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MANUFACTURABILITY CONSTRAINT FORMULATION FOR DESIGN UNDER HYBRID ADDITIVE-SUBTRACTIVE MANUFACTURING

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ABSTRACT

This article addresses the generation and use of manufacturability constraints for design under hybrid additive/subtractive processes. A method for discovering the natural constraints inherent in both additive and subtractive processes is developed; once identified, these guidelines can be converted into mathematical manufacturability constraints to be used in the formulation of design problems. This ability may prove to be useful by enhancing the practicality of designs under realistic hybrid manufacturing conditions, and supporting better integration of classic design-for-manufacturability principles with design and solution methods. A trade-off between design manufacturability and elegance has been noted by many scholars. It is posited that using realistic manufacturing conditions to drive design generation may help manage this trade-off more effectively, focusing exploration efforts on designs that satisfy more comprehensive manufacturability considerations. While this study focuses on two-step AM-SM hybrid processes, the technique extends to other processes, including single-process fabrication. Two case studies are presented here to demonstrate the new constraint generation concept, including formulation of shape and topology optimization problems, comparison of results, and the physical fabrication of hybrid-manufactured products. Ongoing work is aimed at rigorous comparison between candidate constraint generation strategies and the properties of the constraint mapping.

1 INTRODUCTION

Significant advances in design automation methodologies have been made in recent decades; generative design, topology optimization (TO), and machine learning techniques are all excellent examples [1–3]. However, these methods have varying levels of maturity and applicability to production-level design tasks. As a result of these and other factors, adoption of these methods for the design and production of hardware and consumer products is limited in many cases. This is particularly true of system design problems, where the design requires the input of independent stakeholders; many of these stakeholders are non-experts on the technical and manufacturing aspects of the product, which often requires the designers to accommodate nebulous and possibly conflicting requirements during system development [4]. In most practice-based product- and system-design methods, the design progress is assumed to happen in a linear fashion [5–8], each step advancing the product development closer to completion. It is common for system engineers to manage development processes to increase modularity and independence of development tasks so that they can be executed in a largely independent manner by separate design teams. Unanticipated design interactions require loop-backs to earlier stages to accommodate needed design or requirement changes, consuming additional resources [4, 8–10]. Often changes are needed to accommodate manufacturing methods [9, 11], as many elegant designs are not manufacturable using standard manufacturing processes without being optimized for those processes, including emerging AM processes.

In the linear design model, the design typically is completed and optimized before entering the manufacturing and assembly stage, making modifications costly and time-consuming [9, 12]. Depending on the severity of the problem, the loop-back may involve a minor modification to the design, or could involve the establishment of new product requirements, requiring the designer to re-design the product or system from conception [5, 8].

One established strategy for preventing this kind of problem is to apply design-for-manufacturability (DFM) principles during the product requirements and design stages. With this approach, intended manufacturing processes may be selected during the design phase and integrated into the product design from conception; this allows the advantages and restrictions of the production method to be accommodated during the design phase, bounding the design space and preventing delays in production [13–16]. Typically, this is done by introducing a specific set of secondary design requirements (Fig. 1) related to fabrication of the system or system components [9, 13, 17, 18]. This method is universally applicable, but requires that designers have the requisite familiarity with the intended manufacturing processes [19].

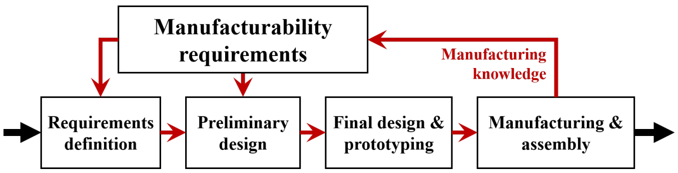

FIGURE 1: Introduction of manufacturability knowledge into the design requirements and methods

Progress has been made recently toward incorporation of manufacturability constraints for specific design processes, particularly in the realm of topology optimization (TO) [20–22]. This has been done most commonly by controlling the length scale within the design at the formulation level [20, 21, 23], often using some type of projection [20, 24–26] or level-set [27–29] method. There is, however, a clear trade-off between improving predicted design performance and manufacturability associated with these methods [20, 21, 30]. Thus far, most DFM work has focused on traditional manufacturing processes, such as machining, extrusion, casting, and other formative processes [20, 21, 26, 31–34], but progress is being made to integrate AM process considerations [30, 31, 35, 36]. The problem is becoming well-studied for specific aspects of TO, but it is one of many possible design methods.

A more general technique for considering manufacturability in designs is yet to be developed, particularly one that could be used with combined (hybrid) additive and subtractive manufacturing processes. Most of the work to date in the literature focuses on problem formulation, but these efforts largely do not incorporate any manufacturing-related design heuristics or "rules-of-thumb" in the formulation of the manufacturability constraints [11, 37–39]. The need for a simple, practice-based method of generating process-specific manufacturability constraints that is universally applicable and not based on a specific solution method (such as TO) or manufacturing process is needed.

The recent rapid growth of additive manufacturing (AM) technologies has started to open an entirely new world of design freedom and manufacturability advantages. Products are built layer-by-layer directly from digital models without the need for specialized tooling or work-holding. This ostensibly can eliminate many restrictions imposed by traditional manufacturing processes [40–42]. However, AM brings its own set of fairly complex manufacturing restrictions, some of which overlap with traditional ones, and some that are unique to AM. With the wide variety of AM processes for different applications and materials [40, 43, 44], it is essential to identify and understand the effects of these manufacturing constraints on design.

