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Review Article

Generation and Enforcement of Process-Driven Manufacturability Constraints: A Survey of Methods and Perspectives for Product Design

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Abstract

Design-for-manufacturing (DFM) concepts have traditionally focused on design simplification; this is highly effective for relatively simple, mass-produced products, but tends to be too restrictive for more complex designs. Effort in recent decades has focused on creating methods for generating and imposing specific, process-derived technical manufacturability constraints for some common problems. This paper presents an overview of the problem and its design implications, a discussion of the nature of the manufacturability constraints, and a survey of the existing approaches and methods for generating/enforcing the minimally-restrictive manufacturability constraints within several design domains. Five major design *perspectives* or *viewpoints* were included in the survey, including the system design (top-down), product/component design (bottom-up), the manufacturing process-dominant case (product/component design under a specific process), the part-redesign perspective, and sustainability perspective. Manufacturability constraints within four design *levels* or *scales* were explored as well, ranging from macro-scale to sub-micro-scale design. Very little previous work was found in many areas, revealing several gaps in the literature. What is clearly needed is a more general, design-method-independent approach to collecting and enforcing manufacturability constraints.

Keywords: Mechanical design, problem formulation, constraint mapping, design for manufacturing, manufacturing processes

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1. Introduction

1.1. Problem Overview

Manufacturing is a fundamental part of the lifecycle of every product, one that is often overlooked in the early phases of design formulation and requirements definition. It is common for the process selection to be done after some level of design maturity is attained, helping to speed up time to market but adding risk [1–3]. If there is a mismatch between the final design and available manufacturing capabilities, it may need to be sent back for design modifications [4–7]; at a minimum, this wastes time and resources and may result in a design that is inferior to one that was intended once adjustments are made for manufacturability. If the final product is relatively simple or derived from a tried-and-true basic design that was previously developed, the manufacturing is usually very straight-forward and this risk is low. However, for more complex designs (such as those created using algorithms, e.g., topology optimization or generative design), it is possible for final designs to be completely unmanufacturable with any of the available methods [8–10]. In the worst case, the design process may need to be reversed several steps or started over to incorporate the new lessons learned by the design team during an unsuccessful manufacturing attempt (Figure 1). This is not dependent on any particular lifecycle design method [1, 5, 8] and could be applicable for a linear model (Figure 1) as well as agile [11], evolutionary [12, 13], and iterative models [14], as well as others.

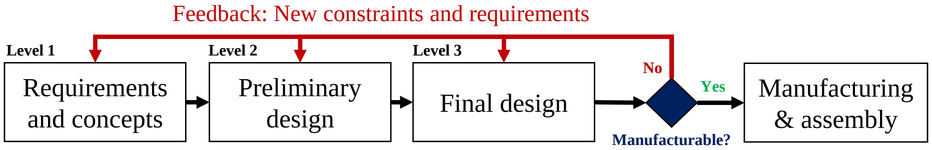
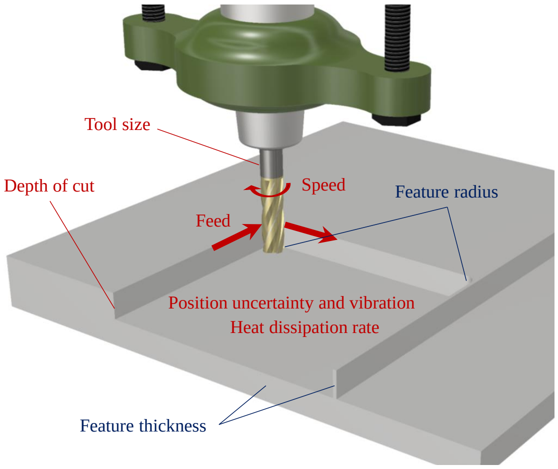


Figure 1: *Manufacturability check and potential loop-back in example linear design process when the final product or part is mismatched with any available manufacturing process.*

1.2. Classic Design and Manufacturing

To address this in part, design-for-manufacturing (DFM) (sometimes known as concurrent engineering or concurrent design) principles have been developed in recent decades [8, 15–17]. As a technical approach, DFM has commonly referred to a set of design rules in which the design is simplified as much as possible to reduce the risk of mismatch with a selected or generic manufacturing process. There traditionally have been a wide variety of these rules which are mainly focused on geometry simplification, low-cost material use, feature and part standardization, liberalization of tolerances, and collecting practical knowledge to guide design decisions [7, 8, 18, 19]. The most important characteristic of this approach is that it is process- and material-independent and typically very generic [8, 15, 20]. This version of DFM is especially effective in a mass-production environment with simple or established designs, but tends to be overly-restrictive for specialized or complex designs and results in designs favoring simplicity [8, 21, 22]. In a mass-customization paradigm, such as the one emerging in recent years [23–25], it is vital for designers to fully utilize the design space and optimize a given design as much as possible [26–29]. This is especially important when producing small-batch, customized, high-value parts such as those needed for aircraft and medical devices. Therefore, a DFM technique which would restrict the design space only enough to guarantee manufacturability is needed. To ensure the minimum restriction on the design space, it is necessary to replace the general design rules with well-defined constraints driven directly by the characteristics of the manufacturing processes or methods selected. The domains of applicability for the three major species of manufacturing processes (subtractive, additive, and formative) are different and often complementary [30–33].



Constraint	**Type**	**Upper limit**	**Lower limit**
Tool size	Fixed value or discrete	Tool set	Tool set
Depth of cut	Continuous function	Max depth of cut	Min depth of cut
Feed	Continuous function	Max feed	Min feed
Speed	Continuous function	Max feed	Min feed
Position error/vibration	Fixed or random variable	Max acceptable	$\varepsilon = 0$
Heat dissipation rate	Fixed or random variable	Determined by material choice	Determined by material choice
Feature thickness	Boundary constraint	No upper limit	Min thickness
Feature radius	Boundary constraint	No upper limit	Tool size

Figure 2: *Example of manufacturing and manufacturability constraints for a machined aluminum component, with constraint type and source of limits demonstrated*

1.3. Manufacturability and Design Constraints

Any manufacturing process can be said to be subject to a set of natural *manufacturing constraints* which affect its use domain and which must be considered in the design process. In addition, it is necessary to consider *manufacturability constraints*, which are on the design or product itself and are in response to the manufacturing constraints. For example, a machined aluminum part design (Figure 2) would be constrained by the tool size, speed, and feed of the mill [30], the level of position error/vibration, and the heat dissipation rate of the selected material (manufacturing constraints). Driven by these constraints, a minimum feature size is necessary to ensure that the part could dissipate the heat and force of machining without warping [34, 35] (manufacturability constraint); in addition, the minimum size of corner radii is also determined by tool choice. The design "ownership" in each domain (which determine the most appropriate decision makers) is different, with production engineers best understanding the manufacturing constraints. This requires excellent communication between the production team and the designers, a task that is not always performed effectively [3, 8, 10, 15, 16]. More general mapping approaches have been suggested for translating manufacturing constraints directly into manufacturability constraints [5, 9, 31, 36–38], but this is an immature area and needs much additional research.

1.4. Article Structure and Research Questions

This article describes a survey which was conducted on the existing manufacturing and design literature to find and articulate the state-of-the-art on the generation and use of manufacturability constraints in product design. After collecting and organizing information on manufacturing constraints for different processes and process families, two major research questions guided the review on manufacturability constraints:

1. How have distinct design perspectives or viewpoints (e.g., from the system perspective, from the component perspective, etc.) influenced the generation and application of manufacturability constraints?

2. How have manufacturability constraints been generated and enforced in different levels or scales of design, specifically the standard macro-, meso-, micro-, and sub-micro-scales?

For each question, the literature collected for this review was scanned for the clear design perspectives and scales and the presentation of the survey was thus organized. The survey design and approach are summarized in Section 2, with the full details given in the Appendix, while Section 3 examines manufacturing processes, process families, and manufacturing constraints. The various design perspectives are discussed in Section 4, while Section 5 focuses on the design scales or levels of analysis. Finally, Section 6 presents some conclusions and closing remarks.

1.5. Novelty and Limitations

This work is the only major review to date (after an extensive search by the authors) focusing specifically on manufacturability constraints, design problem formulation under manufacturing requirements, and including all manufacturing process types and families (and therefore potentially all materials). Four other major contributions were identified by the authors:

1. This work examined the collected information within various common design perspectives and levels. The found literature was compiled and discussed according to these categorizations, making practical applications of the information within specific domains easier.

2. The survey went far beyond classic DFM to include both DFM principles and specific manufacturability constraints for particular processes and process families.

3. The information collected in this survey clearly shows many holes in the design/manufacturing literature and demonstrates the need for a general, automated method for collecting and enforcing manufacturability constraints.

4. In addition to providing rigorous definitions, this work was presented so that it is useful for practicing engineers and designers who are not experts in manufacturing.

