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GUIDED MANUAL DESIGN FOR ADDITIVE MANUFACTURING OF TOPOLOGICALLY OPTIMIZED LEGACY TOOLING PARTS

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Abstract

Design for Additive Manufacturing (DfAM) is a unique conceptual way to adapt a part for Additive Manufacturing (AM). While some of the choices made in DfAM become second nature to seasoned AM designers, inexperienced designers may not know the nuances involved in what is still a developing manufacturing technology. Topology Optimization (TO) in particular tends to create organic shapes that may not be immediately conducive to printing through AM. This paper proposes a comprehensive workflow tool to guide a designer, regardless of their experience, through the decision-making process inherent to DfAM. The guide helps the designer manually edit a legacy tooling design into a topologically optimized part that is readily manufacturable through AM. Discussion of a relevant case study follows the outline of the design tool to exemplify its use.

1. Introduction

AM is becoming more commonplace as an end-use manufacturing method and is often used in conjunction with topology optimization (TO) [1]. TO is a method of removing nonessential material from a physical part. This weight reduction adds value to the part by more efficiently leveraging material when compared with traditionally designed counterparts. The TO simulation's constraints are generally the loading conditions the part will be put under and any areas within the part that are manually excluded from the design space of the simulation [2]. The resultant geometry produced by the TO simulation typically is organic and smooth, which is often different from the blocky, simple geometries common in many traditionally manufactured parts. This is part of the reason why it is a popular pairing to design a TO part and then physically create it with AM. Using TO to reduce the weight of a part adds value to that part as per the E3 product value ideology. The E3 concept categorizes a product's value into its economical, ecological, and experience impacts [3]. Weight reduction from TO adds ecological value, while the small batch sizes and minimal waste material intrinsic to AM add economic value. These added values are especially important in the context of legacy tooling parts; a lighter tool often means less fatigue for the end-user who holds it and other parts it may interface with [4].

Despite the material reduction benefits inherent to the use of TO, conventional TO simulations typically create parts "blindly," without consideration for additive manufacturability. Therefore, some modifications may have to be made to a TO part for it to print as efficiently as possible. Laser-based powder bed fusion (PBF), in particular, has specialized manufacturing concerns, such as consideration of downskin angles, inclusion of drainage holes, and recoater friction [5]. Though complex, AM-specialized TO software does exist, entry-level designers may not have access to it.

As such, the goal of this research is to aid a designer, no matter their level of experience, in making manual modifications to geometry that has been generated with a simple, conventional TO simulation. For this paper, the focus is specifically on tooling parts. They are typically small-batch applications since they will generally be replacing lost or broken legacy parts from an established inventory of tools. Small batch applications are typically far more favorable for AM than for traditional manufacturing methods since the latter often has a high up-front cost [6].

1.1. Establishing Guidance for Design Through AM

There are many different DfAM tools that have been created to guide a designer through creating or modifying a part to be more readily manufacturable through AM [7]. Rosen et al. created a DfAM system that provides an overview of the process from start to finish. It comprises the design, CAD, and manufacturing stages, which are then further broken up into subprocesses [8]. In the context of this research, the TO simulation is interchangeable with the design stage since it generates the overall structure of the part, and the manual DfAM operations take place in adjusting the CAD model for the purpose of manufacturing. Ponche et al. further broke down the DfAM procedure into optimizing the part orientation, functionality, and toolpaths, which is the basis for the procedure laid out in Section 2 [9]. The focus of this research is the detailed stages of altering the orientation of the part and finetuning its macrostructure.

Extensive guides exist for designers who begin the part creation process from scratch with AM in mind [10], but similar principles can be applied to the act of editing a part whose general structure has already been determined. Designing or redesigning a part can be either process-driven or designer-driven, where the former is dictated by a program and the latter is manually done by a person [11]. Specific design considerations must be made in both cases: either indirectly by adjusting settings within the design program or directly through the designer’s active decision-making. Selecting the optimal orientation of the part on the build plate is consistently called out as being a vital part of the pre-printing process [6, 9, 11, 12]. The part orientation affects support material use, feature resolution, surface finish, and the anisotropy of the part due to layering [6]. Some of these attributes that cannot be adjusted further through reorientation may be achievable through slight redesigns of the part [11].