Interest in combining additive and subtractive methods (SM) into either a sequential or simultaneous hybrid process has risen in recent years. The advantages of doing so include possible process speed increase and cost reduction for AM, and relaxing complexity restrictions on SM processes [45–51]. While the use of AM allows significant design freedom, it is can be slow and costly to utilize; SM processes are typically fast and relatively inexpensive to use, but restrict design freedom due to the limited ability of the tooling to reach features. Hybrid processes attempt to find a balance between the two, taking advantage of the benefits and attempting to reduce the negative aspects of both [45]. Figure 2 illustrates the most commonly-used additive and subtractive processes [19, 43, 44]. Any of the AM and SM processes could be combined into hybrid processes, but with varying levels of effectiveness. Figure 2 illustrates some example process combinations, based on the most common processes in each category.

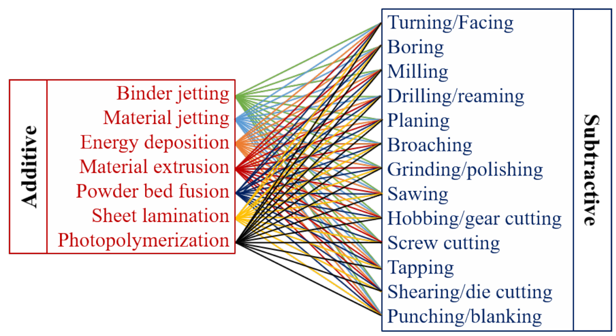

FIGURE 2: Sample set of possible hybrid processes

In addition to advancing the development of hybrid manufacturing methods, the study of the hybrid AM-SM problem is an excellent method of exploring the interface between different manufacturing families. The two processes of greatest interest at the current time are additive and subtractive, but the concepts presented here could reasonably be extended to various other combinations of the fundamental process families (i.e., additive, subtractive, formative, and hybrid).

The present study offers a new perspective on the definition and generation of realistic manufacturability constraints for hybrid AM-SM processes by mapping fundamental manufacturing knowledge to usable design constraints. First, the concepts of constrained design are explored in the context of this problem. Next, a technique for mapping manufacturing knowledge to manufacturing constraints and then to design constraints is proposed and described. This mapping method is then extended to hybrid AM-SM process combinations. Two case studies are presented to demonstrate the concepts and expected outcomes; these case studies include the fabrication of products to demonstrate manufacturability.

2 PROBLEM FORMULATION

In the standard formulation of the design problem, an *objective function* is defined that encompasses the desired performance of the design over its mission; it ideally includes all the attributes or parameters to be optimized relative to each other, expressing overall system utility. Constraints can be added as well to guide designs away from failure modes or other elements that may render designs infeasible [52]. Constrained design problems are meant, in formal negative-null terms, to minimize a function

$$f : \mathbb{R}^n \to \mathbb{R} \text{ over } S \subset \mathbb{R}^n \tag{1}$$

where $f(\cdot)$ denotes some objective function (usually formulated such that the minimum value is the desired solution) and S denotes the set of feasible solutions to this function. In formal design optimization terminology, this is often written as:

$$\begin{aligned} \min_{\boldsymbol{x}} \quad & f(\boldsymbol{x}) \\ \text{subject to} \quad & g_i(\boldsymbol{x}) \leq 0,\ i = 1, \ldots, n \\ & h_i(\boldsymbol{x}) = 0,\ i = 1, \ldots, m \end{aligned} \tag{2}$$

where $g_i(\cdot)$ are the inequality constraints on $\boldsymbol{x}$, $h_i(\cdot)$ are the equality constraints, and $\boldsymbol{x}$ is the vector of design variables to be considered. In most practical problems, considering constraints is necessary, regardless of the chosen solution method. The few cases where constraints are unnecessary usually have very few (or even just one) feasible solutions within the entire design space, and solution methods often converge to these solutions easily [52, 53]. The fundamental purpose of the constraints is bound the design space to regions where feasible solutions can be found. Infeasible designs may fail in some way (e.g., strength, functionality, manufacturable, etc.). Constraints can be hard (fixed) or soft (ideal) constraints, depending on the nature of the problem. When considering the manufacturability of a design, it should be remembered that all manufacturing processes contain both positive and negative production aspects relative to each other; no existing process, neither additive nor subtractive, nor any of the other families of processes, is perfect or applicable to all designs [19]. Therefore, it is important to bound the design space to "manufacturable" designs as early in the design process as possible.

3 MANUFACTURABILITY CONSTRAINTS

Establishment of practical manufacturability constraints for design requires knowledge in both the manufacturing engineering and design domains. The practical considerations behind the chosen manufacturing processes must be studied and converted from their usual form (e.g., expert knowledge or rules of thumb) into formal manufacturing constraints, then to design-specific constraints. Figure 3 illustrates the relationship between these three domains. The formal definition of each can be specified as:

$$\begin{aligned} P_1 &= \{c \in C : \text{ Mfg process characteristics}\} \\ P_2 &= \{r \in R : \text{ Mfg process restrictions}\} \\ P_3 &= \{d \in D : \text{ Design constraints}\} \end{aligned} \tag{3}$$

where the mapping P from the basic manufacturing processes to design constraints is:

$$P : P_1 \to P_2 \to P_3 \tag{4}$$

The first step when deriving the set of manufacturability constraints for a specific design is to select a general category of manufacturing processes (for example "machining") that will be used to realize the design. This selection of a process may be one of the steps in the conceptual design of the product, it may be limited by available production resources, it may be necessitated by the mission of the product, or it may be specified by the stakeholders. In a well-formulated design concept, it should be clear what general production path should be taken for a specific product. By studying these processes from a production perspective (Fig. 4a), the advantages and disadvantages of each can be understood by the designer. Advantages can be leveraged to expand the level of design freedom or increase the efficiency of the process, while disadvantages tend to restrict the design freedom.

