Additive Manufacturing 22 (2018) 230–242

Contents lists available at ScienceDirect

Additive Manufacturing

journal homepage: www.elsevier.com/locate/addma

Part decomposition and assembly-based (Re) design for additive manufacturing: A review

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ARTICLE INFO

Keywords:
Design for Assembly (DfA)
Design for Additive Manufacturing (DfAM)
Part decomposition
Build orientation decision
Part packing
Re-design

ABSTRACT

Additive Manufacturing (AM), also known as *3D printing*, has been highlighted as a complementary method to the traditional (subtractive and formative) manufacturing. This mainly results from its distinctive characteristics to directly produce complex shapes and assemblies without an assembly process. With these aspects, AM has affected the way products are designed and formed, which leads to an exclusive research area, known as *Design for AM (DfAM)*. As a step towards addressing DfAM, this paper reviews the literature on re-designing an original model into assemblies produced in AM, named as *Part Decomposition (PD)*. Although PD has received less attention in DfAM compared with *Part Consolidation (PC)* that is re-designing assemblies into a consolidated single part, PD has been studied with various motives and challenges for AM. To investigate the research trend in PD, 37 main publications are categorized under five motives including printability, productivity, functionality, artistry and flexibility. Additionally, from technical and methodological aspects, relevant studies are organized into decomposition issues (automatic, semi-automatic and manual decompositions), buildup issues (orientation decision for single- and multi-part and packing problem), and assembly issues (connection design and assembly process planning). As witnessed in this comprehensive review, the concept of PD leaves further research challenges spanning several disciplines. Along this line, we further elaborate future research directions of PD under three main categories: (1) enhancing the AM productivity for mass customization; (2) developing novel decomposition methods and guidelines; and (3) applying conventional design methodologies to PD.

1. Introduction

Over the past few decades, the evolution of *Additive Manufacturing (AM)*, also known as 3D printing, has substantially affected academia and industry [1]. However, the process-driven growth has caused the evolution of engineering design to be lagged behind [2]. As a key driver for the new advancement in AM, a considerable number of researchers pay attention to *Design for Additive Manufacturing (DfAM)* defined as *"a type of design methods or tools whereby functional performance and/or other key product life-cycle considerations such as manufacturability, reliability, and cost can be optimized subjected to the capabilities of AM technologies"* [3]. Recently, DfAM has been actively studying in terms of opportunities, methodologies, constraints and economic considerations [2,4–7].

As shown in Fig. 1, there are two main categories of DfAM methods: DfAM for design-making or generating design alternatives, and DfAM for design assessment [8]. This survey only addresses the design-making studies and, particularly, focuses on re-designing a product model. The re-design concept for AM refers to re-designing an original model into another shape compatible for printing with AM technologies. The literature of the re-design for AM is distinguished under three main categories in terms of the part number variation after re-designing: (1) methods that result in the part number conservation, (2) methods that decrease the number of parts, and (3) methods that lead to the increase of part numbers.

Looking at the first group, Fig. 1(a), topology optimization or design for multiscale structures (lattice or cellular) is a re-design approach with the purpose of part number conservation. As a representative design method of the first group, topology optimization is a numerical approach that optimizes the material layout for a given set of loads and constraints [11,12]. This leads to the reduction of material quantity and energy usage by optimizing the object structure for different applications in various disciplines. For example, the aerospace and automotive industries have intensively adopted it to minimize the part weight with the ultimate purpose of energy saving [13,14]. In addition, the biomedical field has been applying topology optimization to bio-implant

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https://doi.org/10.1016/j.addma.2018.04.018
Received 28 September 2017; Received in revised form 21 March 2018; Accepted 14 April 2018
Available online 19 April 2018

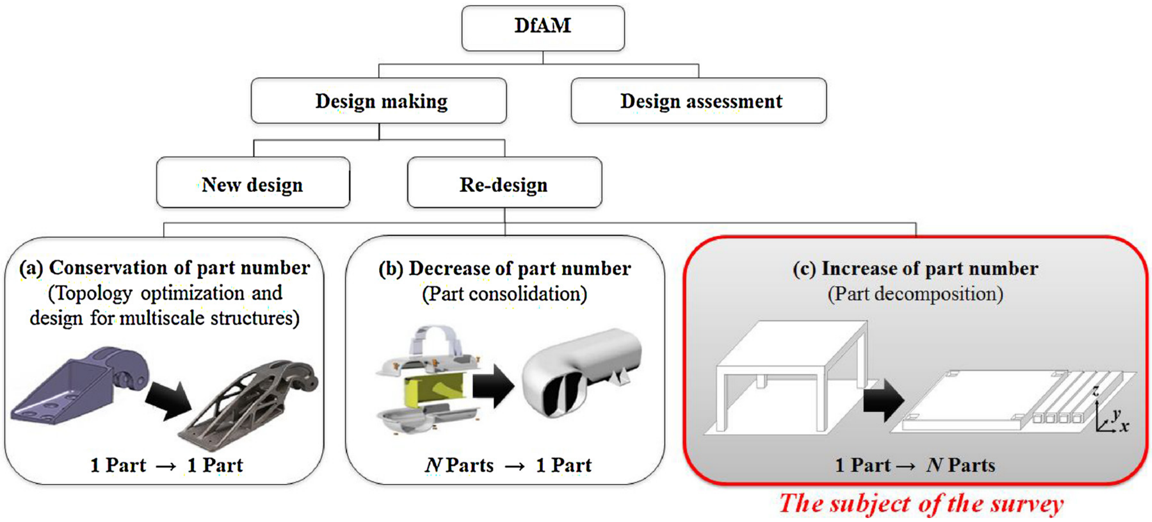


Fig. 1. Classification of the DfAM practices (figures of topology optimization and part consolidation are from [9]; and part decomposition from [10]).

made of lattice or cellular structures to enhance osseointegration [15,16].

In Fig. 1(b), the second group of re-design methods aims to consolidate multiple components into one single part, known as *Part Consolidation (PC)* [17,18]. After PC, the number of parts becomes smaller or even results in only one part. Since reducing the number of parts is an effective method to save process time and cost [18], it has been considered as a general design guideline in *Design for Assembly (DFA)* [19], *Design for Disassembly (DFD)* [20], *Design for Manufacturability (DFM)* [21], and *Design for Manufacture and Assembly (DFMA)* [22]. While designing assemblies is often inevitable for manufacturability in the traditional manufacturing, AM allows engineering designers to generate a single part model regardless of its geometric complexity [23]. Often, PC is conducted as the pre-processing for topology optimization [24].