For the design perspectives, identified areas were top-down (system and assembly focused) design, bottom-up (component or single product focused) design, bottom-up design when a specific manufacturing process was specified in stakeholder requirements, part re-design, and sustainability/green product design. For the part re-design area, only cases where parts were re-designed to deal with manufacturability problems were included. A large amount of literature exists on the re-design of parts to take advantage of additive manufacturing (AM) processes but not to address problems in the original design; this was excluded from the review as it was off-topic from the selected focus and is extensive enough for its own survey. It should also be noted that the discussion related to sustainability was limited to impacts related to manufacturing processes and product design choices. Business development, policies, supply and distribution logistics, or other complex socio-ecological perspectives were not studied as they are beyond the scope of the presented work.

2. Survey Design and Approach

This section summarizes the approach for collecting and screening papers for this survey; the full detailed overview of the keywords, searched journals and databases, and exclusion criteria are presented in the Appendix. The research questions for this review were described in Section 1. To begin the review, a set of potentially relevant keywords were compiled by the authors, which were then used to search for literature in Google Scholar, Scopus, and a list of major manufacturing and design journals and conference proceedings. The reference section for each paper was reviewed for papers missed in the original search. A total of 185 potentially useful papers were found based on keywords, titles, and abstracts. After applying screening criteria (such as excluding earlier conference versions of journal papers) and more careful review for relevance, 52 papers were removed from the set. This left a final set of 134 references to be included in this survey. An additional 108 papers were also found to support the review, such as those describing design needs, manufacturing processes, and similar things not directly related to the review topic but for which discussion was needed.

3. Processes and Manufacturing Constraints

Most standard (non-hybrid) manufacturing processes fall into one of three major families, namely *subtractive*, *additive*, and *formative* [30]. There are numerous finishing, assembly, and validation processes as well, but this survey focused on the material processing aspects of manufacturing, and so these were not examined. Table 1 shows some of the most commonly used processes in each family and an example subset of manufacturing constraints for each one. These were taken from the manufacturing literature and are not a complete set of the possible constraints that can be encountered during design and process selection. Therefore, it is vital for the designers to understand the processes very well when using these; generally, this takes the form of expert intuition but it could also come from rigorous process models and design catalogs for specific processes.

3.1. Overview of Processes and Families

Subtractive manufacturing (SM) processes form geometry by cutting material away from a block or billet which is larger than the desired final shape [30, 87–89]. SM requires little custom tooling besides fixtures and jigs [90], but the design geometry is restricted to that which can be reached by standardized cutting tools; the features must also be large enough resist the machining force and allow sufficient heat transfer since the tools produce friction heat [34, 35, 91]. For appropriate designs, SM is a very cheap, repeatable, and efficient manufacturing approach; it can be very wasteful, however, due to the large amount of material cut off in processing [92] in many cases. On the other hand, additive manufacturing (AM) builds up the desired geometry in layers, allowing great design freedom and highly complex parts [93]. The raw material can take many forms, as long as it can be layered and fused onto a surface in some fashion [94, 95]. Ideally, the process generates very little waste but most designs require a fixed build surface and support material [96]. AM requires almost no custom tooling and is generally complexity-agnostic in terms of material and production cost. However, it can be extremely slow and expensive in some cases [93, 97, 98]. Finally, formative manufacturing (FM) has the largest diversity of processes, as the only requirement to be a formative process is that material needs to be shaped or formed into the final part, usually keeping the same volume as the starting material (or producing easily reusable waste). The raw material may be a cold billet, molten metal, powder, resin, or one of many other options. As with AM, FM produces little to no waste; however, it requires a large amount of custom tooling to produce parts, and the geometry is restricted to the shape and quality of the molds and other tooling [30, 89, 99–102].

Table 1: *Common subtractive, additive, and formative manufacturing processes and some of the common manufacturing constraints discussed in the manufacturing literature. Blank cells indicate that the constraint generally does not apply to a specific process. In the case of AM processes, the tool/work feed refers to the raw material deposition method. Figure 2 gives an example of how these constraints appear in practice for a milling process.*

		Common Manufacturing Constraints																
	Common Processes	Cutting speed	Tool size (Standard)	Depth of cut	Tool/work feed	Feature access	Specialized jigs needed	Heat dissipation	Work area size	Residual stresses	Anisotropy from process	Support material	Post-processing	Limited part size	Specialized tooling	Poor raw tolerances	Vibration/position error	**Refs**
Subtractive	Turning/Facing	🟥	🟥	🟥	🟥	🟥		🟥						🟥			🟥	[39, 40]
	Milling	🟥	🟥	🟥	🟥	🟥	🟥	🟥									🟥	[41, 42]
	Drilling/reaming	🟥	🟥	🟥	🟥	🟥	🟥	🟥									🟥	[43, 44]
	Planing	🟥	🟥	🟥	🟥	🟥		🟥						🟥			🟥	[45, 46]
	Broaching	🟥	🟥	🟥	🟥	🟥		🟥						🟥			🟥	[47, 48]
	Grinding/polishing	🟥	🟥	🟥	🟥	🟥		🟥			🟥						🟥	[49, 50]
	Sawing	🟥	🟥	🟥	🟥								🟥			🟥	🟥	[51, 52]
	Hobbing	🟥	🟥	🟥	🟥	🟥	🟥				🟥		🟥	🟥	🟥		🟥	[53, 54]
	Punching/blanking	🟥	🟥	🟥	🟥	🟥	🟥							🟥	🟥	🟥		[55, 56]
Additive	Powder bed fusion				🟦			🟦	🟦	🟦	🟦	🟦	🟦	🟦		🟦		[57, 58]
	Material extrusion		🟦		🟦			🟦	🟦	🟦	🟦	🟦	🟦	🟦		🟦	🟦	[59, 60]
	Vat photopolymerization				🟦				🟦	🟦	🟦	🟦	🟦	🟦				[61, 62]
	Material jetting				🟦				🟦	🟦	🟦	🟦	🟦	🟦			🟦	[63, 64]
	Binder jetting				🟦				🟦		🟦	🟦	🟦	🟦		🟦	🟦	[65, 66]
	DED/LENS				🟦		🟦	🟦	🟦	🟦	🟦	🟦	🟦			🟦	🟦	[67, 68]
	Sheet lamination				🟦	🟦	🟦		🟦		🟦	🟦	🟦	🟦				[69, 70]
Formative	Forging					⬛	⬛	⬛	⬛	⬛	⬛		⬛			⬛	⬛	[71, 72]
	Sand casting					⬛		⬛	⬛	⬛	⬛		⬛		⬛	⬛		[73, 74]
	Injection molding					⬛		⬛	⬛	⬛			⬛	⬛	⬛			[75, 76]
	Investment casting					⬛		⬛	⬛	⬛			⬛	⬛	⬛			[77, 78]
	Metal forming		⬛		⬛	⬛	⬛	⬛	⬛	⬛	⬛		⬛		⬛	⬛	⬛	[79, 80]
	Blow molding					⬛		⬛		⬛			⬛	⬛	⬛			[81, 82]
	Die casting				⬛	⬛		⬛	⬛	⬛	⬛		⬛	⬛	⬛	⬛		[83, 84]
	Powder metallurgy				⬛			⬛	⬛	⬛		⬛	⬛	⬛	⬛	⬛		[85, 86]

3.2. Manufacturing Constraints: Process-Limited Design Complexity

In general, SM processes tend to have the most restriction on the types of part features that can be created due to the essential requirement that cutting tools be able to reach all of the part surfaces from some force point (commonly a rotating spindle) [103–105]. AM, by definition, does not have tooling-related complexity restrictions, but there are some restrictions due to support material removal [106, 107], natural material anisotropy [108, 109], and process mechanics [93, 94]; however, the possible design complexity is very high for most of the AM processes [93, 94, 110]. Conversely, FM is almost entirely dependent on the tooling used and is limited to the tooling complexity. In the most common case, the tooling (molds, forging tools, and similar) must be made using some SM process, which limits its complexity to that which can be cut or machined [30, 99–102]. However, some FM processes can use free-form or shell molds (for example, investment casting) which strongly enhances the possible part complexity [89, 111–113].

3.3. Manufacturing Constraints: Material Selection

Of the three major domains, AM has the widest range of available materials when all of the major families are considered; the various AM processes can use almost any material which can somehow be applied in a layer and fused with a previous layer [93, 94, 114]. AM materials are most commonly in the form of filament, resin, or powder, but may be as diverse as water (ice prototyping [115]) or rolled metal sheets (ultrasonic consolidation [116]). In general, SM materials are limited to those which can easily be cut with a tool and can tolerate the associated heat load, usually ductile metals and hard polymers [30, 89]. On the other hand, FM materials are limited to those that can be stably melted or cold-formed to conform with some tooling [30, 99, 101]. This is less restrictive than SM, being able to process various bulk and molten materials, resins, and metal powders, but less free than AM because of the dependence on tooling.