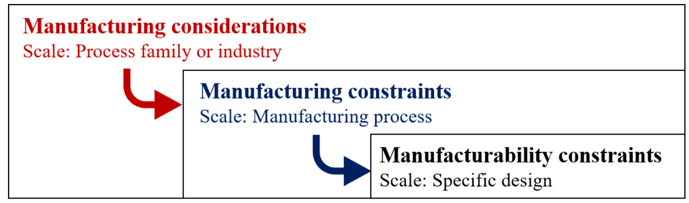

FIGURE 3: Problem reference scales

Once the manufacturing considerations are studied and listed, the designer can then formalize each of them into a manufacturing constraint. Figure 4b illustrates the concept, where each constraint is identified, formally specified, ranked in terms of importance, and finally, combined when possible to reduce the number of constraints. This is the same process commonly seen with non-production-related design constraints [4, 6].

As the designer proceeds to the design phase (Fig. 4c), the formal manufacturing constraints derived previously should now be converted to manufacturability constraints. Unlike the process-based manufacturing constraints, the manufacturability constraints are focused on the design of the product itself. Ideally, these constraints can be combined directly with the other design constraints and the objective function to produce a complete and usable design problem. Detailed examination of the process for producing this complete design will be demonstrated via the case studies presented in Section 5.

There are several ways that the design problems (Fig. 4c) under DFM can be formulated, depending primarily on the choice of manufacturing processes and the design and manufacturability constraints. In traditional design, the product is fabricated independently of the design; however, when using DFM, the design and manufacturing are not independent and must be considered relative to each other. Therefore, either the manufacturing must be planned relative to the design, or the design must be executed relative to the manufacturing processes chosen.

Since design problem formulations cannot usually consider all the potential manufacturability restrictions for a given process or set of processes, using DFM with the design driving the choice of process can still result in a non-manufacturable part [20]. Even if this was not the case, the domain of available manufacturing processes is generally far more limited than the domain of available optimization formulations; therefore, it is logical that

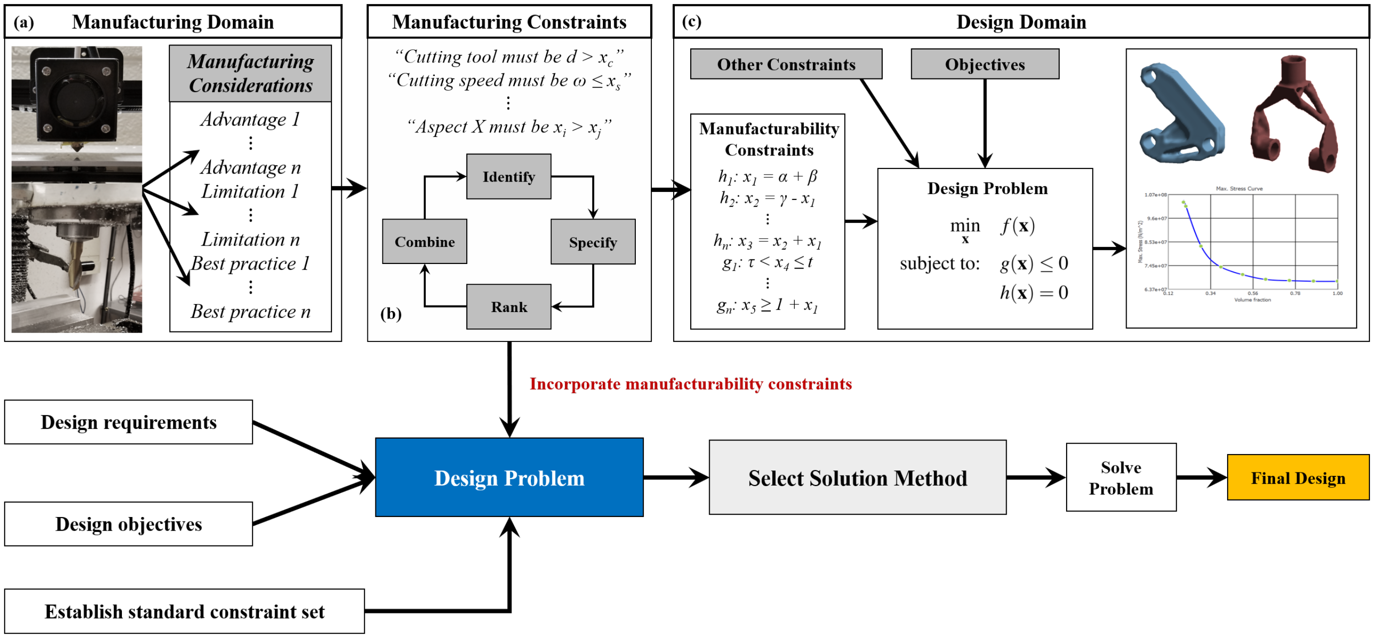

FIGURE 4: Manufacturability constraint derivation and use in engineering design

the design technique should follow the parameters of the chosen manufacturing processes.

Several different formulations of the design problem are possible and, as previously discussed, should incorporate the mechanics of the fabrication processes. The design could be formulated as a single problem (e.g., structural topology optimization), a sequential problem (e.g., combination of shape and structural topology optimization), or a nested problem (e.g., kinematic mechanism optimization). Which is best to use depends on the manufacturing sequence selected, on designer preferences, and on the objectives of the problem.

If the problem is very simple, a single problem solution step may be appropriate. Due to anticipated problem complexity, however, nested, sequential, or other decomposition-based solution approaches may be advantageous for many problems. The choice of models based on the specific conditions of the chosen processes and the design aspects is discussed during the case studies in Section 5.