The third group of re-design methods in Fig. 1(c), the main subject of this survey, aims to partition an original object into several assemblies, *Part Decomposition (PD)*, which results in an increase in the number of parts. The decomposed parts are assembled back into the original shape after a build process. This is the opposite concept of PC, which emphasizes the role of post-processing for assembly. Then, why PD is needed for AM. There are a variety of motives: printability, productivity, functionality, artistry and interchangeability. The printability is a representative motive that an original model is decomposed for fitting in the limited workspace of an AM machine [9]. These five motives are detailed in Section 3.

PD brings about buildup and assembly issues as well as a topic of object decomposition. Object decomposition deals with how parts are broken down to generate assemblies. The buildup issues consider how parts are placed in the limited workspace of an AM machine. This involves topics on part packing planning and build orientation determination. The assembly topics address what kinds of connection methods are used and how to plan assembly sequences. The results of dealing with the buildup and assembly issues affect the build and post processes, respectively. Therefore, as shown in Fig. 2, these issues can be considered early on in the design stage, which is considered as process planning in AM [25,26]. Note that the scope of the survey conducted in this paper includes buildup and assembly topics as well as decomposition in terms of the comprehensive process view. The technical methodologies for the decomposition, buildup, and assembly topics are explained in Section 4.

Over the past decade, the concept of PD has been less highlighted than PC. In an assembly-level review paper for AM, Yang et al. (2016) classified research issues and benchmark under two categories of *consistent assembly (CA)* and *reduced assembly (RA)* studies [27] corresponding to the methods of part number conservation and decrease as listed in Fig. 1(a) and (b), respectively. In their paper, they focused on RA and introduced studies on PC, design guidelines, and function integration. When assembly concept is considered in DfAM, it is generally equivalent of merging assemblies into a single product [8,24,28]. Although there are not a significant number of studies for PD, the concept has recently received some attention by converging subjects such as decomposition and connection issues [29] and decomposition and packing issues [30].

The main objective of this survey is to re-define the meaning of re-design for AM in terms of the part number variation and to extend its research boundary into design methods for PD. We further categorize the decomposition, buildup and assembly issues under PD, and finally identify the research trends and motives. The result of this study can assist researchers, practitioners and engineering designers who are interested in DfAM topics such as part decomposition, packing problem, connection design for assembly, and assembly sequence planning.

2. Literature classification

2.1. Survey methods

Unlike topology optimization and PC, PD is not a common keyword widely acceptable in DfAM. In order to survey the relevant research papers, the major search keywords listed in Table 1 have been chosen to identify PD papers. The selected keywords are a combination of research subjects and applications. Most of the publications have been found on Google Scholar. To assure that most of the significant and relevant studies are included in the survey, we have paid special attention to the literature review section of each paper for further cross-checking.

As mentioned above, the focus is on three major topics: decomposition, buildup and assembly issues. Since decomposition is a necessary step to generate assemblies, all studies in this survey cover object decomposition issue. In the case of orientation decision, there have been a considerable number of studies. Thus, only the studies on orientation decision for multiple parts rather than a single part have been included in the survey to narrow down the scope.

Table 2 shows 37 publications identified using the keywords listed in Table 1. The papers are classified into five categories based on the motives behind the study: printability, productivity (process time, material cost and product quality), functionality, artistry, and flexibility. Studies that deal with the limitation of buildable space in an AM

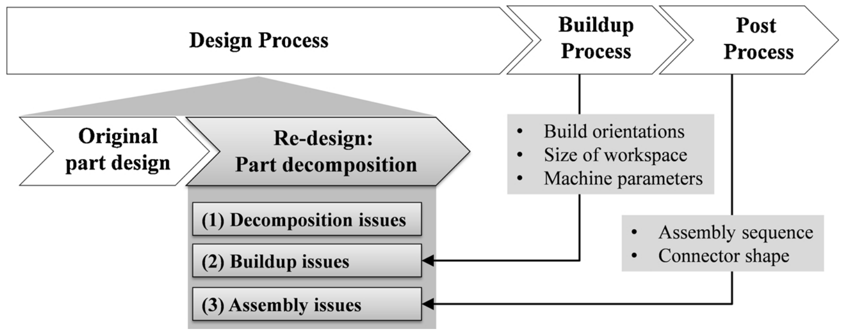


Fig. 2. A product realization procedure in AM: design, build and post processes.

machine or the maximum size of parts are categorized under printability. The productivity column includes the studies that address the minimization of material cost (support volume, part volume to convert into shells, and packing box volume) or process time (build time and assembly time), or the improvement of product quality (surface roughness and structural soundness). The functionality column involves the studies that address mechanical movable connections (articulated joints) or functional components (gears and motors). The studies dealing with puzzles or card boards that are converted from an original model are categorized in artistry. Finally, the studies in which assemblies are interchangeable into one another are classified into the flexibility column. Among these five motives, printability and productivity are direct motives for AM, since printability is a constraint of AM machine and productivity is the objective of AM process planning.

Regarding the three above-mentioned topics of decomposition, buildup and assembly, the studies include a variety of decomposition methods (automatic, semi-automatic and manual). If studies include build orientation, packing, and printing order related topics, they are classified as the buildup issue. Lastly, studies are categorized in the assembly issue if they deal with the design of joints and connection parts such as fixed connections (fastening and interlocking) and non-fixed connections (ball-and-socket and hinge joints), or assembly sequence planning.

2.2. Research trends

As shown in Fig. 3(a), the PD topic has recently been the point of attention in literature for three major reasons. First, as *"design is now the bottleneck for AM to achieve its full potential"*, DfAM has been spotlighted as a solution [65]. Second, researchers in the computer graphics field started dealing with the PD issues for AM. The study by Luo et al. (2012) triggered that the decomposition methods in the computer graphics field are applied to the re-design for AM [29]. Lastly, researchers have begun to consider multi-issue topics considering both decomposition and buildup topics such as decomposition-and-packing problem [30] and the decomposition and build-orientation decision problem [58].

Fig. 3(b) shows the percentage of different topics considered in the literature. The multi-topic dealing with both decomposition and assembly issues has discussed the most by taking 51%. The decomposition topic is the second popular topic in the current literature with 27%. To date, a few studies have addressed the multi-issue of decomposition, buildup and assembly designs simultaneously.

Fig. 4(a) shows the statistics of the number of publications based on the motives behind the studies: either single- or multi-motive papers. As shown in the figure, research on printability and productivity (process time, material cost and product quality) has been studied considerably. In particular, for productivity topics, the number of publications for multi-motive papers is remarkably greater than the number of publications for single-motive papers. This is largely because productivity has been often considered as objective functions with multiple attributes [29,30,52]. Fig. 4(b) provides more information about the productivity literature. It shows the percentage of multi-motive publications including inter-productivity (a combination of process time, material cost, or product quality) and a combination of productivity and the other motives (printability, artistry or functionality). Most of the literature considered either productivity and printability (53%) or inter-productivity topics (32%). When it comes to considering printability as one of the multiple motives, it tends to be considered as a constraint for fitting in the limited workspace [53,61].