3.4. Manufacturing Constraints: Production System Considerations

Due to the need only for standard clamps and fixtures [30, 89, 90] for single parts, SM tends to be able to produce one-off parts relatively cheaply compared to AM and FM. However, it can be more expensive to mass-produce parts using SM because of the need for the special fixtures, jigs, and higher quality cutting tools than needed for one-off parts [30, 89]. The cost for one-off AM parts is high due to the expensive nature of the processing equipment and materials, as well as the generally slow processing speed; unlike SM, AM can be relatively cheaper to perform mass production for some (not all) complex designs since the manufacturing time and cost is mostly dependent on total part volume and not complexity [94, 117]. The supply chain for AM, within the available set of processes and materials, is also often more efficient and less prone to blockages [93, 94]. Finally, FM is very expensive for single parts and very cheap for mass production, making it ideal for many products. The reason for the high up-front cost is the tooling initial cost, but this goes down quickly as the tool is used more [30, 89]; the raw materials for FM are generally much cheaper than those for SM and AM (since they will be formed or melted during processing, high quality finish and precision in the materials is usually not necessary), the supply chain is very efficient, and one good set of tooling may last for hundreds of thousands of parts [30, 101, 102].

4. Manufacturability Constraints: Design Perspectives

In the preceding section, the three major classes of manufacturing processes and their common constraints were explored. Careful consideration of these constraints and their potential impact on design allows the development of customized DFM approaches for specific problems; this, in turn, allows the designer to restrict the available design space just enough to ensure manufacturability. This section examines the various specific DFM methodologies developed within five essential design perspectives in which DFM has been applied effectively. These are (1) the system design (top-down) perspective, (2) the product design (bottom-up) perspective, (3) the case where a specific manufacturing process is required, (4) the part-redesign perspective, and (5) the sustainability/green manufacturing perspective.

4.1. System Design (Top-Down) Perspective

In the system design (top-down) design perspective, the goal is to consider the construction of a system or subsystem (including interfaces) and is less concerned with the optimal design of individual parts; while optimization of each part is important, it is more important in top-down design for each part of the system to be optimal relative to overall system utility [2, 6, 118, 119]. In terms of practical manufacturability constraints, the focus is generally to make the manufacturing process selection such that the parts are manufacturable in an efficient way, and such that the materials and tolerances are compatible. The business case for considering a DFM or other constraint technique is easy to make, as it prevents re-design and resulting delays, as well as ensuring the the possible design space is as large as possible [5, 120–122]. The most obvious application of within this domain is the improvement of any general lifecycle design technique, such as those proposed by NASA [1], INCOSE [118], Pahl *et al.* [6], and Blanchard and Fabrycky [2]. Within such a design engine, more general DFM approaches usually work the best. This allows easier application of classic DFM principles during the design process with a low risk of mis-match with the set of available manufacturing processes [8, 16]. While the general engine does not necessarily need customized DFM methods (especially if the design is very simple), when the lifecycle design approach is applied to a particular domain, the use of minimal-DFM can be very valuable.

Figure 3 shows a version of the NASA systems engineering engine [1], where the main phases affected by manufacturing decisions are highlighted. It can be assumed that little manufacturing knowledge is certainly needed in the conceptual design phase (Pre-Phase A) but it will be needed (in any design scenerio) in the final design and fabrication (Phase C). When DFM is used (especially when defining and imposing manufacturability constraints), Phase A (technology development) and Phase B (preliminary design) will also be heavily affected. In fact, if a proper DFM process is followed in Phase A and Phase B, the risk to

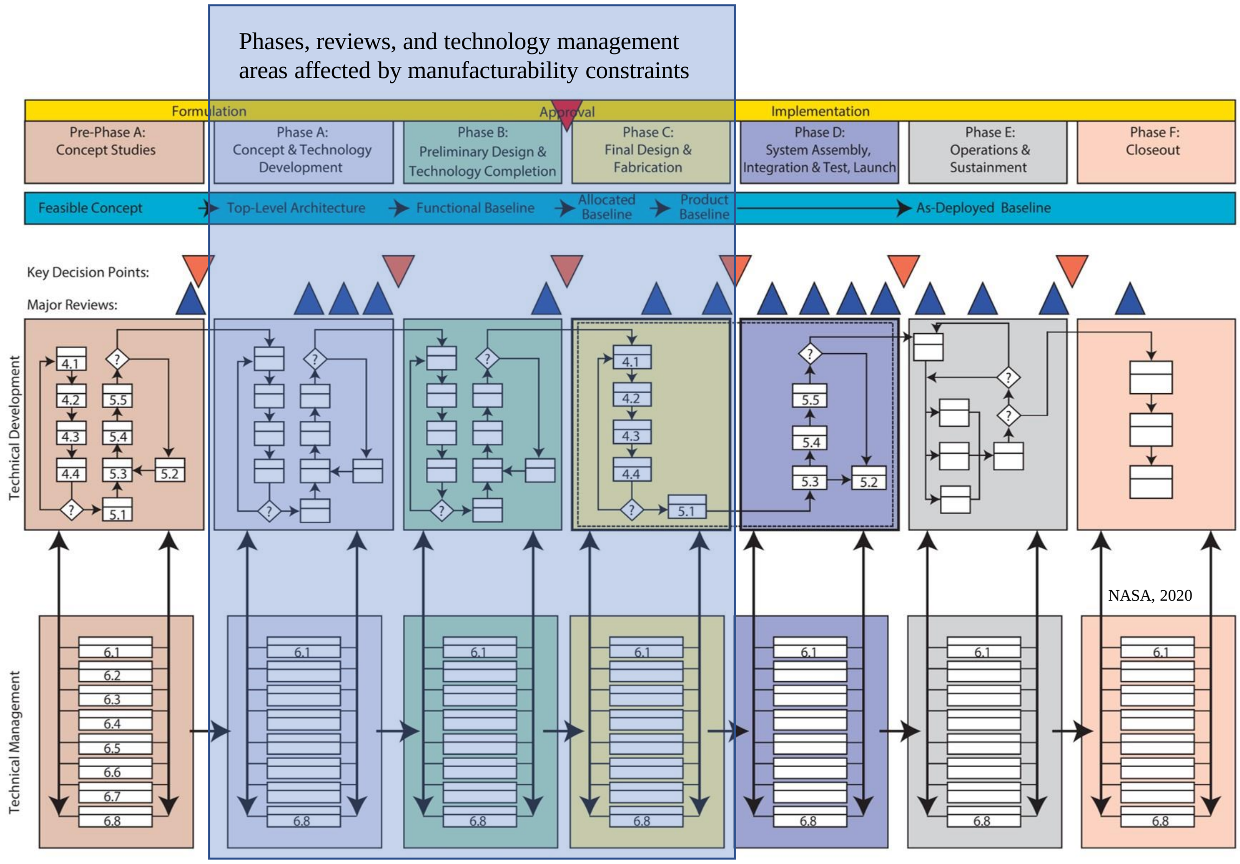


Figure 3: *Example NASA systems engineering engine [1], demonstrating milestones, design reviews, and technical development and management phases. Highlighted areas mainly affected by manufacturability considerations. (Image from a US government document and not subject to copyright in the United States.)*

Phase C could be greatly reduced [1, 6, 8, 118]. This systems engineering model could be used for relatively simple systems and assemblies and has been used successfully for large NASA programs.

This value can be especially apparent in previous work done on aircraft design. Generally, aircraft parts have very tight tolerances, need to be very lightweight, and need to be highly consistent, which dramatically limits the available manufacturing processes for these parts [120, 121, 123]. The set-based concurrent design technique proposed by Vallhagen et al. [123] uses a type of custom DFM technique to eliminate clearly infeasible manufacturing processes early in the design and allows the accommodation of process constraints at several points in the lifecycle. A similar approach focused on ensuring that all of the parts have compatible tolerances and that the various system interfaces are producible was developed by Barbosa and Carvalho [121]. Electronics and mechatronics design is an important application of DFM at the system level. The 2003 study by Bajaj *et al.* [124] explored this in detail, developing a rule-based system for finding and imposing the relevant constraints (of several options available from the system to the designer) to accomplish a good quality design. Several studies by W.H. Wood [125, 126], Shetty *et al.* [127], Berselli *et al.* [128], and Lee *et al.* [129] discussed some of the major issues when designing mechatronic systems and presented a framework for considering formal (mathematical) and heuristic manufacturability constraints related to both the mechanical and electronics sides of the design.

4.2. General Product Design (Bottom-Up) Perspective

The design perspective with the most direct benefit from the use of minimally-restrictive DFM is design of individual parts. When the design focus is bottom-up (i.e. the system is built from several products individually developed) and each part must be optimized individually, the largest possible expansion of the design space is needed. It is assumed in this case that a specific manufacturing process has not been required by the customer and the designer is free to select the one that provides the least restrictive manufacturing profile and design space. Manufacturability constraints in this case are generally geometric in nature, driven by both the needs of the design, the capabilities of the manufacturing process selected, and the limits and nature of the material.