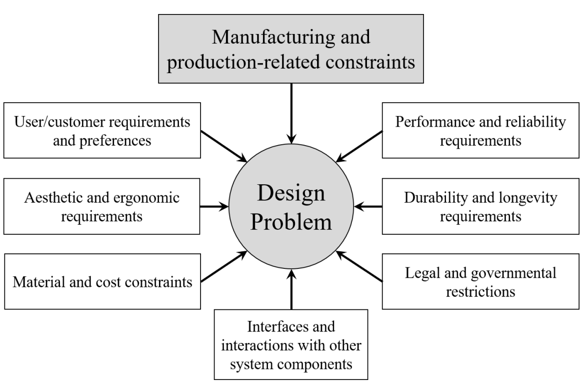

FIGURE 5: Relationship of manufacturability constraints to the design problem formulation and other design constraints

The technique described here has many similarities to existing methods for establishing design constraints from other sources; for example, constraints related to performance or reliability. The rigorous formulation of optimization problems requires the consideration of numerous use and design variables, some of which are invariably related to fabrication of the system or product. As demonstrated in Fig. 6, the manufacturability constraints are one of several sources of design constraints; this list is not exhaustive but does serve to demonstrate the fundamental place of manufacturing-related constraints.

For a hybrid process, there will invariably be conflicting and dominating constraints in the final model, due to the collection of constraints from the design problem and from the manufacturing processes. Some may or may not be necessary and should be examined carefully for potential elimination or combination opportunities. To formalize this, it may be necessary to perform a monotonicity analysis or other formulation analyses (Fig. 6) on the set of hybrid constraints [52].

Design variables	x	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9
Objective	$f(x)$	+	+	+	+	+	−	−	−	−
AM constraints	$g_1(x)$	−	−	−		+		−	+	−
	$g_2(x)$	+		−			+			
SM constraints	$g_3(x)$	−	−		−	−		+		+
	$g_4(x)$		−	+			+		−	+

+ Positive monotonicity
− Negative monotonicity
Inactive constraints
Dominated/ dominating constraints

FIGURE 6: Example monotonicity analysis of hybrid process

4 HYBRID PROBLEM FORMULATION

Manufacturability constraint formulation for hybrid AM-SM processes is similar to the approach discussed in Section 3. For the combination of several subtractive processes or several additive processes, it is expected that many of the manufacturing considerations will be common among the processes.

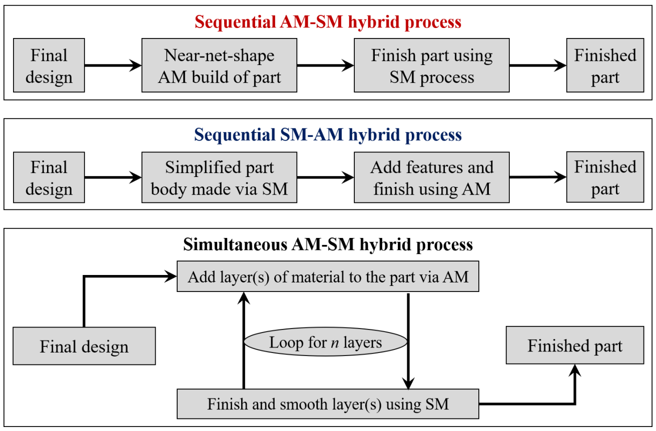

FIGURE 7: Typical hybrid AM/SM process configurations

The combination of AM and SM together presents a special problem, however, as only a few, or perhaps none, of the process attributes would be in common between them. The hybrid process could be sequential in an AM-SM or SM-AM configuration or simultaneous, as illustrated in Fig. 7. Many of the processes described thus far in the literature are simultaneous processes [49], but sequential processes of both configurations are fairly wide-spread in the literature [54, 55].

5 DESIGN CASE STUDIES

5.1 Case Study 1: Design of CNC Tool Shuttle Frame

The first study examined here is the design of the frame on a CNC machine tool shuttle (Fig. 8a). Such carts are often used in manufacturing systems to shuttle tools around to various CNC machines during processing; this way, expensive or specialized tools could be shared among several machines and mid-process tool replacements are easier to automate.

5.1.1 Problem Definition The specific tool shuttle in question is designed to carry three tools at once, up to 3.5 kg of mass each, along a linear rail via grooved track rollers; these rollers allow the cart to be tight and secure, while also allowing curves in the track. Figure 8b shows the dimensions of a sample design that has not been optimized; Figure 8c shows its mechanical configuration and free-body diagram. The cart must be able to carry the three tools, as well as support the tool holder, a total weight of about 100 N distributed evenly along the cart; applying a reasonable 1.50 factor of safety, the design force is 150 N.

The main frame is to be made from ABS plastic and manufactured via a hybrid AM-SM process. The specified concerns of the user are the mass and stability of the carriage, and potential cracking of the plastic frame. To these ends, the designer concluded that the design should minimize mass as much as possible, while also maintaining sufficiently low bending stress to avoid degrading or fracturing the plastic during use [27, 56]. Please see the Supplemental Material [57] for a more detailed description of the setup and formulation of this problem.