3. Motivation: Why part decomposition is needed for AM

Section 3 explains why PD is needed for AM by addressing five motives behind AM studies: printability, productivity (process time, material cost and product quality), functionality, artistry, and flexibility. Among these five motives, printability and productivity are direct motivation for AM since printability and productivity can be considered as a constraint of AM machine and the objective of AM process planning, respectively.

Table 1
Keywords used to search part decomposition studies.

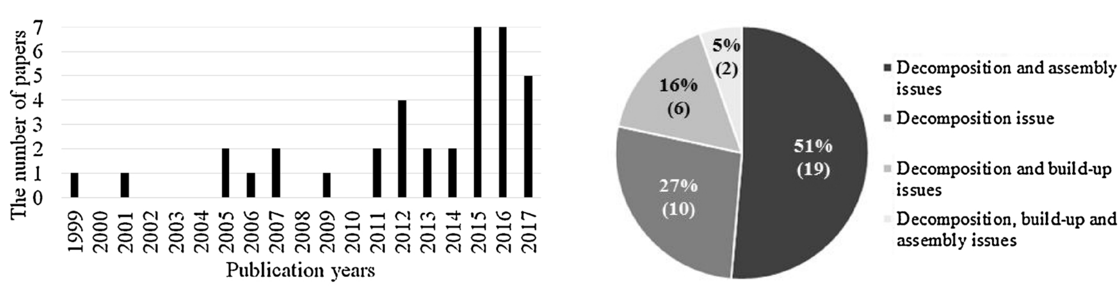
Issues		Keywords: Main subject	Keywords: Application
Decomposition issue		Volume decomposition, object segmentation, model partition, cutting problems, slicing optimization, automatic subdivision, disintegrating object	Additive manufacturing, 3D printing, rapid prototyping, layered manufacturing
Buildup issue	Packing planning	Packing optimization, placement optimization, packing problems, layout planning, part nesting, volume optimization	
	Build orientation decision for multi-part	Orientation optimization for multiple parts, determining build orientations for multiple parts, build direction optimization for multiple parts	
Assembly issue		Design for assembly, interlocking parts, puzzles, card boards, articulated models, folding objects, modular design, assembly-based design, assembly process planning	

Table 2
The classification of the part decomposition studies: motivation (▲) and issue (●).

Reference	Year	Motivation							Issue		
		Printability	Productivity			Functionality	Artistry	Flexibility	Decomposition	Buildup	Assembly
			Process time	Material cost	Product quality						
[31]	1999	▲	▲	▲	▲				●		
[32]	2001			▲					●		
[33]	2005	▲							●		●
[34]	2005	▲	▲		▲				●	●	
[35]	2006	▲							●		●
[36]	2007	▲	▲		▲				●		
[37]	2007	▲							●		●
[38]	2009						▲		●		●
[39]	2011	▲							●		●
[40]	2011						▲	▲	●		●
[41]	2012					▲			●		●
[42]	2012					▲			●		●
[43]	2012		▲				▲		●		●
[29]	2012	▲			▲				●		●
[44]	2013		▲	▲					●		●
[45]	2013				▲				●		
[46]	2014		▲	▲					●		
[47]	2014	▲	▲	▲	▲				●	●	
[48]	2015					▲	▲		●		●
[49]	2015	▲		▲					●	●	
[30]	2015	▲	▲	▲	▲				●	●	
[50]	2015		▲	▲		▲			●	●	
[51]	2015	▲					▲		●		●
[52]	2015		▲		▲				●		
[53]	2015	▲	▲		▲				●	●	●
[54]	2016							▲	●		●
[55]	2016		▲	▲	▲				●		
[56]	2016		▲	▲	▲				●		●
[57]	2016	▲	▲	▲	▲				●		●
[58]	2016				▲				●	●	●
[59]	2016			▲					●	●	
[60]	2016					▲	▲		●		●
[61]	2017	▲							●		●
[10]	2017	▲	▲						●		
[62]	2017				▲		▲		●		●
[63]	2017			▲	▲				●		
[64]	2017					▲			●		

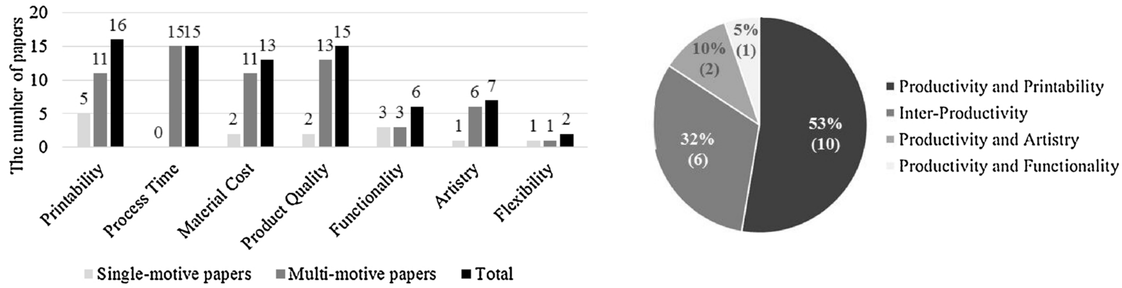
3.1. Printability

Often, PD is required to fit the large-size of a product into the limited print space, known as *printability*, also *manufacturability* or *producibility* [33]. There are mainly two types of printability: *one for one-pack* and *all for one-pack*. Similarly, Zhang et al. (2016) distinguished this topic into subset placement and full placement in terms of production context [66]. As shown in Fig. 5, while the one for one-pack is decomposing into a piece of part to fit in the print space, the all for one-pack is decomposing an object to pack together in the same workspace. The maximum size of a part is usually limited as a constraint of the one for one-pack [29]. In this case, manufacturers may build up assemblies one-by-one with one AM machine, that is a serial process, or multiple AM machines, that is a parallel process. This can be considered as scheduling problems AM how a number of parts are assigned to multiple AM machines [67]. Fig. 5(a) represents the example of one for one-pack in which a rabbit model is cut out until a part is fitted to the printable size of an AM machine [10]. On the other hand, the all for one-pack is packing assemblies as compactly as possible [30]. In this case, an AM machine takes care of all decomposed parts placed in the same printable space. Fig. 5(b) shows a packing example of the assemblies of an octopus model. The studies dealing with the all for one-pack often consider a packing or nesting issue after object decomposition [53].



(a) Yearly distribution (b) Issue percentage

Fig. 3. Research trends: (a) yearly distribution and (b) issue percentage.



(a) Single- and multi-motive papers

(b) Combination percentage of multi-motive papers for productivity

Fig. 4. Research trends: (a) motive distribution and (b) motive percentage.

