Nesting and Scheduling Problems for Additive Manufacturing: A Taxonomy and Review

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Abstract

With the trends of *Industry 4.0* spanning physical and virtual worlds, *Additive Manufacturing (AM)* has been the mainstream for realizing complex geometries designed in computers. Meanwhile, a considerable number of AM studies have focused on effectively building these elaborate designs. However, as the AM technologies have matured, production-driven studies have recently been spotlighted to achieve mass customization. This means that the research scope has been extended to incorporate production management concerns focused on efficiently producing high volumes of heterogeneous parts. Particularly, since AM allows batch processing of multiple parts within the same build volume, nesting methods have been studied to properly place objects in the limited space to improve yield. Since the middle of 2010, the nesting topic has been considered with a scheduling matter for assigning objects to AM machines to minimize production time and cost. The main contribution of this investigation is to show the current status of nesting and scheduling studies applied to AM. This reveals critical issues for future research directions. Since traditional manufacturing usually addresses nesting and scheduling problems separately, each problem is specified with its specialized taxonomies. This causes the existing taxonomies to be limited in comprehensively covering both nesting and scheduling topics. To provide a holistic view covering both topics, this paper proposes an alternative taxonomy based on three dimensions: *Part*, *Build*, and *AM Machine*. Considering combinations of the three dimensions, six classes are defined to identify and cluster problem characteristics and types. Moreover, eight supplementary criteria are added to further refine the organization of the research papers within those classes. In this survey, 53 technical papers are classified and critical issues are discussed.

Keywords: Additive Manufacturing, Nesting, Production Planning, Scheduling, and 3D Printing

1. Introduction

Research in *Additive Manufacturing (AM)*, commonly referred to as *three-dimensional (3D) printing*, has traditionally focused on process-driven [1] and design-driven [2] aspects required to produce complex geometries for niche products. However, as the technology sector has matured, new on-demand production strategies based on AM have emerged capable of producing high volumes of low-cost customized parts (e.g., personalized key chains and luggage tags) [3]. AM-based manufacturers have adapted their business models to participate in on-demand services;

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see, for example, *Factory-as-a-Service (FaaS)* [4], *Manufacturing-as-a-Service (MaaS)* [5], *Production-as-a-Service (PaaS)* [6], *Ubiquitous Manufacturing (UM)* [7] and *Cloud Manufacturing (CMfg)* [8]. As increasing the amount and diversity of additively produced parts requires efficient operational management approaches, production-driven research has recently been spotlighted to efficiently manage the production of large quantities of heterogeneous parts [9], [10]. This trend stimulates the necessity of better process planning and production management for mass customization based on AM [11], [12].

To increase production rate (yield or throughput) in AM systems, nesting and scheduling methodologies are significant for efficient process planning and production management. When processing a batch of parts, nesting methods are addressed to properly place objects (identical or non-identical) in the limited build envelope of an AM machine. In general, the objectives of nesting problems for AM are to maximize the number of simultaneously processed parts or to minimize the build time and cost of a single operation of an AM machine. Moreover, scheduling for AM focuses on improving productivity by sequencing and allocating workloads to AM machines.

In traditional manufacturing, nesting and scheduling approaches are considered separately in different planning stages. Nesting issues for batch processing (e.g., wafer fabrication and injection molding processes) are usually managed during process planning by process and engineering designers. On the other hand, scheduling problems are mostly addressed in production planning and control by production managers [13]. As such, there are few studies simultaneously dealing with both nesting and scheduling approaches in manufacturing applications [14].

In AM, however, nesting methods used in process planning often incorporate scheduling concerns from production planning. For instance, emergency parts (based on due dates) may be grouped into the same build during the nesting process, which then influences scheduling decisions [15]. Moreover, irregular bin packing problems, a type of nesting problem, may consider the different sizes of build volume depending on non-identical AM machines, which affects mapping jobs and resources in scheduling problems [16]. Namely, nesting outcomes (e.g., number of builds, number and volume of parts per build, and maximum part height within the build volume) often affect the jobs (builds) and performance indicators (build time and cost) of scheduling problems. Especially, the build time and cost for each build cycle depend on nesting issues (build orientations, placement locations and geometries of input objects), which is a distinctive characteristic of AM-based scheduling problems [17].

Nesting and scheduling problems in the AM literature can be categorized into three types: *Nesting for AM (NfAM)* (see, e.g. [18], [19]*)*; *Scheduling for AM (SfAM)* (see, e.g. [17], [20]); and *Nesting and Scheduling for AM (NSfAM)* (see, e.g. [15], [21], [22]. Compared with NfAM problems, SfAM and NSfAM problems have been highlighted recently. When it comes to taxonomies of nesting and scheduling problems in traditional manufacturing, there exist a lot of variations and some of them could apply to NfAM and SfAM problems. However, adopting existing taxonomies for joint nesting and scheduling (*NSfAM*) problems is limited in comprehensively identifying both topics. This is mainly because nesting and scheduling problems have been studied in their ways based on different planning stages and applications.

We propose a comprehensive taxonomy covering nesting and scheduling problems based on the AM system organization. Our proposed taxonomy (Figure 1) is based on the physical system hierarchy consisting of three levels: *Part*, *Build*, and *AM Machine*. We derive six problem classes from the intersection or combinations of these levels. This taxonomy structure assists in identifying problems in terms of decision-making levels. In other words, it shows when decisions can be made based on the transitions between the levels. Herein, the transitions of *Part to Build level* and *Build to AM Machine level* imply nesting and scheduling processes, respectively. This holistic view not only looks at how decisions can be decomposed but also considers how those decisions affect other decisions. Our proposed taxonomy complements the usual NfAM, SfAM and NSfAM classification and provides another perspective to help identify and organize the problems.

The rest of the paper is organized as follows. Section 2 defines six problem classes that will be used to classify the AM literature. These classes help identify the objectives, constraints, significant factors, and assumptions of problems. In Section 3, 53 technical papers are classified and critical issues for each class are identified. In Section 4, research directions are described for future investigations and studies. Concluding the study, Section 5 summarizes findings and research contributions.