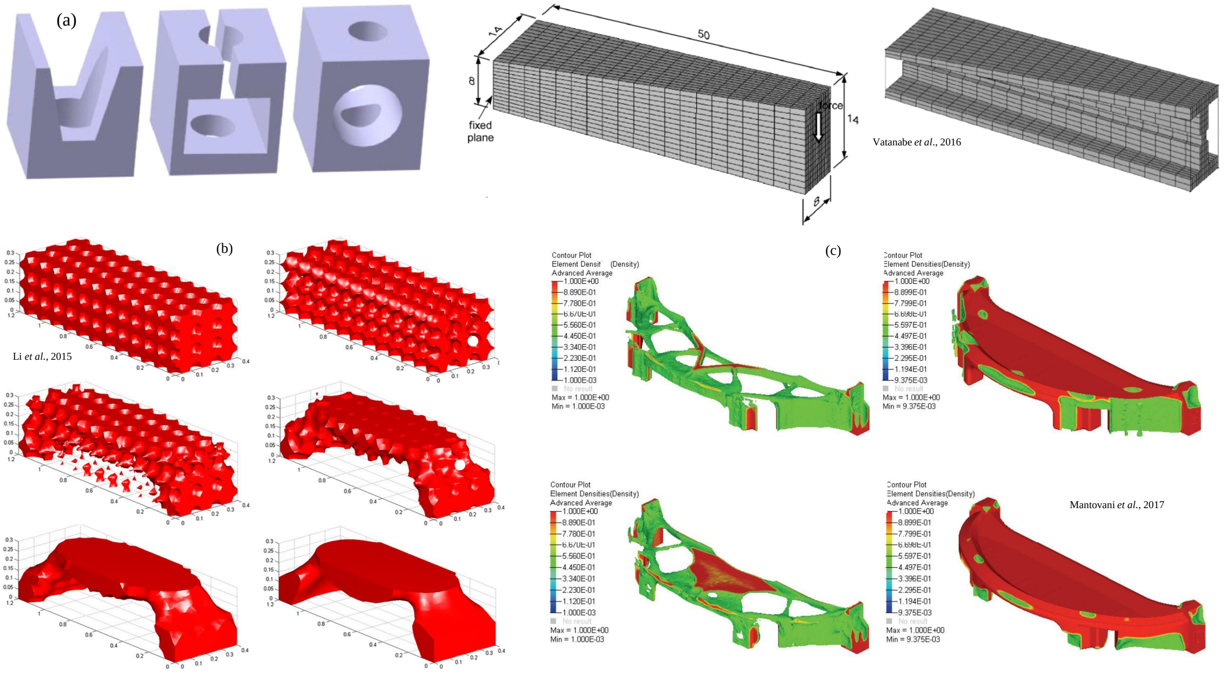


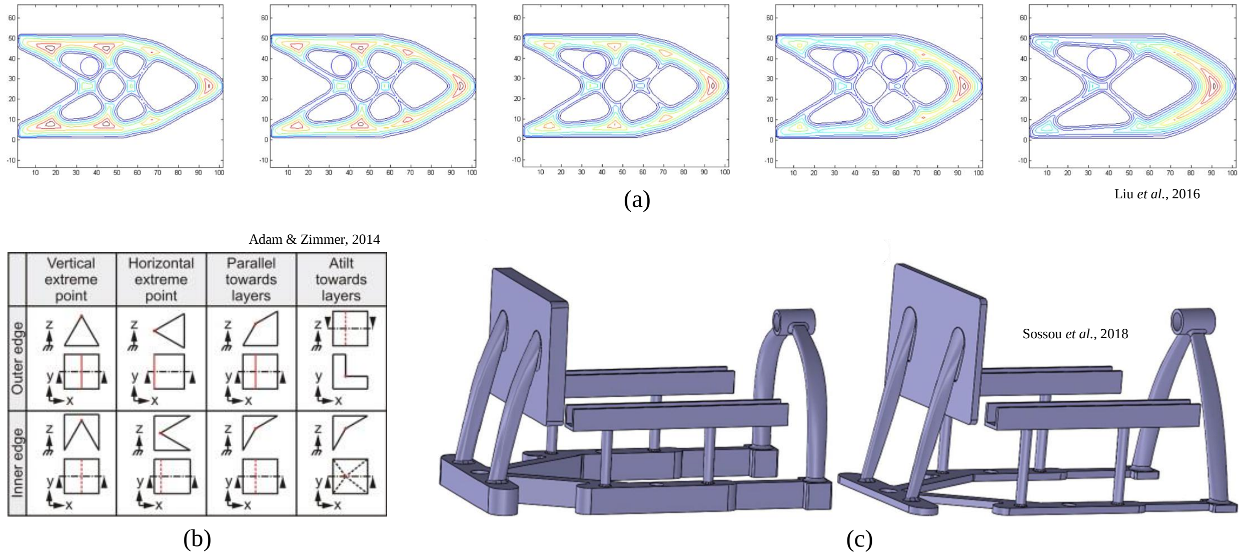
Figure 4: *Some significant successful examples of bottom-up design methods with integrated manufacturability constraints*, including (a) shape optimization [9] and (b) small-scale [130] and (c) large-scale [131] topology optimization. (Panels (a) and (b) © Elsevier Ltd. and reproduced with permission. Panel (c) published under CC-BY 4.0 license.)

In most of the DFM studies found on part design, a specific manufacturing process was defined in the problem statement and so it was not true bottom-up design (where it is assumed that performance is the primary goal and several production processes may be possible) [132, 133]; these cases will be discussed in the proceeding section. The work found in this area was primarily in the domain of decision analysis, where the manufacturability requirements or guidelines are discovered and fed back into the design process as it developed. Works by Barnawal *et al.* [20] and Budinoff *et al.* [134] analyzed this in detail, showing that effective communication of the constraints and manufacturing expectations was the key to ensuring product manufacturability; this was shown to be true for both heuristic, experienced-based constraints and formal mathematical manufacturability constraints. Mirzendehdel *et al.* [135] showed that sometimes this required delaying the actual optimization or design of a part as long as possible while exploring constraint trade-offs. While this is a valid approach for many different types of constraints, ensuring manufacturability (relative to other constraints) is one of the main applications.

A large and detailed case study on the mathematical definition and enforcement of manufacturability constraints was completed by Iyengar and Bar-Cohen [136] in which a side-inlet-side-exit (SISE) parallel plate heat exchanger was developed using constraint sets for eight different processes (extrusion, two types of die casting, bonding, folding, forging, skiving, and machining); it was found that feasible solutions for the design existed under each process constraint set, but the constraints were clearly active and provided very different optimal solutions based on the process selected. Similarly, several studies by Vatanabe *et al.* [9] (Figure 4a), Guest and Zhu [137], Li et al. [130] (Figure 4b), Mantovani *et al.* [131] (Figure 4c), Zuo *et al.* [138], and Reddy *et al.* [139] have examined the impact of manufacturability constraints on shape and topology optimization (TO) solutions. Several of these studies compared the results for several different manufacturing processes simultaneously, with outcomes similar to the heat exchanger problem described above. Since TO is an algorithm-based design process, the manufacturability constraints are usually enforced inside of the algorithm. For example, the study by Vatanabe *et al.* (Figure 4a) applied manufacturability constraints for six different processes (casting, milling, turning, extrusion, rolling, and forging), producing a variety of different topologies under these constraints. The constraints were enforced in the form of topology constraints, such as minimum feature sizes, symmetry, and avoiding undercuts, within the mathematical formulation of the problem.

4.3. Manufacturing Process Perspective

This section continues the discussion from the previous section on product design, with a manufacturing process specified in the design requirements. In this case, one or more specific processes must be selected in advance, requiring special consideration of the relevant constraints.



Liu *et al.*, 2016

Adam & Zimmer, 2014

Sossou *et al.*, 2018

Figure 5: *Successful examples of process-driven design under manufacturability constraints.* (a) topology optimization under machining radii constraints [140], design feature catalog for AM parts [141], and (c) design of a mechanical assembly under AM manufacturability constraints [142]. (Panels (a) and (b) © Elsevier Ltd. and reproduced with permission. Panel (c) published under CC-BY 4.0 license.)

4.3.1. SM Processes

In general, machining requires a careful tool-path planning to ensure that all of the geometry can be cut with the tools [143]; this is true for both manual and computer-controlled machines. For example, Monge et al. [144] proposed a three-step process for designing turbine blades by generating an optimal shape based on a combined set of constraints from a computational fluid dynamics (CFD) model and an optimal toolpath generator; the solution found produced both an improved design and one that was manufacturable using a machining process. More general solutions were developed by Kang *et al.* [145], Deja and Siemiatkowski [146], and Gupta and Nau [147], which are based on feature clustering and checking the optimality of a series of cutting path plans which open the design space as much as possible. Conversely, Mirzendehdel *et al.* [148] defined an “off-limits” region to represent the areas which would not be reachable with a cutting tool; this method was also shown to converge more easily than many other TO-based methods with machining constraints. In addition to path planning for conventionally-designed parts, machining constraints have been developed for use in TO-generated designs as well. Projection-based TO can be very effectively constrained for machining, as it is based on continuous geometric constraints and interfaces well with a toolpath, as shown by Guest and Zhu [137]. Specific machining and milling-related constraints have also been developed for a few cases within the level-set TO approach [140, 149, 150], as well as heavyside projection, gradient, and hybrid methods [138, 151]. Some examples solutions (subjected to machining constraints) from the study by Liu *et al.* are shown in Figure 5a.