3.2. Productivity: Process time, material cost and product quality

PD can improve the AM productivity including process time, material cost, and product quality. Fig. 6 shows an example of decomposing an original model and building up the two separated parts simultaneously. This results in reducing build time by lowering the total height of parts and saving material cost by removing support structure [55]. However, although it reduces build time, generating assemblies causes assembly time in the post-processing. To solve this issue, Oh et al. (2017) explained the trade-off between build time and assembly time and proposed the method to minimize the total process time including the both build and assembly processes. To reduce the material cost, the quantity of input material for AM could be minimized for the support structure [32] as well as the product body [44,59]. Attene (2015) focused on minimizing the packing box volume including all decomposed parts to facilitate package shipments [49]. The product quality can be addressed in terms of surface roughness (accuracy) and structural soundness. Through the optimization of build orientation, the surface quality (roughness or accuracy) can be improved by reducing *stair stepping effect* [45,58] or by decreasing the overhanging areas [63]. The structural soundness means durability after assembling the decomposed parts. Thus, this is affected by connection types and joint parts for assembly. For example, for the case of glue-based connection, Chen et al. (2015) claimed that small interface areas may cause instability [30]. Yao et al. (2017) also considered the interlocking-based assembly for stability [62].

3.3. Functionality

PD can be considered for achieving mechanical functionality. Here, the functionality indicates moveable joints or mechanical components. Original models such as animals or hands are re-designed to include articulated joints [41]. Although re-designed models contain the articulated joints, any assembly process may not be required by building up assembled products [42]. When designers want to place such articulated joints on the specific regions of an original model, the connection region for assembly or the shape of assemblies is often defined by humans. As such, interactive decomposition (semi-automated) methods for both humans and computers are often used. For functionality, Gao et al. (2015) embedded functional modules, such as processor chips, sensors, springs, gears, and motors, in an original model [50]. Additionally, original models are re-designed to include mechanical template containing an assembly of gears and gear trains, cams, or linkages [64].

3.4. Artistry

Original models can be re-designed as assemblies for the artistic purpose [62]. Most of the studies for artistry come from computer graphics fields. As shown in Fig. 7, puzzles such as interlocking pieces [40] and card boards [43] can be considered in this category. Usually, generating puzzles from an original model requires a converting process, such as voxelization for interlocking pieces [38], for simplification or shape abstraction [60]. Although card boards are usually produced in die-cutting, they can be built up in AM as well [43]. When card boards are produced in AM, it can take small build time since the boards are placed in a thin planar sheet.

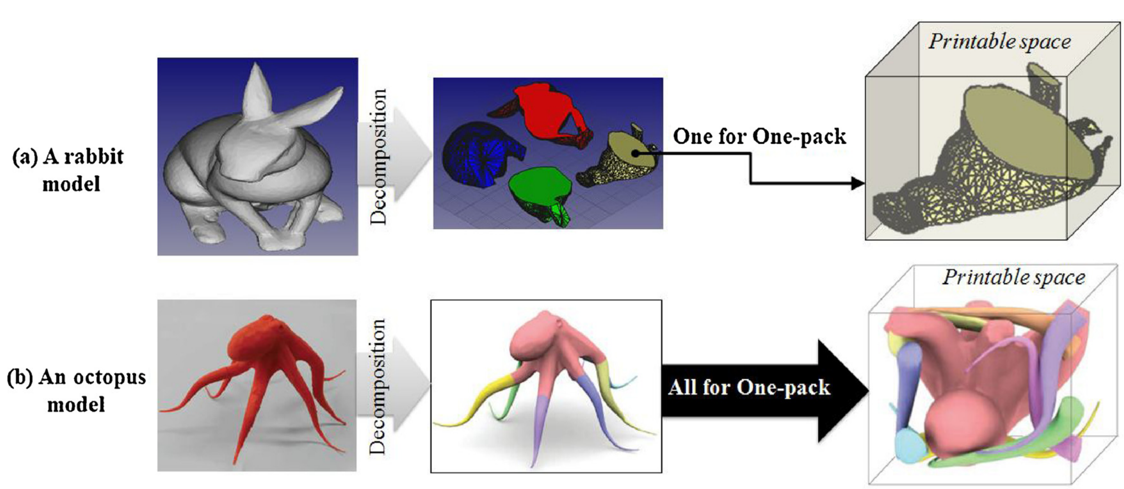


Fig. 5. Two types of printability: (a) a rabbit model (one for one-pack) [10] and (b) an octopus model (all for one-pack) [53].

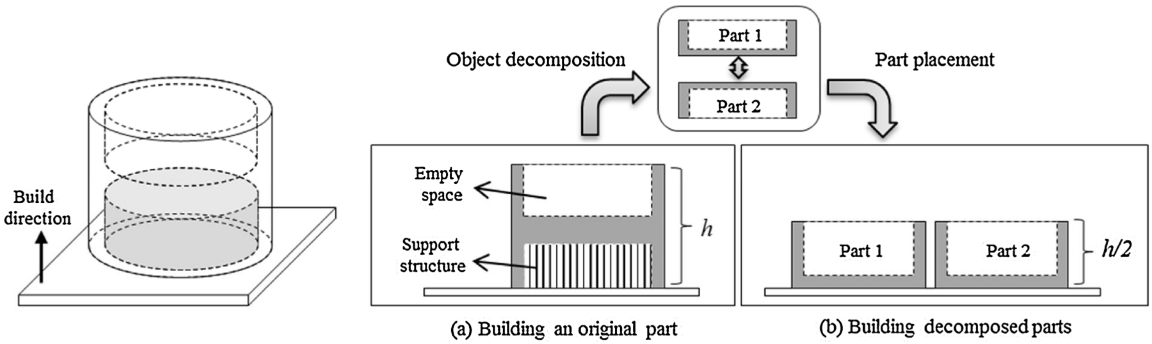


Fig. 6. Comparison of (a) building the single part and (b) building the two parts (modified from [55]).

3.5. Flexibility

Flexibility, also known as *interchangeability*, is another reason for PD. For example, having assemblies for product series can increase flexibility in the design of family products that share interchangeable modules [68]. As shown in Fig. 8, Duncan et al. (2016) developed an automatic algorithm to determine the component boundaries that enable interchangeability among different products [54]. For the purpose of interchangeability, chess pieces are re-designed into two parts: bottom and top [40]. The bottom parts are commonly designed and the top parts have different shapes such as headpieces for the knight and bishop. However, there have been few studies to show flexibility for AM.

4. The topics covered in part decomposition

As indicated in Fig. 2, the scope of this paper covers buildup and assembly topics as well as decomposition. As a perspective of concurrent engineering [69], decomposition topics are closely related to the topics of the overall AM processes including both build and assembly processes. This is because the results of decomposition, such as the number of parts and the surface shape of assemblies, affect the issues in a build process (orientation determination and packing) and in an assembly process (connection types and assembly sequence planning). As such, we consider both buildup and assembly issues in PD. Section 4 reviews the literature related to these three main topics. Each topic is elaborated further with regard to research techniques and methodologies.