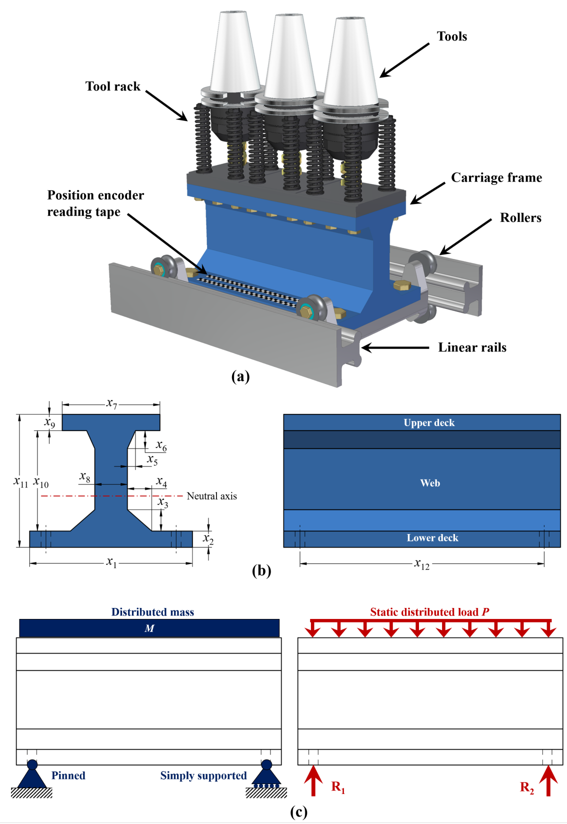

FIGURE 8: Case study 1: CNC tool shuttle frame. (a) configuration, (b) design variables, and (c) loading and free-body diagrams

5.1.2 Formulation and Solution Please see the supplemental document [57] for detailed formulation and solution of this case study. This sections gives a brief outline and summary of results.

The use of the hybrid AM-SM process to manufacture this frame allowed a two-step sequential optimization problem, using not only shape optimization over the design variables, but topology optimization as well. The hybrid process allowed for different regions of the part be optimized differently, as the part could be manufactured using both AM and SM processes in different part regions. This concept was particularly applicable to this design, as large areas of the frame needed to be flat and smooth, while others could be more free-form in shape.

In this type of problem, AM enables fabrication of regions with complex topologies, while the shape-optimized re-

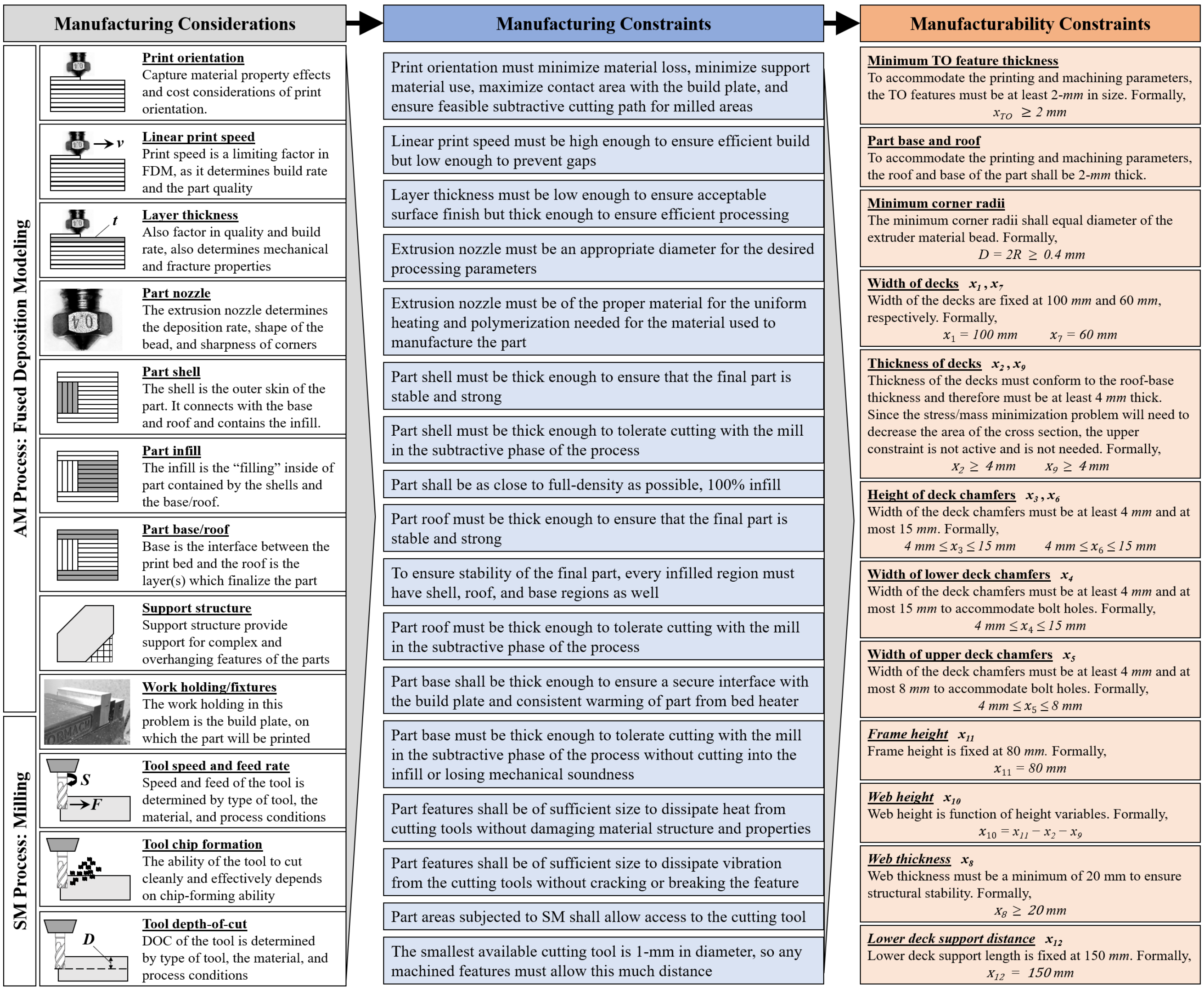

FIGURE 9: Manufacturability constraint formulation for case study 1

gions could be manufactured using subtractive processes. Due to cost and production time, it is usually best to avoid additive processes for simple geometries, such as the decks in this part; subtractive processing will be needed to bring the part to the surface finish requirements, so using it for manufacturing increases the efficiency of the process. The marriage of the two in this hybrid process also allows the hybridization of the shape and topology optimization problems to fit the intended manufacturing processes.