4.3.2. AM Processes

Most of the work done so far in establishing and enforcing manufacturability constraints for AM processes has been for the development of design rules, some for general AM and some for specific processes. The focus of extensive studies by Jee and Witherell [152], Adam and Zimmer [141, 153] (Figure 5b), Bin Maidin *et al.* [154], and Kranz *et al.* [155] was on the development of standardized feature databases in which the AM manufacturing constraints could be applied to standard common part features to ensure manufacturability. The designer could then select the features from the database that are best for the design at hand while ensuring manufacturability. In a more focused effort, Tang *et al.* [156] presented a method for developing a unit structure-performance database to allow discrete optimization of light-weight housings via selective laser melting; this technique for arranging small standard features to optimize a design is useful and complementary with the feature catalogs developed in the previously-mentioned works.

Using the results from an extensive literature survey, Pradel *et al.* [157] proposed a framework for mapping of AM process knowledge for product design. They describe the need for more "practical" application of AM in design and suggest several methods for achieving this for general processes. Some work has been performed to establish AM constraints in TO [158, 159], similar to those discussed in the previous section, but this is still an immature area and needs additional attention. Thompson *et al.* [107] point out that many of the process limitations in AM come from the modeling and software used to drive the processes, but that this is an area where progress is being made. The design of mechanical assemblies under AM manufacturability constraints was explored by Sossou *et al.* [142]. Some of the results from this study are shown in Figure 5c.

In addition to more general AM constraints (minimal feature size [160], overhangs [106], surface roughness, avoidance of stress concentrations [109], material anisotropy [108], support material removal [161], among other things), some processes have more specific constraints which must be considered. While many of these are not well characterized, much work has been done for some of the very common processes. For example, Utley *et al.* [162], Thomas [163], and Kranz and Herzog [155] proposed a series of manufacturability constraints for the selective laser melting (SLM) process directly driven by the process characteristics. These SLM constraints are things such as delamination, laser heat deformation, potential oxidation between the material layers, and scan pattern constraints specific to laser scanning processes such as SLM. Similar work has been done for selective laser sintering (SLS) [164, 165] (such as shown in Figure 6a) and electron beam melting (EBM) [166–168], which have similar manufacturing constraints, with EBM generally being less restrictive than SLS/SLM due to the use of a heated chamber.

Other specific processes for which process-specific design rules have been developed include fused deposition modeling (FDM) [169–172], stereolithography (SLA) [173–175], material jetting [176], and binder jetting [177]. The general design limitations cited from FDM are in the area of minimal feature size (more strict than standard AM constraints), support material design, and surface accuracy and finish. FDM, material jetting, and SLA have similar manufacturability constraints, with the exception that SLA and material jetting have less strict minimal feature size restrictions. Binder jetting, which uses powder as the raw material, has constraints similar to those of the powder bed processes (SLM, SLS, EBM) mentioned above except for those related to heat warping.

4.3.3. FM Processes

An area of significant interest in minimally-restrictive DFM has been in the use of casting processes to fabricate complex geometry generated by topology optimization (TO) algorithms. In the major studies reviewed, this is done by mapping the major casting/FM constraints [178] into the design within level-set [179, 180], gradient [181], and projection [9, 137, 182] methods to generate a topology that is cast-able. Casting constraints are well-suited for TO, since they are much less strict than those for machining processes, and can be defined simply in terms of thickness and a requirement that the geometry be continuous; these constraints ensure that the liquefied material can flow into the mold and reach all features, can dissipate the heat, and that a parting line can be established. While relatively simple to design, in practice even simple casting constraints need careful assessment. For example, correctly predicting the amount of time available to fill the cavity (as well as the solidification pattern of the poured material) before the molten metal solidifies is extremely important both for the production of good products but also for the life of the tooling. Consideration of directional solidification is another important factor for the effective DFM of most FM methods, especially for sand casting [8, 30].

Some work has also been completed on the TO-based design of parts to be fabricated using an extrusion or drawing process. The manufacturability constraints for extrusion are much more simple than those for casting. When using a projection-based TO method, as done by Vatanabe *et al.* [9], the constraints are simply applied to a "slice" of the part; the domain is automatically continuous in an extrusion process, so the manufacturability constraints consist mainly of avoiding features that are too delicate to survive being pushed or drawn through a die. Li *et al.* [130] and Sutradhar *et al.* [10] showed that this can also be done using a type of internal projection within a level-set TO method.

In addition to DFM-based TO solutions in casting and extrusion, some work has gone into finding conventional (non-TO) design rules for closed-tooling processes, particularly injection molding, die casting, and powder metallurgy. Injection molding is typically limited to plastics (e.g., ABS or silicone), die casting to ductile metals (e.g., zinc or aluminum), and powder metallurgy to metal powder (sometimes mixed with a binder); manufacturability analysis within the appropriate tooling is focused primarily on being able to quickly and efficiently fill the mold with material and eject it safely. The manufacturability constraints then are in the form of feature restrictions (they must fit into and be easily removable from the tool), usually with a two-part tool, and the location of the tool parting line [183–186] (Figure 6b shows one of the design results from Singh and Madan [186]). From a simple design perspective, powder metallurgy is often the least restrictive [30, 187], as it can sometimes use a multi-part tool instead of the standard two-part used in injection molding and die casting. However, it is possible to include cores with injection molding/die casting, which is generally not possible with PM. It is also possible to have multi-part tools for injection molding and die casting in some applications. These practical advances in tooling technology allow more complex geometries to be fabricated; this, however, comes at a high design cost due to complex constraints involved, as well as the special tooling. Extensive work has gone into simulation of these processes in order to better understand how the material can flow into the tool and solidify in the way intended by the designer [188–192]; these simulations can be used to guide designs but generally are used just to check manufacturability and plan the process after the completion of the design.

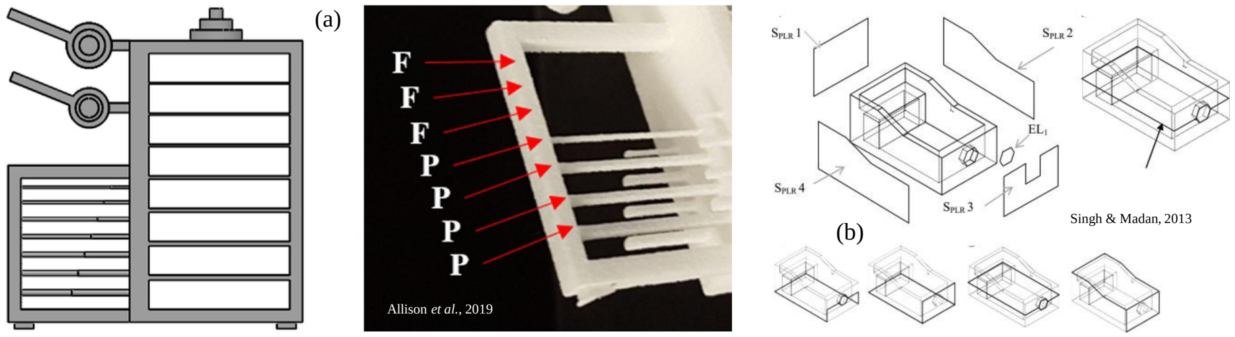


Figure 6: *Successful examples of process-driven design cases* for (a) design of a structure under additive manufacturing [165] and (b) parting line design for die cast parts [186]. (Figures © Elsevier Ltd. and reproduced with permission.)

4.4. Part-Redesign Perspective

From the perspective of green manufacturing, the primary value of the use of manufacturability constraints (besides the prevention of inefficient design and manufacturing) is in the area of re-design. Parts subjected to re-design are generally technically manufacturable but the designer has identified areas of improvement in the manufacturing or assembly. The redesign of parts specifically to make them more efficient or less expensive to manufacture was the subject of several studies for milled [193, 194], turned [195], and stamped [196] parts, as well as the production of part families [197]. While not technically DFM, this redesign approach is interesting as it shows a need for tightening manufacturability constraints once problems or inefficiencies are discovered after completion of the design. These problems could have been avoided by using proper DFM during original design, eliminating the need for corrective action later. The constraints encountered here are generally the same form and type as for product (bottom-up) design, but may be more complex. They may not be purely geometric but may also involve relationships with material behavior or interfaces with other parts (hence the reason they failed before redesign).

4.5. Sustainability Perspective

The main point of increasing sustainability in manufacturing is to ensure that production of human-use products has minimal negative environmental impact [198–200]. Objectives could be to reduce wasted materials, use a more localized supply chain, reduce emissions during processing, or encourage/enable recycling and repair (not replacement) of parts of products.

As sustainability questions become more and more widely considered during design, they necessarily become relevant to the selection and use of manufacturing processes as well. The idea of sustainability is relatively young and still being developed, so it serious influence is limited to certain domains within design and manufacturing; it is not yet universally accepted as a standard factor in design and manufacturing decisions. However, this is changing quickly. When considered, the goals of sustainable design and manufacturing introduces a specific set of constraints and restrictions; these are sometimes comparable to the constraints discussed in previous sections, but are often distinct and less well-defined.