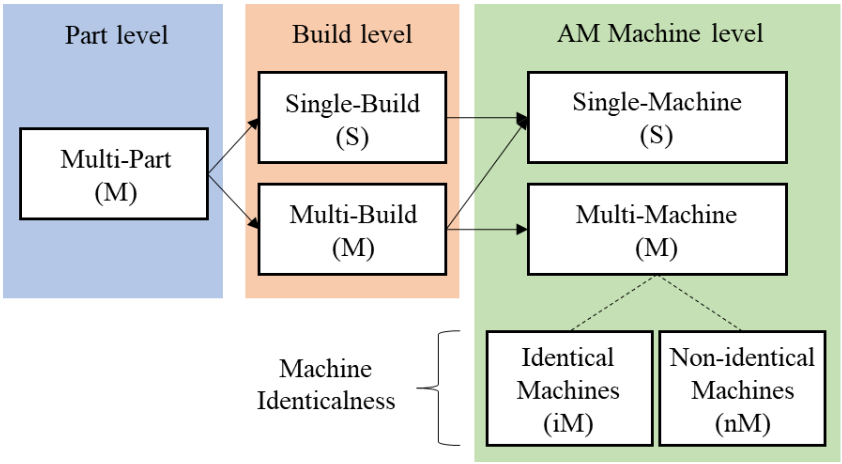


Figure 1. The taxonomy hierarchy for nesting and scheduling problems in AM

2. Taxonomies for Nesting and Scheduling Problems

In Section 2.1, technical terms are defined to use consistently throughout this manuscript. Section 2.2 defines the scope of this investigation to search for research papers. Section 2.3 describes existing taxonomies for nesting and scheduling problems. Section 2.4 provides our proposed alternative taxonomy for AM. Section 2.5 represents supplementary criteria to further refine problem classification.

2.1 Terminology

When it comes to nesting and scheduling topics, the AM studies have used various terms interchangeably. This is mainly because researchers have different perspectives and backgrounds. For example, the term, *part*, could be named as *geometry* and *task* in nesting [18] and scheduling [23] perspectives, respectively. To avoid confusion, the five keywords including *nesting*, *scheduling*, *part*, *build*, and *AM machine* are defined in Table 1 and used consistently throughout this paper. Table 1 also shows other compatible terms used in the AM literature to convey the context of problems. In this paper, most technical terms are derived from the standard terminology for AM in ISO/ASTM52900-15 [24] and a review paper for nesting problems in AM [25].

The terms "nesting and packing" have often been used interchangeably although nesting is usually related to a pattern where some large objects envelope one or more small objects [25]. However, we adopt "nesting" as defined by the standard terminology for AM [24], [26]. Furthermore, the term "scheduling" has a variety of meanings from micro-level, such as process planning for minimizing the number of multi-material changeovers within a specialized AM machine [27], to macro-level, such as order management for on-demand services [28]. However, we narrow down its meaning to production planning at the shop-floor level.

Table 1. Terminology for the five keywords: nesting, scheduling, part, build and AM machine [24], [25]

Terminology	Meaning	Other compatible terms
Nesting	Determining the location and orientation of *parts* within the build volume. Note that, if multiple *builds* are considered, it includes the determination of grouping parts into builds.	Batch placement [29]; batch planning [30]; bed space optimization [31]; layout optimization [32]; layout planning [33]; multi-parts placement [34]; packing [25]; work space planning [19]
Scheduling	Assigning *builds* to *AM machines* for build cycles.	Part-to-printer assignment [35]; production planning [16], [36], [37]; 3D printing shop scheduling [22]
Part	A single physical instantiation of a 3D model that is the joined material forming a functional element.	Geometries [18]; jobs [22]; objects [38]; part orders [39]; pieces [36]; tasks [23]
Build	A group of *parts* simultaneously produced by an *AM machine* in a single build cycle.	Batches [22], [29]; jobs [15], [17], [39]
AM Machine	A machine to complete a *build* including *parts* during a build cycle.	Machines [15]; 3D printers [40]; 3D printing facilities [36]

2.2 The investigation scope

There are a considerable number of nesting and scheduling papers dealing with theoretical studies and other practical applications. However, the investigation scope of this review paper is limited to the AM application, meaning that AM characteristics including productivity factors (e.g., build time and cost), constraints (e.g., the number and size of AM machines), and certain types of AM processes are addressed. As shown in Figure 2, this paper's investigation scope is represented by the areas of NfAM, SfAM, and NSfAM. NfAM papers are involved in the scope of $(N \cap A) - S$, which addresses only nesting problems for AM. SfAM papers are included in the scope of $(S \cap A) - N$, which deals with only scheduling problems for AM. Lastly, NSfAM papers cover both nesting and scheduling problems, which is the common area of $A \cap N \cap S$.

The investigation scope is associated with transitions among *Part*, *Build*, and *AM Machine* levels. Nesting problems for AM deal with how to pack multiple parts into builds, which is from Part level to Build level. This usually includes the following decision-making issues: build orientation for multiple parts; part location within the build volume; and clustering parts into builds. Scheduling problems for AM address how to assign builds to AM machines, which is from Build level to AM Machine level. Herein, the major issues are determining the processing order of builds and mapping builds and AM machines.

The keywords used to search nesting and scheduling papers applied to AM are listed in Table 1. The literature review section of each paper was further investigated for additional significant papers to be included in our survey. Table 4 shows all 53 papers found through this investigation. Review papers [25], [41] and framework design studies [42], [43] are excluded from this list. Theoretical studies [14] are also excluded if the AM application is not directly discussed.

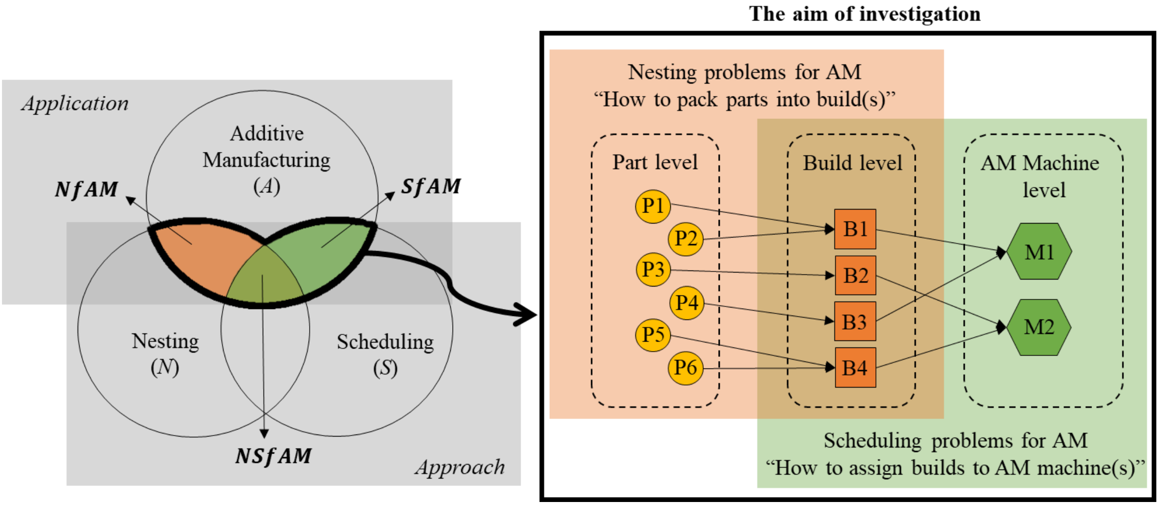


Figure 2. The investigation scope: Nesting for AM (NfAM); Scheduling for AM (SfAM); and Nesting and Scheduling for AM (NSfAM)

2.3 Review of existing taxonomies

Researchers have proposed taxonomies and classification criteria for nesting problems. The operational research field considers similar problems under the umbrella of *cutting and packing (C&P)* problems. For C&P problems, Dyckhoff [44] firstly proposed a typology consisting of a four-tuple ($\alpha/\beta/\gamma/\delta$): *dimensionality*; *kind of assignment*; *assortment of large objects*; and *assortment of small items*. Wäscher et al. [45] pointed out some severe drawbacks of this work. They improved the typology by suggesting new systematic classification criteria based on the four tuples and one additional tuple, *shape of small items*. Araujo et al. [46] proposed classification criteria for the AM-based nesting problems. The authors extended the previous work by proposing a new taxonomy based on a four-tuple (*dimensionality*; *optimization criteria*; *build volume type*; and *attributes/features of the assortment of parts*) and organizing datasets [25].