With the list of manufacturing considerations completed, these were converted into manufacturing constraints, shown in the central column of Fig. 9. There were eight AM- and three SM-specific considerations, as well as one that is common to them both. As a reminder, these constraints are those imposed on the use of the manufacturing processes by the nature of the manufacturing considerations.

From the mechanics and limitations of the manufacturing processes, the design-related manufacturability constraints can be derived, as shown in the right column of Fig. 9. The listed constraints are the final set, with the dominated and inactive constraints eliminated. The problem is also subject to a set of general part manufacturability constraints, in addition to those on the specific design variables, as summarized in Fig. 10.

As stated in the problem definition, the goal of the problem is to simultaneously minimize bending stress $\sigma(x)$ in the frame and the mass $m(x)$ of the frame. It is subject to five performance-related constraints and twelve sets of manufacturing-related constraints, as discussed in the previous sections. As discussed previously, the problem is a sequential shape-topology optimization problem; the formulation is shown in Fig. 11. This approach and its implications are discussed in-depth in the supplemental document [57].

After formalizing the objective function in terms of the design variables, $\boldsymbol{x} = [x_1, x_2, x_3, \ldots, x_{12}]^{\mathrm{T}}$, the composite objective

General Manufacturability Constraints

Part orientation
Part should be oriented such that the largest flat surface serves as the part base

Part symmetry
Part must be symmetric to ensure balance during use

Layer thickness
Layer thickness must allow a strong part structure even after machining. Therefore, the part must have at least five printed layers per millimeter of height.

Support material
Support material must be incorporated into the design. However, it must be easy to remove without damaging the part. Therefore, a single-wall support structure should be used, with a maximum density of 15%.

Extrusion nozzle
Based on the material and design characteristics of this problem, a brass, 0.4-*mm* round nozzle will be used.

FIGURE 10: General part manufacturability constraints

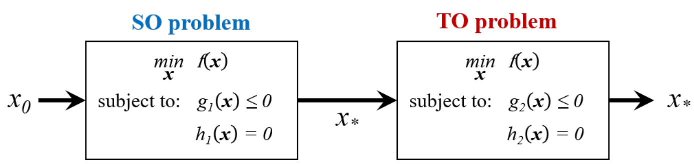

FIGURE 11: Design problem formulation for case study 1

function is:

$$f(x) = \sigma(\boldsymbol{x}) + 10m(\boldsymbol{x}) \tag{5}$$

where each objective component was normalized to make it dimensionless. In addition, the multi-objective problem may be solved directly using an appropriate method to obtain the set of non-dominated solutions.

TABLE 1: Shape optimization results

Variable	$\boldsymbol{x}_0$	$\boldsymbol{x}_*$	Variable	$\boldsymbol{x}_0$	$\boldsymbol{x}_*$
x_2	10.0	4.0	x_6	8.0	4.0
x_3	8.0	4.0	x_8	30.0	40.0
x_4	8.0	4.0	x_9	10.0	4.0
x_5	6.0	4.0	x_{10}	60.0	72.0
$f(x)$				5.9503	3.5519
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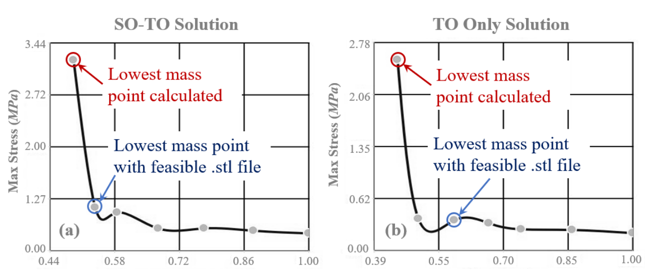

FIGURE 12: TO stress-mass curves for the (a) original and (b) SO-TO designs

As shown in Table 1, the shape optimization results $x_\dagger$ were then used as the initial points for the topology optimization problem. The TO problem was solved using the software package Pareto (Sciartsoft Inc.). Only the web and chamfers of the frame were considered during topology optimization, as previously described; surfaces subjected to SM were retained before being analyzed by Pareto. The stress-mass-fraction Pareto curve was generated for the TO problem, shown in Fig. 12a, and this was used to select the final volume fraction used to generate the optimal design. The best calculated volume fraction was 0.49 for the SO-TO problem and 0.45 for the TO-only problem. More details of the setup and solution of this problem can be found in the supplemental document [57].

TABLE 2: Shape optimization results

Case	Mass (kg)	Max Stress (MPa)	$f(\boldsymbol{x})$
Initial	0.5890	0.0603	5.9503
SO only	0.3244	0.6158	3.8599
TO only	0.3593	0.3544	3.9473
SO-TO	0.1752	1.1101	2.8621