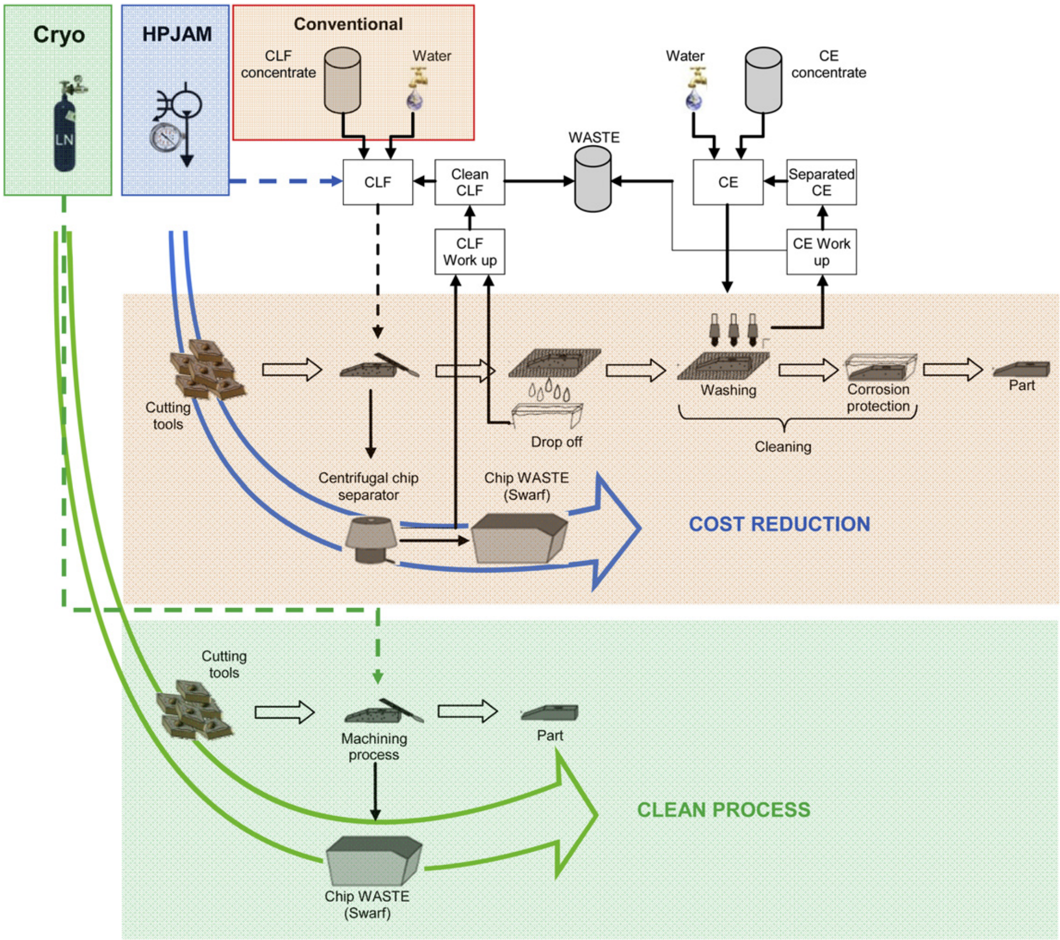


Figure 7: *Comparison of different machining techniques (with different manufacturability constraints) and their tradeoffs related to cost and sustainable production [201]. Detailed knowledge of manufacturing process mechanics and inputs is essential for judging the sustainability of specific processes or family of processes. (Figure © Elsever Ltd. and reproduced with permission).*

Sustainability goals can provide both objectives (to be used alone or in combination with other objectives) and constraints. Examples of goals could be social equity, economic efficiency, or environmental responsibility [202], while constraints may include things such as limitations on materials used, recyclablity requirements, reduction in labor, and similar. Since sustainability goals generally involve limiting design options or decreasing efficiency (in cases where the efficiency was accomplished using non-sustainable means), there is often a trade-off between sustainability, cost, and performance that has to be considered carefully. Sustainability considerations are closely related to policies and directives of regional, national, and intergovernmental entities. Thus, activities of sustainable growth in manufacturing and design are often analyzed in terms of socio-ecological impacts [198–200]. Careful manufacturing process selection while considering sustainability is an effective way to achieve some degree of sustainable manufacturing [203, 204]. The modification and adjustment of existing processes is far more complex of a problem, one that may be best solved by the development of new processes specifically under sustainability goals. The recent rise in popularity of AM in production has introduced new opportunities to improve sustainability in terms of resource efficiency, material life cycles, and process redesign [205].

Energy consumption, efficient energy utilization, and control of energy are the most studied topics related to sustainability. In the system design phase, simulation tools can not only maximize manufacturing efficiency but also minimizing environmental impact, demonstrated in Ref. [206]. Energy-aware process scheduling [207, 208], dynamic energy control in manufacturing processes [209], and reactive scheduling of flexible manufacturing systems [210] are examples of energy-related sustainability enforced, specifically from the top-down manufacturing design perspective. Manufacturability constraints have a large impact on this, as the constraint set can determine the available product design space; in addition, increasing design freedom can also have a negative impact on sustainable production in the cases where less efficient or clear processes are necessary for a specific design case [201]. Because of competing objectives, formulating and assessing the cost of sustainability in manufacturing process becomes important [201, 211, 212]. A more holistic evaluation of trade-offs between cost, performance, and sustainability is presented in some of the literature, such as in Helu *et al.* [213] and Lu *et al.* [214].

Life cycle assessment (LCA) in manufacturing processes and product design is another important consideration for sustainability. One of the primary objectives of LCA is to assess the overall environmental impact (throughout the whole lifecycle) and optimally choosing, scheduling, controlling, and utilizing manufacturing processes to reduce this impact as much as possible. [92, 201]. The diagram produced by Pusavec *et al.* [92] (Figure 7) demonstrates this well; several classic machining processes are compared (each has distinct manufacturability constraints) relative to cost and sustainability. The balance of each that is selected will affect the feasible processes that can be used, which in turn affects the manufacturability constraints on any fabricated product. If specific manufacturability constraints are required, this may constrain (or even specify) which process may be used and therefore affect the balance of cost versus sustainability. LCA techniques, including simulation-based LCA approaches, can be utilized as design tools or as a means for assessing design constraints associated with manufacturing process design, as demonstrated by Harun et al. [215]. In addition, in the LCA framework, sustainability considerations extend to advanced concepts of product lifecycle, such as re-manufacturing, maintenance, or product reform [216, 217]. In addition, design-for-assembly (DFA) and design-for-inspection (DFI) need to be concurrently considered with the DFM to achieve economic and sustainable product design and manufacturing outcomes [218, 219].

5. Manufacturability Constraints: View of Design Scales and Levels

The design of features and part details can be completed at different design levels, each of which requires different kinds of manufacturability constraints. The main difference, from a design perspective, of each of the levels is the scale of feature sizes created within each domain. The macro-level is defined as containing features at least a millimeter in size, while meso-level features may range from a few hundred micrometers to one millimeter, the micro-level may range from one to a few hundred micrometers, and sub-micro-scale is less than one micrometer in size. A visual comparison for each can be seen in Figure 8.

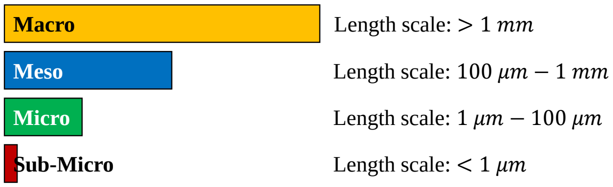


Figure 8: *Design-related process characteristics for SM, AM, and FM, shown with examples of common processes and common manufacturing constraints for processes within each domain*

5.1. Macro-Level Design

One of the major tasks when designing at this level is the generation and refinement of macro-level structures and aggregates such as lattices, overhangs, mounting bosses, and similar features. Design at this level is generally straight-forward, and is usually done using design rules and feature catalogs which provide manufacturable features [141, 153, 220]. Definition of these rules for most traditional manufacturing processes (such as machining and injection molding) is based on simple DFM principles, as discussed in depth in Sections 4.2 and 4.3. Figure 9a shows an injection-molding caliper case, which is an example of a standard product with macro-scale features.

Fabrication of macro-scale features for AM processes is more complex due to the layered nature of the resulting material and the presence of natural voids, stress concentrations, and residual stresses [109, 221]. While it is important to use feature catalogs and feature families, the manufacturability constraints will be more strict than they would for more simple processes. Research has been performed specifically for AM processes; for example, the studies by Adam and Zimmer [141, 153] and Bin Maidin *et al.* [154] developed a list of macro-level standard design features and their transitions. The rules presented are developed for several specific AM processes and incorporate process knowledge directly from these processes into the design of edges, wall thicknesses, gap heights, and other design features. Some AM processes (such as SLM) require the ability of the material to transfer heat rapidly during processing and small features need to be adjusted for this, including controlling the porosity [222]. Maximum length scale constraints for structural and fluid topology optimization is another important application; it can limit the size flow channels and structural members as needed, as shown by Guest [223] and Lazerov and Wang [224].