4.1. Object decomposition

4.1.1. Traditional object decomposition methods

The object decomposition has broadly been studied in computer graphics and computer-aided design fields. The research has a large body of literature known as mesh partitioning, volume decomposition, and image segmentation. There are a considerable number of studies according to human involvement, object types, techniques, and constraints [70]. When humans are involved in the computational object decomposition, it is named as interactive segmentation. If computers can complete decomposition processes with no humans involvement, it is automatic segmentation [71]. Object decomposition can be also distinguished based on the types of segmentation: part-type and surface-type segmentation. In part-type segmentation, the object is represented by mostly volumetric parts. In surface-type segmentation, the object model is partitioned into patches [70]. When it comes to segmentation techniques, Shamir et al. (2008) suggested five approaches [70]: region growing, hierarchical clustering, iterative clustering, spectral analysis, and implicit methods. Chen et al. (2009) summarized segmentation techniques into seven algorithms [72]: K-Means, random walks, fitting primitives, normalized cuts, randomized cuts, core extraction, and shape diameter function.

4.1.2. Decomposition methods for AM

All the papers listed in Table 2 have their own decomposition methods applied to AM. The corresponding decomposition methods are classified based on three criteria of human involvement, decomposition techniques, and boundary shape. Table 3 summarizes the categorized decomposition methods.

4.1.2.1. Human involvement: Automated, semi-automated (interactive) and manual methods. Based on the degree of human involvement, decomposition methods are categorized into three groups of automated, semi-automated (interactive) and manual methods. In the automatic group, most of the studies use heuristic algorithms such as *Binary Space Partitioning (BSP)* [29], *Normalized Cuts (NCut)* [46], *Support Vector Machines (SVM)* [58], and region growing [47,59]. The automated decomposition methods are often used to find the optimality of single-objective [45,58] or multi-objective [29,53].

The automatic methods may decompose an object into several pieces which are not the intent of designers to cut. This is why semi-automated methods are needed. In an interactive process with computers, humans can decide about connection areas [54] or combination sequence and priorities of decomposition methods [33]. In many cases that the motive of PD is to enhance functionality, interactive methods are used since only users can specify and decide which parts or areas have mechanical functionality such as articulated joints in hands [41] or gears and wheels in cars [64].

Without computer algorithms, some decomposition guidelines have been developed to help human designers. This is mainly due to the point that object decomposition for AM often requires human experience and intuition to find the preferred decomposition positions. The studies dealing with manual decompositions usually provide general

Fig. 7. Examples of card boards and interlocking pieces: (a) a dinosaur model [43] and (b) a rabbit model [51].

(a) Input shapes: a horse, a camel, and a wolf (b) Interchangeable head

Fig. 8. An example to show interchangeable parts in a set of input models [54]: (a) input shapes and (b) interchangeable head.

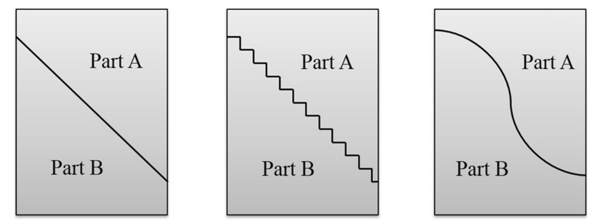
design guidelines of principles for engineering designers [36,55]. When it comes to a specific AM technology, Urbanic and Hedrick (2016) organized *fused deposition modeling (FDM)* based design rules for building large and complex components [57].

4.1.2.2. Decomposition techniques: Top-down and bottom-up approaches. For automated decomposition, two types of decomposition techniques are applied. Decomposition techniques are the methods of generating assembles from an original object. In general, two decomposition approaches exist: top-down and bottom-up. In the top-down approach, an original model is literally cut into several pieces one by one. In this method, a heuristic algorithm starts from one root object representing an original model. The process of partitioning a certain part into two (or more) sub-parts is recursively conducted until a stopping condition is satisfied. The stopping condition could be the desired volume [35] or the number of sub-parts [45]. Many studies pursuing the top-down approach use plane-based cuts between two assemblies yielding a BSP or BSP tree [10,29,43,63].

On the contrary, the bottom-up approach starts from primitives such as cells [46], meshes [44] or voxel [38] and goes through growing the primitives into sub-parts. Generally, it follows two steps: seeding and clustering. In seeding, as starting points, some primitives are selected [46]. Then, to create sub-parts, the initial primitives cluster or merge with other primitives in various ways such as an affinity measure [46] or SVM [58]. Note that, in the current study, a decomposition method that extends cores from the inside of object volume to outside is also categorized under the bottom-up approach. The cores can be cubic [50], polyhedron [56], or even interlocking puzzles (single knot) [40].

In Table 3, the study by Chen et al. (2015) is classified as both top-down and bottom-up approaches. This is because although they suggested a global optimization algorithm (*Dapper: Decompose-and-Pack for 3D printing*) based on the top-down approach which is decomposing pyramidal polycubes with a hyper plane [30], the pyramidal parts as starting components for their algorithm are created by the bottom-up approach of Hu et al. (2014) [46]. Moreover, the study by Yao et al. (2015) is also categorized under both since the decomposition and packing system that they developed supports various mesh segmentation algorithms including both top-down and bottom-up methods [53].

4.1.2.3. Boundary shape: Plane, free-form and voxel. Automatic decomposition methods result in a certain pattern among disintegrated parts. As shown in Fig. 9, the patterns can be distinguished into three types of boundary shape: plane, voxel and free-form [53]. For the plane, the boundary shape could be piece-wise planes, that are usually generated from bottom-up decomposition approaches [40,46,56,58], or hyper planes, that mostly result from top-down approaches [29,61]. In the case of the hyper plane boundary, the direction and position of a plane should be decided and the hierarchical data structure of decomposed pieces, such as binary tree [29] and octree [35], needs to be considered in the cutting algorithm.



(a) Plane **(b) Voxel** **(c) Free-form**

Fig. 9. Three boundary shapes: (a) plane, (b) voxel and (c) free-form.

The voxel boundary shape is caused by voxels that are regular grids in three-dimensional space. Generally, the decomposition algorithm to create the voxel boundary shape includes a voxelization process, sometimes called polyomino tiling [38]. This usually happens when interlocking puzzles are generated [51].

Note that the semi-automated and manual methods are categorized under free-form in Table 3 since users can design any boundary shape. Moreover, when the automated decomposition algorithm generates curved border, we consider the boundary shape as free-form. Most of the decomposition methods resulting in free-form boundary are considered under bottom-up approach [53]. However, the free-form boundary shape may cause obstruction during assembly. To solve this, the free-form boundary can be refined for an assembly process [46,49].