In the manufacturing field, scheduling problems have been addressed as a representative topic of operations management. For production scheduling problems, Graves [47] proposed three classification dimensions: *requirements generation* (open and closed shops); *processing complexity* (one-stage one-processor; one-stage parallel processor; multi-stage flow shop; and multi-stage job shop); and *scheduling criteria* (schedule cost and performance). These dimensions have been updated and specified into systematic taxonomies [48]–[51]. Additionally, solution approaches for scheduling problems have often reviewed and classified [52]–[54].

2.4 A comprehensive taxonomy

Since existing taxonomies focus on either nesting or scheduling, this section proposes an alternative taxonomy comprehensively covering both topics for AM. The proposed taxonomy is based on a physical hierarchy consisting of Part, Build, and AM Machine levels (Figure 1). While Build and Machine levels have both single- and multi-ones, Part level has only multi-part since addressing a single part is meaningless in nesting and scheduling problems. Note that this taxonomy could be applied to other applications based on batch processing as well as AM. In other applications, builds and AM machines could be replaced with jobs and other types of machines and facilities.

According to the taxonomy hierarchy, four classes with codes are defined as follows:

- [M/S/S]: Multi-Part → Single-Build → Single-Machine
- [M/M/S]: Multi-Part → Multi-Build → Single-Machine
- [M/M/M]: Multi-Part → Multi-Build → Multi-Machine
- [–/M/M]: Not Available (N/A) → Multi-Build → Multi-Machine

Furthermore, depending on the identicalness of AM machines, Multi-Machine is subdivided into two sub-categories: Identical and Non-identical Machines. Therefore, the hierarchy allows the six classes of [M/S/S], [M/M/S], and the following classes:

- [M/M/iM]: Multi-part → Multi-Build → Identical Multi-Machine
- [M/M/nM]: Multi-part → Multi-Build → Non-identical Multi-Machine
- [–/M/iM]: N/A → Multi-Build → Identical Multi-Machine
- [–/M/nM]: N/A → Multi-Build → Non-identical Multi-Machine

This classification based on six classes is associated with the categorization based on NfAM, SfAM, and NSfAM types. For example, the papers of [M/S/S] class are all included in NfAM type since a single build and a single machine cause nesting concerns rather than scheduling issues considering processing sequences and build assignments.

The six classes represent the investigation scope as well as classification criteria. Especially, as discussed in Section 2.2, the papers included in this investigation must consider AM characteristics, which means addressing the AM Machine level of the hierarchy. For example, if a paper only covers Part and Build levels without reaching to AM Machine level (i.e., [M/S/–] or [M/M/–]), it is considered a theoretical nesting problem regardless of AM. Therefore, only papers addressing AM characteristics are considered in this review paper. Additionally, [–/S/S] class is not considered since assigning a single build to a single machine is trivial in terms of operational scheduling.

As defined in Table 1, an AM machine takes care of a build including parts during a build cycle. This means that parts should be grouped as a build for AM processing even if a build includes only one part. In other words, builds are necessary to produce parts through AM machines. Therefore, [M/–/S] and [M/–/M] classes are not addressed in the manuscript. Although some studies [35], [55] do not mention the concept of builds by describing that parts are directly assigned to AM machines, we assume that these parts are grouped into builds. Especially, if papers assume that an AM machine takes care of only one part for a build cycle, we classify the papers into [–/M/M] class by considering parts as builds [40], [56].

2.5 Supplementary criteria for problem classification

Supplementary criteria are provided to further refine problem classification within the six classes. Problem classification for each class is represented in Tables 5 to 9. For every class, three common criteria (AM processes, objectives, and methodologies) are used to generally comprehend the AM studies. Moreover, eight specific criteria are adopted depending on the classes. According to the standard guidelines in ISO/ASTM 52900-15 [24], we categorize AM processes as follows: *binder jetting (BJ)*; *directed energy deposition (DED)*; *material extrusion (ME)*; *powder bed fusion (PBF)*; and *vat photopolymerization (VP)*. For solution methodologies, meta-heuristics such as *genetic algorithm (GA), tabu search (TS)* and *simulated annealing (SA)* are often employed.

Table 2 represents the eight specific criteria consisting of the nesting-related (N_α, N_β, N_γ, and N_δ) and scheduling-related (S_α, S_β, S_γ, and S_δ) tuples. The first element of the nesting-related tuples is dimensionality (N_α) that shows whether parts are placed on the build surface (*2D*) or packed within the build space (*3D*) [34]. If 2D nesting is considered, all parts are in contact with the build surface that is often the build platform. Note that the concept of 2D nesting in this paper is different from the traditional definition of 2D nesting in theoretical nesting papers [57] usually dealing with 2D geometries (e.g., polygons). On the other hand, if 3D nesting is considered, parts are allowed to be stacked with other parts.

The second element is the rotation freedom of parts (N_β). In the middle of a nesting algorithm, parts are typically rotated to determine build orientations. For N_β, rotation directions, *A*, *B*, and *C*, are adopted to represent that a part is rotated around X-, Y-, and Z-axes, respectively [26]. To determine the build orientation of a single part, Rotation C could be negligible since it is usually not critical to build time and surface quality [37]. However, in nesting problems for multiple parts, Rotation C is indispensable since it affects the location of other parts. In this case, all three rotation directions (*ABC*) should be considered in build orientation determination. However, some scheduling-focused studies simplify nesting issues by only considering Rotation C (*C*).

Build volume boundness (N_γ) represents whether the build volume is closed (*Bounded*) or opened (*Unbounded*). If unbounded nesting is considered, certain dimensions of the build volume are flexible. For example, Figure 3-(a) presents unbounded nesting that X-dimension is open. Unbounded nesting is one of the key characteristics of traditional strip-packing problems of which the objective is usually to minimize the unbounded dimension [58].