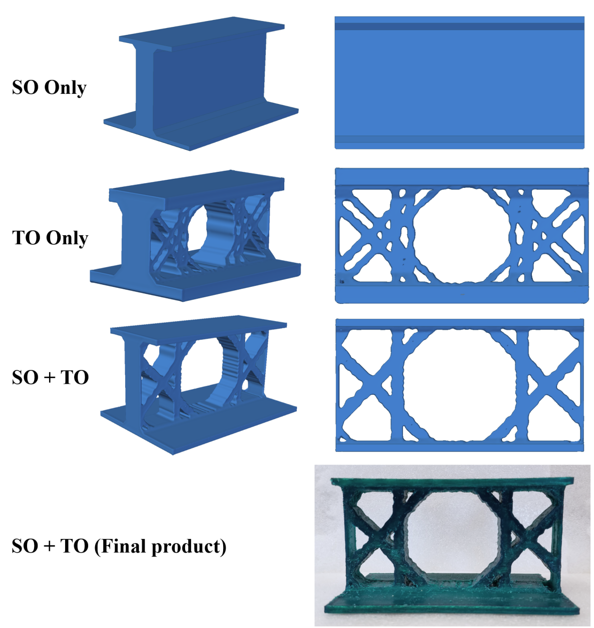

FIGURE 13: Case study 1 results

The TO problem was also repeated using the initial point (eliminating the shape optimization step) to see the effect on the TO problem. These results are illustrated in Fig. 12b. Unfortunately, the design corresponding to the lowest calculated mass volume fraction could not produce feasible stl files for either case; since the design must be manufacturable, the best feasible case was taken as the best solution (0.54 and 0.61). It was clear from examining the results that this is a consequence of using the PARETO software for the particular problem at hand and not a result of a defect with the design method (the issue did not repeat in Case Study 2).

A comparison of the mass-stress values for the original design, the shape optimization results, the hybrid problem, and the TO problem are shown in Table 2. Clearly, the hybrid problem, with shape optimization and then TO, produced the best overall feasible design, even though all are manufacturable. Figure 13 shows the geometries for these and the final manufactured frame. For the FEA and other analyses, the yield stress for 3-D printed ABS is assumed to be 29 MPa.

5.2 Case Study 2: Design of Pulley with Brake

The second case study examined a V-belt drive pulley for an electric generator illustrated in Fig. 14a. The configuration was a standard two-belt drive pulley, with the additions of a radial encoder to track its rotation and a pneumatic emergency brake. The pulley is mounted on a frame, also containing the brake and encoder, and connected to the generator via a drive shaft.

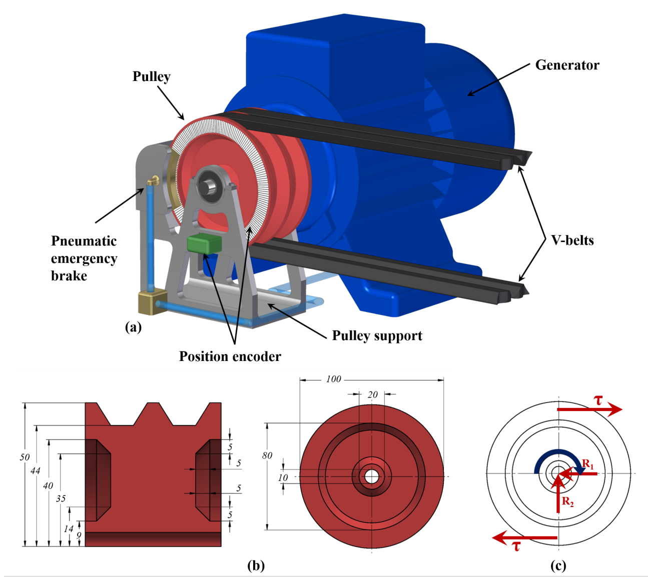

FIGURE 14: Case study 2: Pulley (a) configuration, (b) dimensions, and (c) free-body diagram

5.2.1 Problem Definition

The generator pulley being designed in this case study is subjected to a torque load during operation, a load that could peak as high as 50 N-m during ramp-up and ramp-down. If the pulley is subjected to a shock load or the emergency brake is engaged, it is designed to break, while being retained by the pulley support bracket; a factor of safety is not needed. The pulley must be made from ABS plastic and will be fabricated using a hybrid AM-SM manufacturing process. The customer needs the mass to be reduced as much as possible, while also reducing the compliance of the pulley; the reduction of mass is the most vital requirement and is a factor of five more heavily weighted than reducing compliance, as long as the compliance remains under 1.0 N-m.

5.2.2 Solution and Results

Please see the supplemental document [57] for detailed formulation and solution of this case study. This section gives a brief outline and summary of results. The approach in this problem is identical with Section 5.1, except in this design problem, the region on the edge (interfacing with the brake and the encoder), the drive shaft, and belt groves for the pulley are fixed and cannot be optimized. Therefore, only the web is subject to improvement. This can be performed by solving a single TO problem, retaining the fixed surfaces.

The frame was manufactured using a combination of fused deposition modeling and turning/facing/boring on a lathe, where the basic form of the frame was manufactured using the AM process and the interfaces and decks were cut to the proper size using the SM process. The manufacturing considerations are the same as those given in Fig. 9, with the exception of those for the milling process. The additional manufacturing considerations from the lathe are shown in Fig. 15 below. Note that Figs. 9 and 15 should be used jointly in examining this problem, which will be subjected to the same nine AM-based manufacturing considerations. The objective function for this problem, based in the stated requirements for the problem, is:

$$f(\boldsymbol{x}) = c(\boldsymbol{x}) + 5m(\boldsymbol{x}) \tag{6}$$

where $c(\boldsymbol{x})$ is a compliance metric and $m(\boldsymbol{x})$ is the mass of the pulley. The terms were normalized to make them dimensionless.

The topology optimization problem was solved using PARETO, as was done with Case Study 1. Two points were taken from the compliance-mass curve, one at the lowest mass which produced a feasible STL file, and one that balanced the mass and compliance. These are shown in Fig. 16. Table 3 and Fig. 17 show the results of this study, including both the calculated designs and the manufactured final parts.