4.2. Buildup design

4.2.1. Build orientation determination

The decision-making on build orientations has been highlighted in DfAM since it affects various manufacturing performance measures such as build time, surface roughness, the amount of support, shrinkage, curling, distortion, and resin flow [73]. Generally, build orientation determination has been studied for a single part [74–76]. Recently, orientation decision studies have been targeting multiple parts [66,77].

4.2.1.1. Build orientation decision for a single part. Although, theoretically, an infinite number of build orientations exist for a single part, not all of them are practical. Therefore, most of the studies consider how to choose practical build orientations for AM. Usually, decision-making for build orientations includes two main steps: (1) generating a feasible set of part orientations and (2)

Table 3
Decomposition methods for AM.

		Automated		Semi-automated (interactive)	Manual
		Top-down	Bottom-up		
Boundary shape	**Plane**	[31,32,34,35,37,39,43,29,45,48,52,61,10,63]	[40,44,30,50,56,58,59]	–	–
	Free-form	[53]	[46,47,49,30,53]	[33,41,42,53,54,60,62,64]	[36,55,57]
	Voxel	–	[38,51]	–	–

selecting the best one [78]. In the current paper, three types of methods are introduced for the first step: feature-based; convex hull-based; and listing every angle. In the feature-based method, build orientations are generated considering AM features pre-defined by users [78–81]. In convex hull method, part orientations are generated by considering faces of the convex hull of a part [82]. The third method is to check all angles with an angle interval [83–87]. In the second step, two design evaluation methods have been often employed: single attribute and multiple attributes. Frank and Fadel (1995) relied on a single attribute, surface roughness [80]. Masood et al. (2000, 2003) used the volumetric error as a single evaluation attribute [86,87]. Decision-making based on multiple conflicting attributes has also been used to evaluate build orientations, which is known as *Multi-Attribute Decision Making (MADA)*. Zhang and Bernard (2014) dealt with a vector consisting of *n* attributes such as surface roughness, elongation, tensile strength and build time [81]. Zhang et al. (2016) considered surface quality, support volume, mechanical properties, build cost, and post-processing [78].

4.2.1.2. Build orientation decision for multiple parts. The concept of multiple parts means both independent and dependent parts. While independent parts are not related objects to each other, dependent parts are assemblies to complete a single product. Usually, the orientation determination for multiple parts follows the two-step method mentioned above for a single part. When packing issue is considered, the build orientation decision for multiple parts is closely related to the packing since packing problems should consider the positions and rotations of parts. Table 4 categorizes the studies based on part types (dependent and independent), the two-step method (orientation generation and selection) and whether the packing issue is included or not. Although both independent and dependent parts are considered in this section, Table 2 in Section 2 includes studies only for dependent parts.

A considerable number of studies list all practical angles with a certain interval [30,49,53]. Gogate and Pande (2008) listed acceptable angles with rotating to X- and Y-axes and then selected the best orientation among them [88]. Here, they do not consider angles with rotating to Z-axis in the build orientation optimization since it merely affects part height, support amount, and surface roughness. After the build orientation optimization, rotating to Z-axis is considered for packing since it influences the part position to place parts.

For dependent parts, most of the studies considered the bottom-up decomposition approach to generate assemblies [30,47,49,53,58,59]. For the selection method in Table 4, most of the studies dealt with multi-attribute problems, except the studies by Wang et al. [58] and Wei et al. [59]. These two studies considered surface roughness and the amount of support as a single attribute, respectively.

4.2.2. Part packing

The packing issue for AM deals with how to optimally place multiple parts (with same or different shape) into a limited build space (3D) or onto the build tray (2D) with respect to user-defined objectives [66].

4.2.2.1. Traditional packing problems. The traditional 2D and 3D packing problems have been proven to be NP-hard [93]. Therefore, heuristic-driven exhaustive or stochastic search algorithms including *branch-and-bound* [94], *simulated annealing (SA)* [95], and *genetic algorithms (GA)* [96] are often adopted [97]. The packing problems also have a wide range of applications including inventory management, transportation, and supply chains [98]. For the past decades, a variety of optimization methods have been adopted to solve this problem. For 2D packing problems, simulated annealing [99,100], and iterative local search [101] have been used to place a set of two-dimensional polygons. For 3D packing problems, SA [102], branch-and-bound [103], and GA [104] have been applied. In *operations research (OR)*, *cutting and packing (C&P)* issues, also known as cutting stock problems, have considered over the last decades [105]. This deals with problems of cutting standard-sized pieces of stock material into pieces of specified spaces while minimizing material wasted. In 2007, Wäscher et al. introduced an improved typology of C&P problems from the publication by Dyckhoff (1990) [105,106]. This shows a holistic category that how C&P issue has been studied in the literature.

4.2.2.2. Packing problems for AM. Unlike the classical packing problems, the AM packing considers manufacturing productivity related to AM such as build time, material cost and product quality. Often, the productivity factors are used as objectives for packing optimization. In addition, the AM packing that considers build orientation determination has a distinct characteristic from the traditional orientation optimization. Usually, part rotation according to the Z-axis is not imperative in the classical build orientation decision, since it does not have a critical impact on AM productivity such as minimizing build time or support structure. On the contrary, the part rotation for Z-axis could be essential on the AM packing since it affects boundary constraints of the packing by altering the part position in the placement.

Table 5 modified from Zhang et al. (2016) organizes the AM studies including automatic or semi-automatic packing methods [66]. For placement mode, there are 3D packing and 2D nesting. While most of the studies focused on 3D packing to save space wasted [88], [92], Zhang et al. (2016) proposed the two-dimensional nesting method by pointing out that 3D packing causes surface damage when the support structure is removed [66]. For part representation, there are three major categories including polygon mesh, voxel, and bounding box. For polygon mesh, a CAD model can be described by its boundary with multiple adjacent planar polygons. A *STL (STereoLithography)* format, where models are represented by triangulated meshes, is universally accepted as a standard file format in the AM industry. A voxel is a

Table 4
Orientation decision studies for multiple parts.

Reference	Part type	Orientation generation method	Selection method	Packing issue
[89]	Independent	Listing orientations according to the normal vector of mesh	Multi-attribute	Included
[90]	Independent	Listing angles with interval	Multi-attribute	Included
[88]	Independent	Listing angles with interval	Multi-attribute	Included
[91]	Independent	Listing angles with interval	Multi-attribute	Included
[92]	Independent	Listing angles with interval	Multi-attribute	Included
[47]	Dependent	Listing angles with interval	Multi-attribute	Included
[77]	Independent	Feature-based	Multi-attribute	Not included
[49]	Dependent	Listing angles with interval	Multi-attribute	Included
[30]	Dependent	Listing angles with interval	Multi-attribute	Included
[53]	Dependent	Listing angles with interval	Multi-attribute	Included
[66]	Independent	Feature-based	Multi-attribute	Included
[58]	Dependent	Listing orientations according to the normal vector of mesh	Single-attribute	Not included
[59]	Dependent	Listing orientations according to the normal vector of mesh	Single-attribute	Not included

Table 5
AM studies for packing problems (modified from [66]).

