrates its constraints as it is limited to contain only the components' geometrical data. Therefore, a number of new formats, such as the Additive Manufacturing File (AMF) and the 3D Manufacturing Format (3MF), which are based on the extensible markup language (XML) data format, were created. The new formats are human-readable and enable the inclusion of information about the material, texture, substructures, part constellation, surface mesh, and colour. Moreover, these formats are designed to be able to adapt to future needs, meaning that they can be extended to incorporate additional required data [29]. This potentially opens the door for integration of AM into companies' ERP systems and supply chains while streamlining the production process.

#### 2.1.1. Capacity utilisation in LS

Research on the relationship between cost efficiency and capacity utilisation in AM [4,33] has shown that the build configuration affects the observed unit cost, which is addressable by automated build volume packing approaches [1]. The degree of capacity utilisation in AM execution is determined during two steps in the process flow, machine setup, and production planning. Therefore, cost efficiency and capacity utilisation in AM depend on both the build configuration and the production schedule, resulting in a connected optimisation problem. Coordinating and controlling the elements of the process through integrated optimisation requires control of how decisions are made and how competing aspects are weighed [7]. With full information and without disturbances, such as technical failures or unforeseen demand fluctuations, centralized control structures outperform decentralized structures with autonomous decision making [36].

### 2.2. Pre-set kitting supply

Kitting, as an established practice in assembly industries (such as electronics), refers to the supply of all the required components