The set of nested parts (N_δ) is an element to present whether all parts are nested (*Full*) or only some parts are nested (*Subset*). Figure 3-(b) presents subset nesting that some parts of the entire set are chosen and placed. This is one of the essential characteristics of traditional knapsack problems of which the objective is to maximize the profits of chosen items [59]. Figure 3-(c) represents multi-build nesting that parts are grouped into multiple builds, which is the main characteristic of traditional bin-packing problems. If multiple AM machines are considered, the build volume for each build can be different.

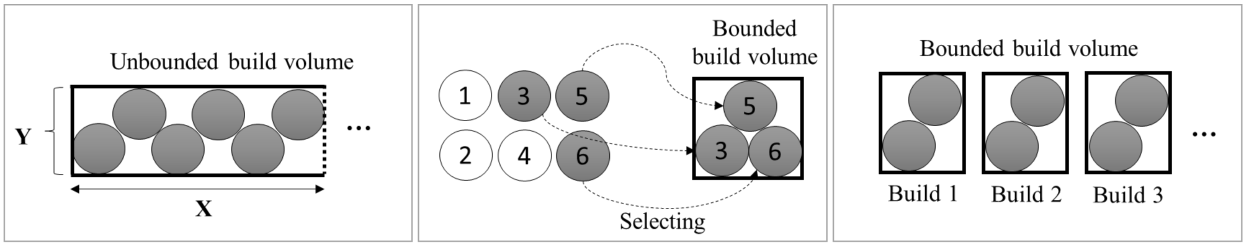
The other four tuples (S_α, S_β, S_γ, and S_δ) are related to scheduling problems. Before mapping builds (tasks) and AM machines (resources) in scheduling problems, the builds are generated in the following ways (S_α). First, builds can be clustered from parts by a nesting algorithm (*Nested*). In this case, since a scheduling algorithm is fed builds that are outcomes of the nesting algorithm, it is prone to that nesting and scheduling approaches are closely related. However, the nesting process is often simplified by clustering parts into builds based on the maximum capacity of part volume [60] and area [17], [61] (*Grouped*). This is different from the previous case (*Nested*) since the location and orientation of parts are not determined through a certain nesting algorithm. Without considering parts, builds can be randomly generated (*Created*) based on a range of parameters including size and volume [56]. The problems of [–/M/M] class are usually classified into the *Created* category. Additionally, build information such as the total volume and maximum height within a build can be provided in a problem (*Given*). However, this case weakens the key characteristic of AM problems that such build information is unexpected.

The second element (S_β) indicates three types of scheduling models: single-machine (*SM*); parallel-machine (*PM*); and flow-shop (*FS*) [62]. Figure 4 represents examples of AM-based scheduling models. Flow-shop problems assume that all tasks are to be processed on the same set of machines with identical processing steps [47]. For AM-based flow shop problems, AM machines are usually placed in the first stage [40], [63]. While [M/M/S] class corresponds to either SM or FM model, [M/M/M] and [–/M/M] classes correspond to PM model.

In the scheduling problems for AM, a customer order includes a variety of requests. Apart from a default request for part geometry, four order properties (S_γ) are considered in this paper: due-date (*Du*) for delivery, material type (*Ma*), and part quality (*Qu*). In addition, non-identical machine property (S_δ) is addressed when the locations (*Lo*), sizes (*Si*) and process parameters (*Pr*) of AM machines are different. It should be noted, when process parameters (e.g., processing time for coating/forming, operation cost and nozzle speed) are different among AM machines, they are considered as non-identical machines in this paper. Moreover, if AM machines are placed in physically remote locations, they are also considered as non-identical machines.

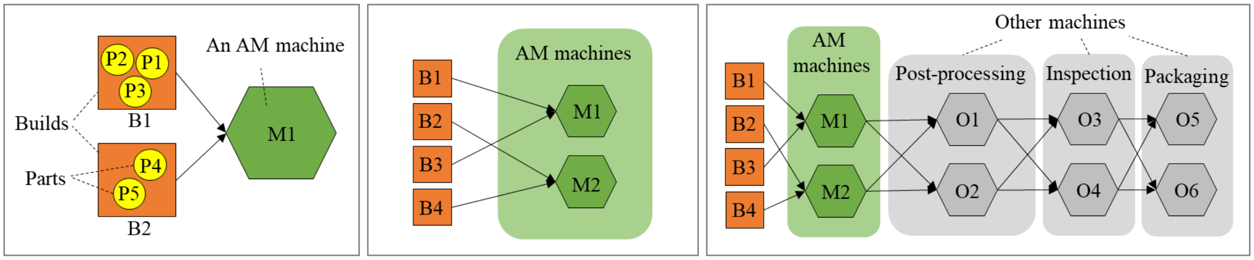
Table 2. Specific criteria for nesting and scheduling problems

	Element	Description	Values
Nesting-related tuples	N_α	Dimensionality	2D; 3D
	N_β	Rotation freedom of parts	ABC; C
	N_γ	Build volume boundness	Bounded; Unbounded
	N_δ	Set of nested parts	Full; Subset
Scheduling-related tuples	S_α	Generation methods of builds	Nested; Grouped; Created; Given
	S_β	Scheduling models	Single-machine (SM); Parallel-machine (PM); Flow-shop (FS)
	S_γ	Order property	Due-date (Du); Material (Ma); Quality (Qu)
	S_δ	Non-identical machine property	Location (Lo); Size (Si); Process parameter (Pr)



(a) Unbounded nesting (b) Subset nesting (c) Multi-build nesting

Figure 3. Nesting types: (a) unbounded; (b) subset; and (c) multi-build nesting



(a) One-stage: Single-machine (b) One-stage: Parallel-machine (c) Multistage: Flow-shop

Figure 4: Scheduling models for AM: (a) single-machine; (b) parallel-machine; and (c) flow-shop

As shown in Table 3, specific criteria are different depending on the classes. In Table 3, insignificant specific criteria are presented by X while significant ones are expressed by O. For the problems of [M/S/S] class, the scheduling-related four criteria are not significant since scheduling issues are less critical by simultaneously producing all parts of the same build. If bounded full nesting is considered, problems are often included in either [M/M/S] or [M/M/M] (M/M/iM and M/M/nM) class allowing multiple builds to produce every part in the limited size of the workspace. Moreover, the nesting-related criteria are not significant for [–/M/M] class since a nesting process packing parts to builds is not addressed in the problems. Additionally, S_δ is only significant for [M/M/M] and [–/M/M] classes that multiple machines are allowed.

When research papers are classified in Section 3, the significant specific criteria can be considered for each class. For example, [M/S/S] class has four significant specific criteria, N_α, N_β, N_γ, and N_δ, expressed by O in Table 3. As such, Table 5 for [M/S/S] class has four columns for the corresponding specific criteria. Note that all papers of [M/S/S] and [M/M/S] classes referred from this investigation are based on bounded full nesting. Therefore, N_γ and N_δ of [M/S/S] and [M/M/S] classes are not included in their classification tables in Section 3 for simplification.