Reference	Part type	Placement mode	Part representation	Placement method	Production context
[107]	Independent	2D / 3D	Bounding box	Serial	Subset
[96]	Independent	3D	Polygon mesh	Parallel	Subset
[89]	Independent	3D	Voxel model	Serial	Full
[108]	Independent	3D	Voxel model	Serial	Subset
[109]	Independent	3D	Bounding box	parallel	Full
[90]	Independent	2D	Bounding box	serial	Subset
[88]	Independent	3D	Voxel model	Serial	Full
[91]	Independent	2D	Polygon mesh	Serial	Subset
[47]	Dependent	3D	Polygon mesh	Serial	Full
[92]	Independent	3D	Voxel model	Serial	Full
[49]	Dependent	3D	Polygon mesh	Serial	Full
[30]	Dependent	3D	Voxel model	Serial	Full
[53]	Dependent	3D	Polygon mesh	Parallel	Full
[66]	Independent	2D	Polygon mesh	Parallel	Full

volume unit representing a value on a regular grid in 3D space. A voxelized model consists of numerous voxels to represent it. While voxelized models require less memory, they suffer from low precision. Additionally, a bounding box, that is the minimum box to enclose an object, can be used to simply represent a 3D model. Although this method guarantees to rapidly calculate packing processes, it causes some wasted space. Additionally, there are two types of placement method: serial and parallel. In serial placement method, parts are packed one by one according to pre-set rules. In parallel placement method, parts are positioned simultaneously. Moreover, there are two types of production context: subset and full placement. Subset placement means that only a subset of parts fill a build volume. Full placement means all parts fill a build volume.

For AM, some studies deal with both decomposition and packing topics known as *PackMerger* [47], *decompose-and-pack* [30], *partitioning and packing* [53] or *split-and-pack* [49]. Vanek et al. (2014) suggested a method to go through build orientation optimization first and then enter the fixed orientations to packing optimization algorithm [47]. Later, other studies conduct the orientation and packing optimizations simultaneously [30,49,53].

4.3. Assembly design

4.3.1. Traditional part connection methods

Traditionally, the part connection has been studied in DFA. Particularly, the determination of the connector type for assembly is an essential part of the DFA principle. Lee and Hahn (1996) proposed four joint types for assembly: discrete fasteners, adhesive bonding, energy bonding and integral fits [110]. The discrete fastener is a method to use separate components such as screws or rivets, where fasteners are usually a pair of male and female units for assembly. In the case of integral fits, also called integral attachment, assembly parts include physical fastening units. In this case, since the units are integrated into parts, it is possible to fasten parts without any tools. Adhesive bonding uses bonding materials for assembly such as glues, silicones, and acrylics. Lastly, energy bonding is a method to use external energy such as ultrasound or inductive heating to melt joint areas for bonding. Soldering, brazing, and welding are categorized into this method. Fig. 10 shows examples of connection types. Based on the study by Lee and Hahn (1996), Sonnenberg (2001) organized connection elements based on different criteria such as design issues, the number of fastening elements, assembly steps, damage during assembly, and cost for changes [111].

4.3.2. Connection types in AM

When it comes to considering connection types applied to AM, there are mainly two categories: fixed connection (fastener-based and interlocking-based) and non-fixed connection (ball-and-socket joints and hinge joints) as shown in Table 6.

4.3.2.1. Fixed connection type. The *fixed type* involves adhesive- (or glue-), fastener- and interlocking-based connections. When the adhesive-based connection is considered, most of the studies briefly mention the connection type since parts can be linked without special connection features [45–47,52]. Only a few studies detailed that the adhesive-based connection requires a condition that the contact surface between parts, where the adhesive is placed, has enough area for connection soundness [29,30]. Practically, since the adhesive-based connection can be used with any other connection types, such as fasteners [37] or even iron wires [49], Table 6 does not distinguish this type of connection especially.

The fastener type connection is often used for assembly. It usually requires a pair of male and female features for assembly. As shown in Section 4.3.1, this can be divided into discrete fastener and integral attachment. For the integral attachment, male features are generated as specific patterns such as cylinders [29], tabs [38] and spheres [37]. Chan and Tan (2005) suggested female-connector-female type for assembly connection [33] and Song et al. (2016) proposed bolts and nuts that are produced in AM [56]. One of the critical issues for fastener type connection is addressing *geometric dimensioning and tolerancing (GD&T)*. In 2015, Ameta et al. (2015) investigated GD&T practices for AM processes [112]. In their paper, they introduced various specification issues caused be AM processes and suggested possible solutions.

As a fixed type connection, interlocking is another major option for assembly. The interlocking is a connection type that assemblies can be attached to their own tangling shape without requiring any extra connectors or glue. Often, this method has been applied to furniture assembly [113,114], and puzzles [40,115]. The shape of interlocking pieces is various including polyominoes [38] and card boards [43]. Usually, these studies emphasized on the assembly sequence for assembleability [40,115]. The assembled object enables to be easily and repeatedly disassembled and reassembled. However, when building up interlocking parts, it is challenging to avoid support structure since their geometry is twisted and crooked for the sound connection of assembly.

4.3.2.2. Non-fixed connection type. The *non-fixed connection* includes joints, gears, knuckles and hinges for mechanical functionality to create moveable parts. In many cases, engineering designers plan assemblies from the beginning. However, for re-designing assemblies, moveable parts are generated from an original single object. For object decomposition, assemblies are usually generated in an interactive method where humans are involved in the computational design process. Bächer et al. (2012) proposed the method to create a printable articulated model from an input mesh [41]. In this method, they used a set of potential point locations extracted and user-specified range constraints such as joint limits. Their method that results in many joint candidates could cause a collision issue. To solve the issue, Calì

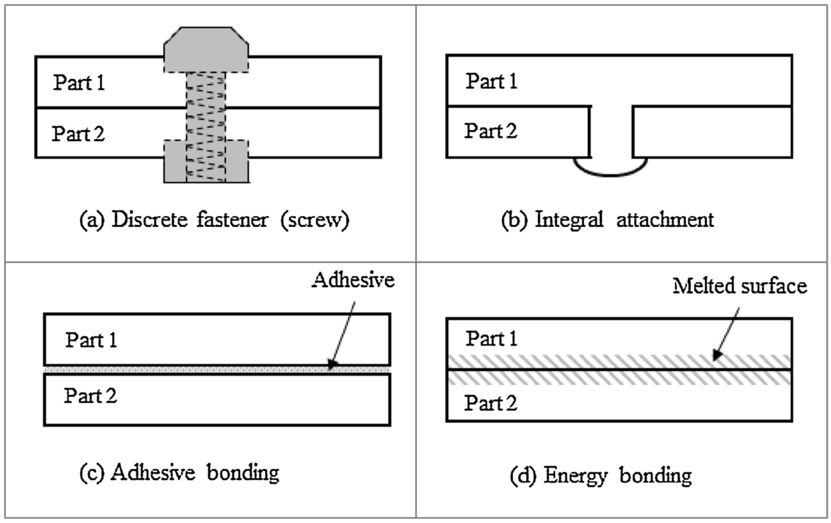


Fig. 10. Examples for four connection types: (a) discrete fastener (screw); (b) integral attachment; (c) adhesive bonding; and (d) energy bonding [55].