TABLE 3: Topology optimization results

Case	Mass (kg)	Compliance (Nm)	$f(\boldsymbol{x})$
Original design	0.262	0.298	1.608
Balanced	0.218	0.338	1.428
Min Mass	0.180	0.473	1.373

6 DISCUSSION AND CONCLUSIONS

In this study, the use of practical manufacturability constraints for design under hybrid AM-SM processes was explored. A method was introduced for generating these constraints, mapped directly from the mechanics of the chosen processes. Two in-depth case studies were performed to test the real-

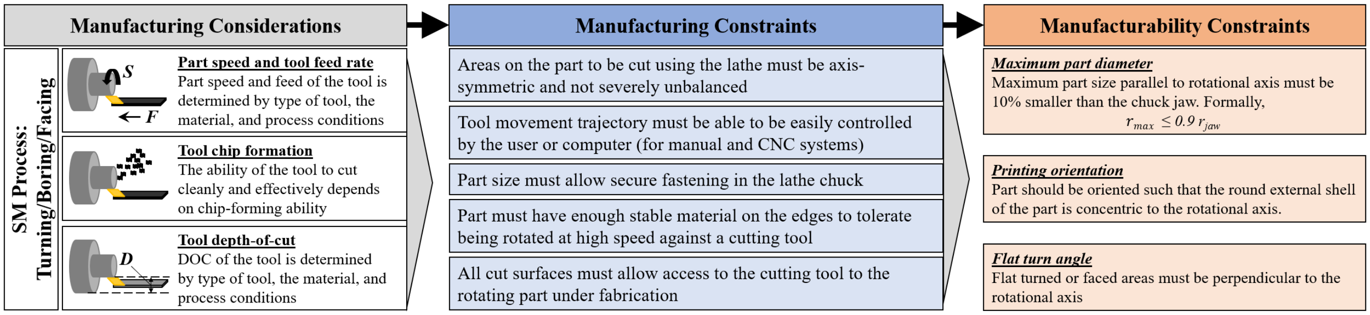

FIGURE 15: Case study 2 manufacturability constraints

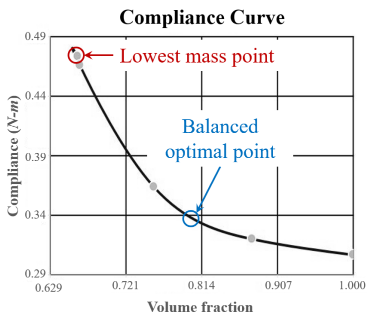

FIGURE 16: Compliance-mass curve for case study 2

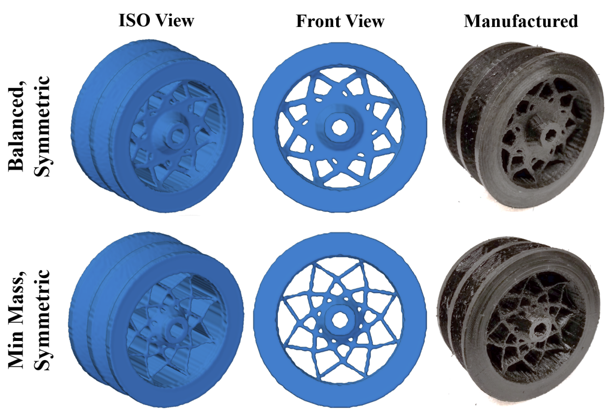

FIGURE 17: Results for case study 2

world feasibility of this method, both of which produced significantly improved designs that were highly manufacturable using the hybrid FDM-Mill and FDM-Lathe processes described earlier. The technique proposed and demonstrated in this work, once fully-developed, should be universally applicable to any practical combination of AM-SM in a hybrid process; it could also easily be adapted for a more complex fabrication plan with several different processes.

As noted in the description of the mapping technique, the introduction of manufacturability constraints into the problem helps to guide the design to a manufacturable solution. The manufacturability constraints are not the full set of constraints needed, but help to assist the others in generating the best design, while also ensuring manufacturability. One of the pillars of DFM is to simplify the parts as much as possible before fabrication; using the directly-mapped manufacturability constraints helps to simplify the parts only enough to ensure they are manufacturable using the chosen method. The geometric complexity offered by topology optimization and other optimal design methods can still be utilized alongside the use of universal DFM methods.

When adding manufacturability constraints to the optimization problem, checking first for dominated and inactive constraints can help limit increase in problem complexity and solution difficulty. Addition of these constraints also should not hinder the interpretation of the final design. The manufacturability constraints were found to be active in both case studies, showing that their presence was necessary to ensure a manufacturable design. Some simplifying assumptions, such as the aspect ratio constraint, could be treated in a more realistic way (e.g., physics-based constraint), possibly leading to improved performance while still avoiding failure. The final designs presented here are practical to make, which is an improvement over results derived from standard topology optimization methods without explicit manufacturability considerations beyond factors such as minimum radii.

Several lessons were noted in the results of the case studies, three of which stood out in particular. For Case 1, it was noted that even when satisfying all explicit manufacturability constraints, it was not always possible to generate a feasible STL file; the cause of this is likely mesh separation within the TO problem, a topic of ongoing study. Improved mesh generation strategies used in the design optimization problem may eliminate this problem. It was also noted in Study 1 that the shape and topology optimization produced very different designs, but they were almost identical in terms of their quality (i.e. objective function value). The combination of the two optimization strategies, however, resulted in a significant performance benefit not seen in either of the independent designs. Finally, in Case 2, it was noted that imposing symmetry on the TO problem produced very different results from the problem without this constraint. The best design of the five described, in terms of objective function value, was the non-symmetric design with a balance between the two objectives.

This study provided new insights into the use of manufacturability constraints, and their impact on design outcomes. It also provided an interesting view into the idea of using SO-TO hybrid optimization formulations, where the SO solution fed into the TO problem to produce an optimal design. Future work in this area should focus on the combination of different manufacturing processes, more complex process arrangements, comparison with simultaneous (or other integrated) solution methods, comparison of alternative constraint mapping strategies, and on the use of other effective design optimization strategies, such as lattice design instead of TO.

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