Table 3. Specific criteria depending on the classes: significant (O) and insignificant (X)

	N_α	N_β	N_γ	N_δ	S_α	S_β	S_γ	S_δ
M/S/S	O	O	O	O	X	X	X	X
M/M/S	O	O	O (Bounded)	O (Full)	O	O	O	X
M/M/M (M/M/iM and M/M/nM)	O	O	O (Bounded)	O (Full)	O	O	O	O
–/M/M (–/M/iM and –/M/nM)	X	X	X	X	O	O	O	O

3. Classification and Review

In Section 3, the nesting and scheduling papers are classified using the taxonomy and criteria introduced in Section 2. An overview of the 53 papers referred to this investigation is provided in Table 4. The papers are categorized in terms of the four classes ([M/S/S], [M/M/S], [M/M/M], and [–/M/M]) and the three types (NfAM, SfAM, and NSfAM). A paper can be classified into multiple classes. For example, the paper of Kucukkoc [17] is classified into [M/M/S], [M/M/iM], and [M/M/nM] classes since the three classes are all addressed in this paper.

Table 4. The research classification depending on the classes and the problem types

	M/S/S	M/M/S	M/M/M (M/M/iM or M/M/nM)	–/M/M (–/M/iM or –/M/nM)
NfAM	[18], [64], [19], [30], [34], [65], [66], [67], [68], [69], [70], [71], [33], [72], [73], [74], [32], [75], [76], [77], [78]	[29]	[79]	N/A
NSfAM	N/A	[80]	[81], [82], [83], [39], [37], [22], [15], [21], [31], [16], [23], [35], [38]	N/A
SfAM	N/A	[84], [85], [17], [60]	[86], [17], [20], [87], [61], [88]	[89], [36], [20], [40], [56], [55], [63], [90]

3.1 [M/S/S] class

The problems of [M/S/S] class (see Table 5) usually have traditional nesting objectives such as the maximization of nesting rate [30], [72] and the minimization of maximum height [18], [32], [66]. However, except for the nesting-oriented objectives, AM-based objectives are also considered such as minimizing build time and cost [68] and improving surface quality [70].

Numerous nesting problems of [M/S/S] class address build orientation determination to maximize nesting rate. To determine the build orientation of parts, (1) *two-step* and (2) *integration* approaches are mainly proposed for a nesting problem. In the two-step approach, the build orientation of parts is determined first and then the location of parts is decided with the orientations fixed in the previous step [70]. In some cases, Rotations A and B for build orientations are considered in the first step and then Rotation C and part location are determined in the second step [30], [33], [34], [73]. Although the two-step approach usually provides less computation complexity than the integration approach, it often finds a local optimum rather than the global optimum. In the integration approach, the first and second steps are repeated or integrated to reach the global optimum. Since considering multiple parts at the same time could cause high computation complexity [32], placing parts one by one is often applied [74], [76].

[M/S/S] class often involves 3D nesting problems while other classes usually include 2D nesting problems. This is mainly because the problems of [M/S/S] class have an advantage at focusing on a more complicated nesting topic, namely 3D nesting, by excluding scheduling concerns. Note that, to minimize the surface damage caused by support structures, 2D nesting could be more preferred than 3D nesting [29], [34]. However, Zhang et al. [19] claimed that 2D nesting could be more preferable even for *Selective Laser Sintering (SLS)* not generating support structures due to heat diffusion.

Decomposition and Packing (D&P) problems for AM address decomposing an original 3D model into several pieces and then placing them in the limited build volume. Most D&P problems for AM are included in [M/S/S] class. In terms of the theoretical view, the D&P problems are similar to the C&P problems of operations research. The D&P problems of [M/S/S] class are usually based on 3D unbounded full nesting [65]–[67], [69].

It should be noted that the work of Zhang et al. [68] dealing with the build orientation determination of multiple parts is classified into unbounded full nesting in Table 5 even though part location is not considered. A feature-based approach [34] is categorized into *ABC* in N_β since part rotation is not limited to a certain axis. The paper of Jiang et al. [64] is classified into *2D* in N_α since every part is in contact with the build surface even though parts can be overlapped. The study of Hur et al. [75] proposed two objective functions depending on the number of parts. If parts are too many so that the build volume cannot include all of them, the objective function is to maximize nesting rate for subset nesting. Otherwise, the objective function is to minimize build height for full nesting.

3.2 [M/M/S] class

Table 6 shows the four papers of [M/M/S] class. The problems of this class require multiple builds and multi-build nesting as discussed in Section 2.5. As a large number of parts are addressed, the number of builds increases. In this class, builds are all processed in the same AM machine, thereby resulting in the same size of build volume for all builds. When it comes to the same size of build volume for all builds, [M/M/S] class is similar to [M/M/iM] class addressing identical multiple machines. Determining the build orientation of parts is essential not only in [M/S/S] class but also in [M/M/S] class. This is mainly because the build orientation of parts affects the number of builds as well as part location [80].

Unlike [M/S/S] class only addressing a nesting topic, [M/M/S] and [M/M/M] classes cover scheduling concerns as well as nesting issues. This results in three different characteristics from the problems of [M/S/S] class. First, the setup time is considered for each build. Therefore, reducing the number of builds is often highlighted since it affects the total process time including a setup process [17], [29]. Secondly, the priority for each part is contemplated. The priority is often represented by the due-date and tardiness of orders [60]. This affects the processing sequence of builds by producing an urgent build first with high priority parts. Lastly, multiple builds are considered as the inputs of a scheduling algorithm. Builds can be generated by a bin-packing algorithm dealing with how to place parts to multiple builds [29], [80], which is *Nested* in S_α. Otherwise, parts can be clustered into builds by the maximum constraints of builds including volume [60] and production area [17], which is *Grouped* in S_α.

AM-based scheduling problems have three main characteristics compared to traditional scheduling problems based on batch systems [17], [91]. First, while the processing time for each batch is usually fixed in the traditional scheduling problems, the build time for each build is an uncertain factor in AM-based scheduling problems [39]. This is because an AM machine allows producing different geometries for each build [60]. Secondly, unlike the traditional scheduling problems, nesting issues are often considered in AM-based scheduling problems. Therefore, decisions on the build orientations, locations, groups of parts in the nesting phase concretely affect the objectives (usually minimizing time and cost) of the scheduling phase [17]. Lastly, compared to the traditional scheduling, AM-based scheduling problems relatively consider a number and variety of customer orders. This results from the fact that AM has an advantage in producing heterogeneous parts for mass customization [12]. Usually, the number of parts per order (even one part per order) is small in AM for mass customization.