Table 6
Assembly connection types applied AM.

		Reference
Fixed connection	Fastener-based	[33,38,37,39,29,53,54,56,58,61]
	Interlocking-based	[38,40,43,44,51,56,62]
Non-fixed connection	Ball-and-socket joint	[41,42]
	Hinge joint	[41,48,60]

et al (2012) suggested offering an intuitive interface for users to design an articulated model with a real-time interface [42]. Zhou et al. (2014) proposed a method to produce a single and connected object that can be folded by hinges. In their study, a 3D model is voxelized and the voxels are converted into a tree linkage structure that is foldable. The linage structure can be folded to a box of a cubic shape, named as boxelization.

4.3.3. Assembly sequence planning applied to AM

AM enables to build an assembled product that does not need any assembly process [42], [116,117]. This is one of the major reasons that DfAM has not highlighted *assembly process planning (APP)*, containing *assembly sequence planning (ASP)* and tool and fixture planning. However, some motives for PD such as printability and productivity could highlight APP issue by building up assemblies separately. In the traditional manufacturing, APP is usually applied to the automated process to find optimal or near optimal assembly plans for reducing manufacturing costs [118]. In AM, however, the assembly process in post-processing is usually non-automated, therefore ASP may be a more critical issue than tool and fixture planning. In particular, PD requires assembly/disassembly sequence planning to prevent collisions during assembly/disassembly process [58]. The collisions are usually caused by the bottom-up decomposition methods. This is why Attene (2015) proposed a top-down tree structure to easily deploy assemblies into an assembly sequence although the algorithm proceeds bottom-up approach by clustering tetrahedral [49]. Yao et al. (2017) defined *sequential one-push assemblability (SOPA)* in which it makes it possible to join assemblies to each other in some sequential order where each subsequent part is attached to the earlier parts using a single collision-free translational motion and they find SOPA compatible disassembly sequences [62]. For interlocking pieces, assembly or disassembly sequence is considered [40]. Lo et al. (2009) applied the concept of dependency graph to build interlocking puzzles with a bottom-up order [38].

5. Discussion and perspectives

The objectives of this paper are to survey the PD studies and identify relations between the PD studies and DfAM. In terms of part number variation, this paper views the re-design for AM under three main categories of part number conservation, decrease and increase. Among them, the methods that result in the increase of part numbers have been focused. The main contribution of this review paper is extending the research boundary of DfAM since most of the prior studies have been aimed to the part number conservation and reduction.

In this paper, 37 publications for PD are investigated to present future research trends. We have discussed why PD is needed for AM and have classified the literature under five main motives of printability, productivity, functionality, artistry and flexibility. In addition, three major design topics including decomposition, buildup and assembly designs have been discussed with their corresponding technical methodologies.

As witnessed in this comprehensive review, the concept of PD leaves further research issues spanning several disciplines. In perspective, we suggest the future research directions of PD as three main streams: (1) to further improve the AM productivity for mass customization; (2) to develop new decomposition methods and guidelines for AM; and (3) to apply conventional design methodologies to PD.

(1) Further improvement of the AM productivity for mass customization
(2) To consider *productivity (process time, material cost, and product quality) as the main objective* rather than printability, how to fit assemblies into a limited workspace. So far, printability has been the major objective of object decomposition. However, for AM-based mass customization, multiple productivity-related objectives could be addressed while printability is considered as a constraint.
(3) To consider *the whole production procedure for AM including both build process and post process*. Generating assemblies may reduce build time and material cost and improve surface quality while it may increase assembly time and cost in the post-processing. Therefore, analyzing the trade-off between the productivity of build process and post process and finding the optimal assembly design is critical.
(4) To develop the PD methods dealing with *production planning issues including multiple parts and multiple AM machines*. Multiple initial products could be considered together in the production planning for AM where one initial product could be separated into several

assemblies after object decomposition. In addition, multiple AM machines could have different specifications, such as the size of workspace and the build speed, and the machines may compose serial, parallel, or mixed processes, which makes production planning difficult.

(5) Novel decomposition methods and guidelines for AM
(6) To develop *automatic decomposition methods based on thermal-mechanical modeling and simulation to predict warping, distortion and residual stress*. In DfAM, product deformation and changing the original shape have created significant practical challenges such as warping and distortion issues. PD could be one solution for these issues by decomposing the region that causes warping and distortion issues.
(7) To develop *selection methods or guidelines to choose the proper decomposition means*. The question of how a part should be decomposed is a critical issue since it affects the determination of build orientation, packing, assembly connection and assembly sequencing. Therefore, PD should be decided considering the overall AM process performance (time, cost, and quality) and decomposition options (automatic, semi-automatic, and manual methods). The selection of decomposition method based on different motives, material types, AM machine parameters, and the number of machines is an important research topic.
(8) To apply traditional design methodologies to PD
(9) To apply DFA to PD including *assembly design for connection types, assembly sequence planning, and assembly complexity*. Material types can affect the determination of assembly connections. For instance, energy bonding might be effective to metal parts while adhesive bonding might be suitable to plastic parts. Moreover, the assembly sequence planning for AM can consider assembly time and cost as well as assembleability. Additionally, the complexity of assembly or difficulty of manual assembly processes can be considered. When the surface area between parts is sufficiently large, the complexity of assembly decreases making it easy to assemble manually. However, this results in less aesthetic since the large connection area usually causes a large seam. The trade-off between assembly complexity and aesthetics can be another research direction.
(10) To apply *classical decomposition and packing methodologies to AM*. Both decomposition optimization and packing optimization have considerably been studied in computer graphics and computer-aided design fields by generating various algorithms. These heuristic algorithms could be applied to automatic decomposition for PD considering AM process performance and constraints.

Acknowledgements

This material is based upon work supported by the National Science Foundation – USA under grant # CMMI- 1727190. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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