5.2. Meso-Level Design

The primary applications found for meso-level design were in the design of meso-scale features which act as a controllably-anisotropic material. Since, in most cases, the material for parts made using SM and FM process is approximately isotropic, this design level has been applied mainly to additively-fabricated parts. The use of AM to design and build meso-level materials structures was the topic of several studies; Chu *et al.* [225], Yu *at al.* [226], Garcia *et al.* [227] and Florea *et al.* [228] developed different theoretical frameworks for single- and multi-material problems, while Sivapuram *et al.* [229], Gopsill *et al.* [230], and Gardan *et al.* [231] explored the practical implications and requirements for using AM to build meso-scale tailored materials. Examples of some AM-generated mesostructured materials are shown in Figure 9b.

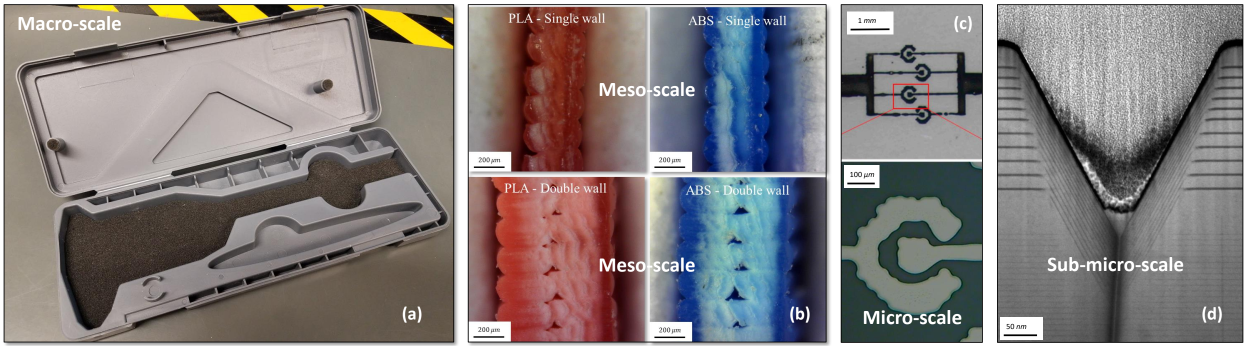


Figure 9: *Examples of design features at various levels. (a) macro-scale injection-molded caliper case, (b) meso-scale 3-D printed thin-walled structures, (c) micro-scale electrodes [232], and (d) sub-micro-scale LED pits [233]. (Panels (c) and (d) published under CC-BY 4.0 license.)*

5.3. Micro-Level Design

Manufacturing constraints derived for micro-scale features and parts (Figure 9c) could be more restrictive than larger-scale designs due to the small length scales involved. Most conventional manufacturing processes, including casting, forging, machining, and additive manufacturing, do not have the capacity to fabricate extremely small geometry; therefore, it is vital that a production process be selected and considered at the design stage to ensure that the final product is manufacturable.

The small number of manufacturing processes that can reliably fabricate at the the micro-scale are well-understood, so it is relatively straight-forward to find and enforce the manufacturability constraints in most cases. For example, Ashman and Kandlikar [234] examined several types of manufacturing processes for fabricating heat exchangers with hydraulic diameter of less than 200 micrometers. Etsion [235] presented a comprehensive review on micro-level laser surface texturing (LST) in connection with hydrodynamic lubrication and wear reduction as well as surface texturing in general. Romig *et al.* [236] discussed issues in association with micro-electro-mechanical systems (MEMS) design and fabrication, including materials, manufacturability, performance, and reliability. AM-based fabrication has been discussed by Frazier *et al.* [237] and Dede *et al.* [238]; while AM offers great potential for micro-scale fabrication, there are clear problems with the processes that need to be addressed before they can be effectively used for micro-scale fabrication. Current challenges include material defects, anisotropic properties (which affect the fabrication more for smaller geometries), inconsistent cooling, residual stresses, complex material behavior, and other related concerns.

In addition to feature size restrictions, design topologies and shapes also should have specific constraints when fabricated at this scale. As an example, considering a micro-milling process with a ball end mill, Lee *et al.* [239] applied a spline-interpolated smooth free surface with a maximum slope angle as a manufacturability constraint in the surface texture design-for-lubrication problem. Even though the target design size is larger than micro-level, features in the design may still be smaller than those which can be fabricated at this level by certain processes. Specifically, keeping the feature size larger than the manufacturing resolution should not be overlooked in topology and shape optimization. Sigmund [240, 241] showed examples of manufacturing failure due to feature size, and introduced robust topology optimization frameworks that can filter out infeasibly small features.

5.4. Sub-Micro-Level Design

An example of a feature at this scale is a nano-scale LED pit, as shown in Figure 9d. This is an extremely important design scale and many important applications require designed features at this scale. Some of these applications include friction and wear reduction [242, 243], nano-electro-mechanical systems (NEMS) [244], and superhydrophobic surfaces [245]. Sub-micro-level surface treatment using micro- and nano-texturing and surface modification strategies are similar to those discussed for other scales, except that the tolerances are much tighter and the manufacturability constraints are very restrictive. Sub-micro-scale surface texturing and treatment methods for corrosion and wear resistance often involve combinations of thermal, electrochemical, and mechanical processes, which alter surface electrochemical and molecular properties, mechanical shapes and patterns, or sometimes material itself [246]. Often, sub-micro-level features and parts are manufactured using the same or similar techniques that are applied to fabricated nano-scale structures; these fabrication techniques can be typically classified into two categories: top-down and bottom-up approaches.

Top-down fabrication approaches mostly utilize nanolithography, deposition, and etching processes. This approach is commonly used in the semiconductor industries, but the usage is expanding to more intricate applications, including NEMS, sensors and actuators, optoelectronics, as it is capable of fabricating structures down to nanometer resolution [244]. Due to the layered nature of fabrication processes, the top-down approach is mainly limited to 2D or 2.5D structures in manufacturing. Structures can be fabricated by repeated material deposition and removal processes, supporting very accurate manufacturing, but present manufacturability problems when the length scale is less than a few nanometers [247, 248]. The bottom-up approach places material at the desired locations, similar to 3-D printing processes. Currently, a direct-write nano-deposition (specifically, two-photon polymerization, 2PP) method is available to fabricate structures smaller than the micrometer level easily, and at its limits down to a length scale of approximately 50 nm [249, 250]. This approach has similar characteristics and constraints to what is commonly seen in 3D printing; however, even with the wide freedom in shape and topologies that AM enables, postprocessing of structures fabricated using nanoscale AM via 2PP is still challenging. The main challenge is the removal of support structure and any extra raw material, as this is very difficult or impossible when dealing with extremely small parts [251].

6. Discussion and Closing Remarks

The purpose of this survey was to explore the generation and imposition of process-driven manufacturability constraints for product design problems. First, a description of the problem was presented, showing that many designs require the use of manufacturability constraints as a strategy to take advantage of the largest possible design space. Next, the various major manufacturing processes and their common manufacturing constraints were discussed in depth. After discussion of the manufacturing constraints, the design literature was explored from several different perspectives and levels for existing approaches in applying process-driven manufacturability constraints to design problems. Five different design perspectives were examined: (1) from the perspective of system-based design, component-level design for both the (2) general case and the (3) case where a manufacturing process is specified, (4) from the perspective of part re-design to address manufacturability problems, and finally (5) from the perspective of sustainability. Additional perspectives (including reliability, assembly, and retirement) but not enough relevant information was found in the literature to make a significant contribution to this survey. Four different design levels (or length scales) were analyzed, ranging from standard macro-scale ("consumer product size") design to sub-micro-scale problems. The overall survey provided four main take-aways for designers and practicing engineers to consider:

1. The information collected in this survey and discussion demonstrated a wide variety of design problems involving (explicit and implicit) manufacturability constraints. These problems, formulations, and solutions can provide a basis for solving new problems related to manufacturability and design.
2. This survey looked at a number of design perspectives and levels, making it more useful as a guide for specific problems.
3. This survey exposed the need for a general formulation method which is design-method-independent and which works with very complex problems, as well as methods for several areas of little to no coverage in the existing literature.
4. It is clear from the existing literature that manufacturability considerations (explicit or implicit) are required for most design problems. The information collected is organized and presented in such a way that it will be useful to designers and engineers who are not experts in manufacturing science or processes, making it easier to apply in real problems. This will result in better-quality design processes and less cost and schedule risk related to manufacturing.

This work focused on design under single, non-hybrid manufacturing processes that are standardized and with which most designers should be familiar; joining processes (such as welding) and secondary manufacturing (i.e., the production of manufacturing tools) were not considered, as they were beyond the scope of this work and are deserving of their own in-depth reviews. The design and fabrication of material microstructure and architected materials were also not addressed in the present survey. A new field of part redesign for emerging technologies (instead of redesign to address manufacturability problems) has been developing over the past several years, but is not yet mature and was not examined in this work.