It should be noted that the paper of Kucukkoc [17] is categorized into [M/M/M] class as well as [M/M/S] class since the author addressed both classes. Although most D&P problems are based on [M/S/S] class, Oh et al. [29] firstly addressed a D&P problem based on [M/M/S] class. In Table 4, although Oh et al. [29] consider setup time for each build, this paper is classified into NfAM rather than NSfAM since their study focuses on a nesting concern.

3.3 [M/M/M] class

As well as [M/M/S] class, [M/M/M] class covers both nesting and scheduling topics. However, since multiple AM machines are considered in [M/M/M] class, it is more challenging to deal with the two topics at the same time. Therefore, depending on the aim of problems, less significant concerns are often simplified. To name a few, if scheduling issues are more focused, nesting concerns are simplified by considering only Rotation C for build orientation determination [15], [21], [37] and converting parts into simple geometries such as rectangles and cubics [16], [39]. When nesting issues are more focused, an infinite number of AM machines with the same conditions can be assumed to reduce scheduling concerns [79].

As discussed in Section 3.2, the problems of [M/M/S] class have two main scheduling issues: (1) how to cluster multiple parts into multiple builds; and (2) how to determine the processing sequence of builds. As well as the two issues, [M/M/M] class considers one more scheduling issue of (3) how to assign the builds to multiple AM machines, which is load balancing for parallel AM machines. The third issue is critical due to the risk of bottlenecks that a certain AM machine takes care of more tasks than other machines, thereby causing a long process time from a global view [22]. To address load balancing, the minimization of makespan, the longest processing time in scheduling [20], is often used as an objective function. However, the third issue can be compromised at the expense of assuming that an infinite number of AM machines are provided [79]. For the first scheduling issue, parts are often sorted based on height and due-date and then clustered into builds to minimize build time [37], [79] and tardiness [15]. In particular, height-based sorting is usually adopted in 2D nesting that allows reducing the height difference of parts within the same build volume. It should be noted that the three scheduling issues are not independent but linked to each other.

The *two-step* and *integration* approaches discussed in Section 3.1 can be similarly applied to nesting and scheduling problems. In the two-step approach, a nesting algorithm is conducted first to generate multiple builds (scheduling inputs) and then a scheduling algorithm is applied in the second step. In this approach, nesting and scheduling problems can have different objective functions [15], [21]. In the integration approach, nesting and scheduling algorithms are combined [22] or conducted iteratively [31]. Section 3.3 provides two subsections, [M/M/iM] and [M/M/nM] classes, to explain different issues between identical machines and non-identical machines.

3.3.1 [M/M/iM] class

Table 7 shows the six references of [M/M/iM] class dealing with identical AM machines. In this case, builds can be assigned to any machines due to the same conditions for every AM machine. This characteristic is often described as the high production flexibility of AM [17], [79].

As discussed in Section 3.2, [M/M/iM] class is similar to [M/M/S] class in terms of considering the same size of build volume for all builds. Therefore, a traditional bin-packing algorithm could be applied to the problems of [M/M/iM] class as well as [M/M/S] class. However, since [M/M/iM] class considers parallel AM machines, load balancing should be considered to minimize makespan [17]. Moreover, the setup time for each build should be also considered [20].

In Table 4, the work of Griffiths et al. [79] is classified into NfAM rather than NSfAM since scheduling issues are not highlighted by assuming that enough machines are available. With this assumption, two scheduling issues of determining the processing sequence of builds and assigning builds to machines can be compromised. The study of Kim [20] is categorized into [–/M/iM] class as well as [M/M/iM] class since the author addresses both classes. The author considers different materials as a condition to deal with setup time.

3.3.2 [M/M/nM] class

[M/M/nM] class (see Table 8) tends to focus on scheduling problems by simplifying nesting concerns. For example, instead of developing nesting algorithms, an external library [39] and a commercial application [38] are adopted for the nesting phase.

In the problems of [M/M/nM] class, non-identical AM machines are addressed. Although there are a variety of criteria to define the “non-identicalness” of machines, three representative properties including location (*Lo*), size (*Si*), and process parameter (*Pr*) are adopted in our review. The non-identical machine properties (S_δ) can be considered as constraints for machine selection. For example, if AM machines are located in physically remote places, it is more likely to choose certain machines with close distances to minimize logistics costs [56]. Furthermore, order properties (S_γ) including due-date (*Du*), material (*Ma*), and quality (*Qu*), can be also considered to choose AM machines. If a part has a high priority based on due-date, it can be assigned to a certain AM machine with a high production rate [17], [39].

In some cases, builds are generated before a nesting process [37], [38]. Therefore, assigning builds to machines is not required after a nesting process. Wang et al. [37] proposed a method that parts are grouped for their target AM machines by considering the required material before a nesting approach. Then, grouped parts are placed based on a nesting approach. Since target machines where builds are assigned are already determined, an assignment step after nesting is not needed.

3.4 [–/M/M] class

The papers of [–/M/iM] and [–/M/nM] classes are listed in the same table (see Table 9). Some AM-based scheduling problems assume one part per build [36], [40], [56], which results in that a nesting process is not needed. As discussed in Section 2.4, such studies are classified into [–/M/M] class by considering a part as a build.

In [–/M/M] class, builds are generated in either *Created* [36], [55], [56] or *Given* [20], [40], [63], [90] method. Herein, *Nested* cannot be considered since there is no nesting process in the [–/M/M] problems. Therefore, the problems of [–/M/M] class can more focus on scheduling concerns rather than other classes. However, if the build time and cost are *Given,* the characteristic of AM problems that build information is uncertain could be weakened in scheduling problems. The work of Chen [36] is classified into *Created* in S_α since the build time of a part is generated depending on a distribution function even if the geometry and orientation of parts are not considered.

Kim and Lee [63] firstly addressed a scheduling problem for the flow-shop model based on AM. The authors extended their research in the follow-up studies [20], [40]. Their studies assume that identical products are produced by a flow-shop including AM machines and each product is composed of two sub-assemblies. Therefore, an assembly process is followed up after a build process. To minimize makespan, Kim [20] compared two cases of parallel production: (1) multiple parts per build ([M/M/iM] class); and (2) a part per build ([–/M/iM] class). However, their studies dealing with *Given* parts are limited in considering a large number of heterogeneous parts for the on-demand AM.

Table 5. The references of [M/S/S] class

Ref.	AM process	Objective	Method	N_α	N_β	N_γ	N_δ
[18]	PBF	Min. build height	GA; heuristic	3D	ABC	Unbounded	Full
[64]	ME	Max. overlapped volume	Heuristic	2D	ABC	Unbounded	Full
[19]	ME	Min. overlap	GA	2D	ABC	Bounded	Full
[30]	VP	Max. nesting rate	GA	2D	ABC	Bounded	Subset
[34]	ME	Min. total overlap area	GA	2D	ABC	Bounded	Full
[65]	ME	Min. build height	Heuristic	3D	ABC	Unbounded	Full
[66]	BJ; ME	Min. build height and vertical gap	Heuristic	3D	ABC	Unbounded	Full
[67]	ME	Min. master bounding box	Heuristic	3D	ABC	Unbounded	Full
[68]	VP	Min. total build time and cost; max. surface quality	GA	2D	ABC	Unbounded	Full
[69]	VP; ME	Min. master bounding box and support volume	TS	3D	ABC	Unbounded	Full
[70]	PBF; ME	Min. build height, surface roughness, support volume	GA; heuristic	3D	ABC	Unbounded	Full
[71]	VP	Max. nesting rate	GA	2D	C	Bounded	Subset
[33]	N/A	Max. productivity indicator	GA	3D	ABC	Bounded	Full
[72]	PBF	Max. nesting rate	GA	2D; 3D	ABC	Unbounded	Full
[73]	VP	Max. nesting rate	GA	2D	ABC	Bounded	Subset
[74]	N/A	Min. the point moment metric	SA; heuristic	3D	ABC	Bounded	Subset
[32]	VP	Min. build height	SA	3D	ABC	Unbounded	Full
[75]	PBF	Min. build height if full nesting; max. nesting rate if subset nesting	GA	3D	ABC	Bounded	Subset; Full
[76]	PBF	Min. point moment metric	SA	3D	ABC	Bounded	Subset
[77]	PBF	Min. distances of parts from the global origin and the amount of intersection between parts	GA	3D	ABC	Bounded	Full
[78]	VP	Max. nesting rate	GA	2D; 3D	C	Bounded	Subset

Table 6. The references of [M/M/S] class

Ref.	AM process	Objective	Method	N_α	N_β	S_α	S_β	S_γ
[84]	N/A	Min time and cost	TS	N/A	N/A	Grouped	SM	Du
[85]	PBF	Min. total time	Mathematical model	N/A	N/A	Grouped	SM	N/A
[17]	PBF	Min. makespan	Mathematical model	N/A	N/A	Grouped	SM	N/A
[80]	VP	Min. makespan	Commercial S/W for nesting; heuristic for scheduling	2D	ABC	Nested	SM	N/A
[16]	VP	Min. makespan	GA	2D	ABC	Nested	SM	N/A
[60]	PBF	Min. time and cost	GA	N/A	N/A	Grouped	SM	Du

Table 7. The references of [M/M/iM] class

Ref.	AM process	Objective	Method	N_α	N_β	S_α	S_β	S_γ
[81]	ME	Prediction of manufacturing time	Machine learning	2D;3D	N/A	Nested	PM	N/A
[82]	N/A	Min. lateness	GA; heuristic	3D	ABC	Nested	FS	Du
[17]	PBF	Min. makespan	Mathematical model	N/A	N/A	Grouped	PM	N/A
[22]	VP	Min. makespan	Heuristic for nesting; GA for scheduling	2D	C	Nested	PM	N/A
[15]	PBF	Min. total tardiness	Mathematical model	2D	C	Nested	PM	Du
[31]	ME	Max. productivity indicator	Heuristic; GA	2D	C	Nested	PM	N/A
[79]	PBF	Min. total build cost	TS	2D	ABC	Nested	PM	N/A
[20]	ME	Min. makespan	Heuristic	N/A	N/A	Given	PM	Ma

Table 8. The references of [M/M/nM] class

Ref.	AM process	Objective	Method	N_α	N_β	S_α	S_β	S_γ	S_δ
[86]	PBF	Min. makespan	Heuristic	N/A	N/A	Grouped	PM	N/A	Si; Lo
[83]	PBF	Max. profit	Heuristic	N/A	N/A	Nested	PM	Du; Ma	Si; Pr
[17]	PBF	Min. makespan	Mathematical model	N/A	N/A	Grouped	PM	N/A	Si; Pr
[39]	PBF	Max. profit	S/W library for nesting; heuristic for scheduling	2D	C	Nested	PM	Du; Ma	Si; Pr
[37]	ME	Max. nesting rate	Heuristic	2D	C	Nested	PM	Du; Ma	N/A
[21]	PBF	Max. total covered area if nesting; min. makespan if scheduling	Heuristic for nesting; SA, TS, Hill climbing for scheduling	2D	C	Nested	PM	Du; Ma	Si
[87]	PBF	Min. max lateness	GA	N/A	N/A	Grouped	PM	Du	Si; Pr
[16]	VP	Min. makespan	Heuristic	2D	ABC	Nested	PM	N/A	Si
[56]	ME; VP	Min. production time	Heuristic	2D	N/A	Nested	PM	Ma; Qu	Si; Lo
[61]	PBF	Min. production cost	Mathematical model; heuristic	N/A	N/A	Grouped	PM	N/A	Si; Pr
[35]	ME	Min. total cost; max load balance; min. total tardiness; min unprinted parts	Mathematical model	N/A	N/A	Grouped	PM	Du	Si; Pr
[88]	PBF	Max. resource utilization	Heuristic	N/A	N/A	Grouped	PM	Du	Si; Pr
[38]	PBF	Min. cost	Commercial S/W for nesting; mathematical model for scheduling	3D	ABC	Grouped	PM	Du	Si

Table 9. The references of [-/M/M] class (-/M/iM and -/M/nM)

Ref.	Problem class	AM process	Objective	Method	S_α	S_β	S_γ	S_δ
[89]	-/M/nM	N/A	Min. makespan	Mathematical model	Given	PM	N/A	Lo
[36]	-/M/nM	N/A	Min. makespan	Mathematical model	Created	PM	N/A	Lo
[20]	-/M/iM	ME	Min. makespan	Heuristic	Given	PM	Ma	N/A
[40]	-/M/iM	ME	Min. cycle time	Mathematical model	Given	FS	N/A	N/A
[56]	-/M/nM	N/A	Min. delivery time	GA	Created	PM	Du; Ma; Qu	Lo; Si; Pr
[55]	-/M/iM	N/A	Min. makespan	GA	Created	PM	N/A	N/A
[63]	-/M/iM	ME	Min. cycle time	Mathematical model	Given	FS	N/A	N/A
[90]	-/M/nM	N/A	Min. completion time	GA	Given	PM	Ma; Qu	Lo; Si; Pr

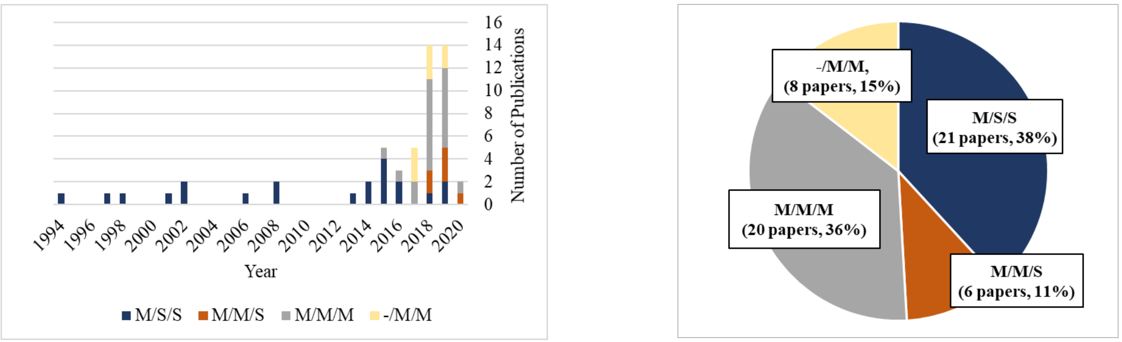
4. Opportunities for Future Research

Section 4 provides future research topics (Section 4.2) from analyzing the trends of 53 papers in Table 4 (Section 4.1). In Section 4.2, we suggest four future research directions: taxonomy extension, scheduling model extension for AM, advanced AM machines, and order processing.