In addition to the larger take-aways, some important observations and conclusions were made after reviewing the collected literature on the topic:

- Significant progress has been made in the effort to include relevant manufacturability constraints (both explicit and implicit) in specific domains and design scales. The representation of different methods is very uneven, with topology optimization of metal AM and FM parts being the most over-represented. On the other hand, there are considerable gaps in the literature; some of the affected areas were observed to be sheet metal forming, forging and rolling, traditional casting and plastic injection molding (where classic FDM is typically used), and most subtractive processes beyond simple milling and turning.
- It is not clearly specified in most studies what the best verification and validation methods are for ensuring the appropriateness of the manufacturability constraints. In some cases, simulations are done, while others use physical experiments or field studies. These are useful for the specific studies in question but there is no general guidance. This appears to be an issue with traditional DFM as well from the conclusions made in the found works.
- Specific comparison with classic DFM was very rarely found during the survey. In future studies, this practice should be adopted to better justify using specific constraints instead of classic DFM ones.
- Throughout all of the design perspectives and levels, clear dependencies exist between the choice of process and the manufacturability limitations for specific designs.
- The impact of trade-offs between the manufacturability and the performance of the final design was not addressed in most of the found studies.
- The processes for finding and enforcing manufacturability constraints depends heavily on which domain (SM, AM, FM) the process in question belongs to. For most SM and FM studies found, the essential constraints were tool access and minimum feature size.

- The established manufacturability constraints for SM processes tend to be related to surface topography, while AM constraints generally relate to part cross-section and material behavior, and FM constraints seem to be driven primarily by material behavior when interacting with and being removed from the tooling. This is an important consideration during early design efforts when the ideal manufacturing method may not be selected.
- Part re-design solutions presented in the literature to address manufacturability problems show that a simple and effective way to address manufacturing problems is to tighten the manufacturability constraints for the design.
- If it can be shown that all the manufacturability constraints are inactive, it is very likely that the design is manufacturable without the constraints. This is the ideal case for many problems, as a smaller number of design constraints will usually result in less expensive decision making processes and a larger design space.
- The smaller the design scale, the more restrictive the manufacturability constraints become and the fewer process types are capable of fabrication.
- Research involving different design scales is dominated by specific types of manufacturing processes. This appears to be largely the choice of researchers (e.g., studies at micro- or sub-micro scales tend to rely more on AM processes) based on what is most practical for a specific problem. In the future, this will need to be expanded to include a wider variety of processes.
- Parts conventionally-designed (i.e., not designed using an algorithm) under several common FM and SM processes do not appear to have formally-defined methods for ensuring manufacturability of the parts beyond visual observation and rules-of-thumb. Especially noted were investment casting, blanking/coining/stamping, turning/facing processes, rolling, and forging processes.
- The design of conventional sand and shell casting parts seem to be completed using mainly heuristic-based design and traditional DFM principles (i.e., "make it simple").
- In top-down (system-level) design, the manufacturability constraints need to consider global as well as local manufacturability problems.
- In bottom-up (component) design, the same product can have vastly different final designs from the same starting point when active manufacturability constraints for different processes are considered.

Future work should focus on addressing the areas where minimally-restrictive manufacturability constraints are not in regular use, as they can help to open up the design space and allow the further optimization of the design. There is a great need for a standardized (whether formally-standardized or in common use) method for mapping the manufacturability constraints directly to design constraints. If this can be developed and automated, it could significantly speed up the design process and increase its reliability for new areas of design exploration.

Acknowledgments, Conflicts of Interest, and Funding

No external funding was used to perform the work described in this survey. Opinions and conclusions presented in this work are solely those of the authors.

Appendix

While this project was intended as a detailed survey and not a meta-analysis review, every effort was made to include all the relevant literature and provide an accurate view of the topic under study within the limitations discussed in the main paper. It should be noted that the collection of references for this survey had some limitations in scope, specifically excluding references in the following categories:

- Papers not published in English

- Most review papers where the authors could not find new and unique information not available from the primary sources
- Patent literature, editorials, posters, and viewpoint papers except those reporting major field problems and/or experimental results
- Technical reports and theses published before 2005 (more than 15 years old)
- Conference papers for which a later journal version was published and available
- Conference papers published before 2000 (which did not have a journal version), were not hosted by a major society (such as IEEE, ASME, IISE, ESIS, AIAA, etc.), or were not indexed (such as in ACS and Scopus).
- Any paper from an online-only mega-journal (which publishes papers without a focus on a specific field), with the exception of papers from IEEE Access, Scientific Reports (Nature), AIP Advances, and PLOS One.
- Any paper from a journal considered to be possibly predatory (failure of the Think-Check-Submit test (https://thinkchecksubmit.org/), an unknown publisher, a publisher on Beall's List (https://en.wikipedia.org/wiki/Beall%27s_List), or a combination of these)

These exclusions were made to ensure that only credible works which could be competently evaluated by the authors were included in the survey and that works were counted only once (in the case of excluding earlier conference versions of journal papers). It should be noted that small, new, or national-level journals or conferences were considered legitimate if the authors could establish credibility and they were not widely suspected to be predatory.

To begin the survey, a set of relevant keywords were compiled by the authors, which were then used to search for literature in both major indexes which hold engineering-related papers (Google Scholar and Scopus); in each case, the search was ended when reaching the third page with no useful results. The results were sorted based on relevance and no date restrictions were placed on the search criteria. In addition to the standard indexes, a set of peer-reviewed journals and major international conferences related to manufacturing and design were specifically queried.

A total of 180 unique potentially useful papers were found, based on title and abstract, after the search. The papers were then subjected to a review of reference sections to uncover any additional references that were missed in the search; 15 more were found, bringing the total to 195. The set of papers were then subjected to the standard quality screening employed by the authors when completing review papers, screening out any papers that fall into one or more of the categories described above. The final list of papers was then screened carefully for relevance to the topic of this review. After both screenings, 52 papers were excluded from the review. Therefore, a total of 143 papers were explored and discussed in this review. In addition to papers directly on the topic of the review, an additional 108 papers were found to support the review, such as papers describing manufacturing processes or design needs or papers providing information needed to understand the context of the review. These papers were specifically searched for and only the best 1-2 found on each topic were included in the reference section. With these additional papers, the total number of references for the main paper stands at 251.

The primary search keywords for this survey were

- Design for manufacturing
- Manufacturability
- Manufacturing constraints
- Manufacturing design constraints
- Manufacturing considerations
- Manufacturability constraints
- Additive manufacturing

- Subtractive manufacturing
- Formative manufacturing
- Tooling design
- Manufacturing design
- Manufacturing system
- Systems engineering manufacturing
- Top-down design
- Bottom-up design
- Product design
- Product design manufacturing
- Sustainable manufacturing
- Sustainability manufacturing
- Green manufacturing
- Macro design, macro design + constraint
- Meso design, meso design + constraint
- Micro design, micro design + constraint
- Sub-micro design, sub-micro design + constraint

In addition, the names of each of the most common subtractive, additive, and formative manufacturing processes followed by "design", "constraints", and "optimization" were also queried.

In addition to the general database searches, the following journal and conference proceedings were also searched specifically:

- **ASME Journals**: Journal of Manufacturing Science and Engineering; Journal of Mechanical Design
- **Elsevier Journals**: Additive Manufacturing; Advances in Engineering Software; CIRP Annals – Manufacturing Technology; Composites Part B: Engineering; Computer Aided Design; Engineering Fracture Mechanics; International Journal of Machine Tools and Manufacture; Journal of Cleaner Production; Journal of Manufacturing Processes; Journal of Manufacturing Systems; Journal of Materials Processing Technology; Manufacturing Letters; Materials & Design; Procedia CIRP; Procedia Structural Integrity; Robotics and Computer-Integrated Manufacturing
- **Emerald Journals**: Assembly Automation; Rapid Prototyping Journal
- **Liebert Journals**: 3D Printing and Additive Manufacturing
- **MDPI Journals**: Journal of Manufacturing and Materials Processing; Designs; Machines; Materials
- **Sage Journals**: Concurrent Engineering; Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture; Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science
- **Springer-Nature Journals**: International Journal of Advanced Manufacturing Technology; International Journal of Fracture; JOM; Journal of Intelligent Manufacturing; Progress in Additive Manufacturing; Structural and Multidisciplinary Optimization
- **Taylor & Francis Journals**: IISE Transactions; International Journal of Computer Integrated Manufacturing; International Journal of Production Research; Journal of Engineering Design; Machining Science and Technology; Virtual & Physical Prototyping

- **Wiley Journals**: International Journal for Numerical Methods in Engineering
- **Independent Journals**: International Journal of Bioprinting
- **Conference Proceedings**: Solid Freeform Fabrication (SFF) Symposium: An Additive Manufacturing Conference; ASME International Mechanical Engineering Congress and Exposition (IMECE); ASME International Design Engineering Technical Conferences & Computers and Information in Engineering Conference (IDETC/CIE)

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