4.1.1 Trend analysis of the referred papers

Figure 5 summarizes the literature by publication year and proportion of papers contains in each problem class ([M/S/S], [M/M/S], [M/M/M] and [–/M/M]). In Figures 5-(a) and (b), the total number of papers is 55 since some papers are classified into multiple categories.

As shown in Figure 5-(a), [M/S/S] class has been studied consistently since 1995 and all of them are NfAM problems. This represents that AM researchers have traditionally studied on how to pack multiple parts into the limited build volume. As shown in Figure 5-(b), the papers of [M/S/S] class account for 38 % in our investigation. Earlier [M/S/S] studies did not much care about AM-specific characteristics such as build time and surface roughness [74], [77]. While AM is mentioned, their studies were closed to theoretical nesting problems. Compared to [M/S/S] class usually dealing with NfAM type, scheduling issues have recently been studied for AM. In 2015, a scheduling topic was firstly combined with a nesting approach for AM [38]. In 2016, the first SfAM paper was published [88]. Since then, the number of scheduling-related papers has dramatically increased. The trend change indicates that the research scope of AM is expanded from a single build within a single machine into multiple builds covering multiple machines. As such, some papers deal with multiple objective functions to deal with both nesting and scheduling problems [15], [21].



(a) Publication year depending on the classes (b) Publication ratio depending on the classes

Figure 5. Publication year and ratio

4.2 Future research directions

In this paper, we define the research scope dealing with the three levels (*Part*, *Build*, and *AM Machine*) to cover both nesting and scheduling problems. However, the proposed taxonomy hierarchy based on the three levels can be further extended to a fourth, *Enterprise* level. We exclude the Enterprise level in this paper since it is too high level to include nesting issues. In future research, the relationship between AM Machine and Enterprise levels can be more specifically represented. A variety of logistics and inventory issues including supply chain management [92], [93] and spare parts management [94]–[96] can be discussed for different enterprises based on partially or entirely AM. For this research direction, AM characteristics should be emphasized to distinguish from the traditional logistics and inventory topics.

Most of the scheduling studies for AM are based on the single and parallel machine models. This shows an opportunity to extend the research boundary into the flow-shop and job-shop models, which means that the scope is broadened from the one-stage model to the multi-stage model. Although a few papers based on the flow-shop model are introduced in the current investigation [40], [63], various scheduling issues for AM can be considered in terms of complex production systems such as hybrid manufacturing [97]–[99] and assembly kitting [100].

In this review paper, we usually focused on simple AM machines with a single nozzle and a single laser in a single-step process [24]. This is mainly because most AM papers for nesting and scheduling problems are based on the simple AM machines. However, the investigation scope could be extended for specialized AM machines supporting multi-material [27], multi-laser [101], multi-extruder [102] and multi-axis [103]. Advanced AM machines that are capable of a multi-step process [24] can reduce the complexity of operational management. Most nesting and scheduling studies based on general AM machines simply assume that parts within the same build volume have identical process parameters. This is one of the main reasons that some parts are grouped into a build for sharing the same process parameters. However, some AM machines can produce a build including parts with different process parameters (colors and materials).

Order processing in cloud manufacturing for AM is another future scheduling research topic. For cloud manufacturing, Liu et al. [28] extended the scheduling concept by addressing customer orders. In this service model, order processing consists of three main topics: (1) order acceptance/rejection; (2) order decomposition; and (3) order composition. The first topic is a decision-making problem to address whether customer orders are acceptable. This problem type can be complicated when nesting and scheduling issues are considered at the same time [39]. The second and third topics deal with how to generate tasks (or builds) from customer orders. For the second topic, orders requesting small volume production (even one model per order) can be combined into builds by a nesting approach. This is because AM allows batch processing for the small size of parts. The last topic can be addressed if a single order requests to produce a considerable number of parts (large volume production per order). In this case, the single order should be decomposed into small tasks in which each task is acceptable for a single build cycle.

5. Conclusion

Nesting and scheduling problems are related in AM. However, nesting and scheduling topics have been studied separately for traditional manufacturing. To overcome the limitation of existing taxonomies that focus on either nesting or scheduling problems, this paper proposes a comprehensive taxonomy.

The proposed taxonomy consists of three dimensions (Part, Build, and AM Machine), resulting in six classes: [M/S/S], [M/M/S], [M/M/iM], [M/M/nM], [–/M/iM] and [–/M/nM]. By comprehensively covering both nesting and scheduling topics based on AM, this taxonomy complements the usual NfAM, SfAM and NSfAM classification and provides another perspective to help identify and organize the problems. Furthermore, eight supplementary criteria are suggested to further refine the organization of the research papers within these classes.

In this investigation, we surveyed and classified 53 technical papers into our six proposed classes as well as the traditional classes (NfAM, SfAM, and NSfAM). Then, critical issues are discussed in terms of the six classes. Since [M/S/S] class only includes the problems of NfAM type, these problems usually cause nesting-oriented issues such as build orientation determination. [M/M/S], [M/M/iM] and [M/M/nM] classes cover both nesting and scheduling topics that are categorized into any of NfAM, SfAM, and NSfAM types. The problems of [M/M/nM] class tends to simplify nesting issues and to focus on scheduling issues. The references of [–/M/iM] and [–/M/nM] classes are all included in SfAM type, thereby usually addressing scheduling-oriented issues. It should be noted that the main contributions of referred papers are simply introduced in the manuscript since we had to consider a broad range and number of issues and papers.

This investigation shows how research trends have been changed. While nesting-oriented problems for AM have consistently been studied, scheduling-oriented problems for AM have recently been highlighted. This means that the research scope of AM is expanded from a single build withing a single machine into multiple builds covering multiple machines. Furthermore, we provide four future research directions: (1) the extension of the proposed taxonomy; (2) flow-shop and job-shop scheduling models for AM; (3) nesting and scheduling problems for specialized AM machines; and (4) order processing for cloud-based AM.

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Disclaimer

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