1.2. DfAM Principles Considering Topology Optimization

Topology optimization algorithms can be modified to accommodate certain features of AM, but that is not the focus of this research. To do so is mathematically intense [13, 14, 15], and strays too far from the aim of assisting a designer in modifying a TO geometry created by as simple a simulation as possible. For example, Mirzendehdel and Suresh presented a TO algorithm that attempts to minimize support material through various means as a secondary objective, but it required extensive manipulation of the programming behind the simulation solution method (Pareto level-set, in this case) [16]. Even when TO algorithms are modified to work in conjunction with AM, they still require design adjustments before they are ready/optimal to print [17, 18]. Lindemann et al. suggested several ways to go about doing this, one of which was to take the TO simulation output, apply DfAM principles to it, and then model those alterations with standard CAD features [19]. However, the details of applying DfAM principles were not laid out explicitly or robustly. Though some commercial software can merge TO and DfAM, these licenses can be very costly [20], especially in addition to CAD or slicing software, which are typically the respective preceding and follow-up steps to a TO simulation. An expensive license may not be worthwhile for a designer to purchase if these tooling redesigns are for small-batch, customized parts. AM-specialized programs can also be limited in terms of which printers they support, which is why this research focuses on manual editing of a part that can be customized for any printer. Leary et al. were able to do just that and leverage DfAM principles to create an entirely support-free design from a standard density-based TO simulation [21]. The main design steps chosen for the L-PBF-based DfAM procedure are optimizing the support use, internal voids, surface finish, and fine feature resolution, based on ASTM 52911-1, the standard for designing parts for L-PBF of metals [12]. Similar DfAM guides have been created that list out these design considerations but do not have the detail to navigate and assist an inexperienced designer through making these decisions for a specific part [22, 23].

2. Proposed Guide for Legacy Tooling Redesign

Considering these previous methods for integrating TO and DfAM frameworks, a novel design guide is proposed specifically for entry-level AM designers to modify a TO version of a legacy tooling part. The guide shows the logical progression of major phases (TO simulation and DfAM modifications) between three parts—the legacy design, raw TO part, and DfAM-modified part. The steps described in each phase are intended to navigate a designer through making informed decisions in each major step of the process. The resulting flowchart, Figure 1, is broken up into two general phases: the topology optimization simulation and the DfAM decision-making guide. After the designer accepts the results of the TO simulation, it must be re-imported into a manual CAD environment so the designer can edit the raw TO part to make it more readily printable.

In order of precedence, the main four design considerations are (1) supports, (2) closed internal voids, (3) surface finish, and (4) fine feature resolution. After each guided decision has been made, the chronological flow loops back to start at the beginning. This ensures the process iteratively analyzes every design consideration and doesn't contradict early decisions later downstream. After any changes have been made, as suggested by the yellow ovals in the figure, the likely effects of these changes are listed. For example, reorienting a part will change the support volume, where this change is symbolized by a Greek delta Δ. This change may be positive or negative, so it is shown in yellow. There are certain part redesign actions which may result in less mass or more stiffness, both of which are desirable and colored green. Conversely, negative effects, such as an increase in mass or decreased stiffness, are colored red. These effects are based on whether the designer is adding or removing material to the part. Removal of material may make a part slightly weaker, but also decrease the overall part weight. One such example is widening an internal channel's cross-section to account for post-processing. This will decrease the stiffness of the part but also its weight. The flowchart references essential surfaces (ES), which are features whose performance will be negatively affected by having a final geometry differing from the original designed CAD part. Examples of this would be screw threads, mating surfaces, or handles gripped by a user. These ES may be part of the TO simulation constraints and they will drive much of the support and surface finish-related considerations in the DfAM portion of the flowchart.

2.1. Topology Optimization Phase

Because of the cost and machine limitations of AM-specific TO software, this design tool aims to guide a user through modifying the output of a commercial, non-specialized program. This will reduce up-front costs and solidify a fundamental understanding of DfAM for companies and designers who are new to AM. Ideally the chosen simulation software should include CAD modeling capabilities to further reduce costs. The inclusion of TO capabilities is crucial, since one of the desired goals for the redesign of the proposed legacy tooling parts is to make them as light as possible. The TO simulation should include relevant objectives, which are what the simulation will try to achieve, and constraints, which will limit the simulation from achieving the objective [6]. Both are necessary components, and therefore require the designer to balance the tradeoffs of prioritizing one over the other [2]. A typical goal is to minimize weight, while constraints may be to retain strength and avoid removing material around, say, a bolt hole. The simulation will take away as much material as it can without interfering with the constraints. A more aggressive mass reduction objective is ideal, when possible, to counteract any material that may be added in the DfAM phase of the process, as will be shown later in Section 3.

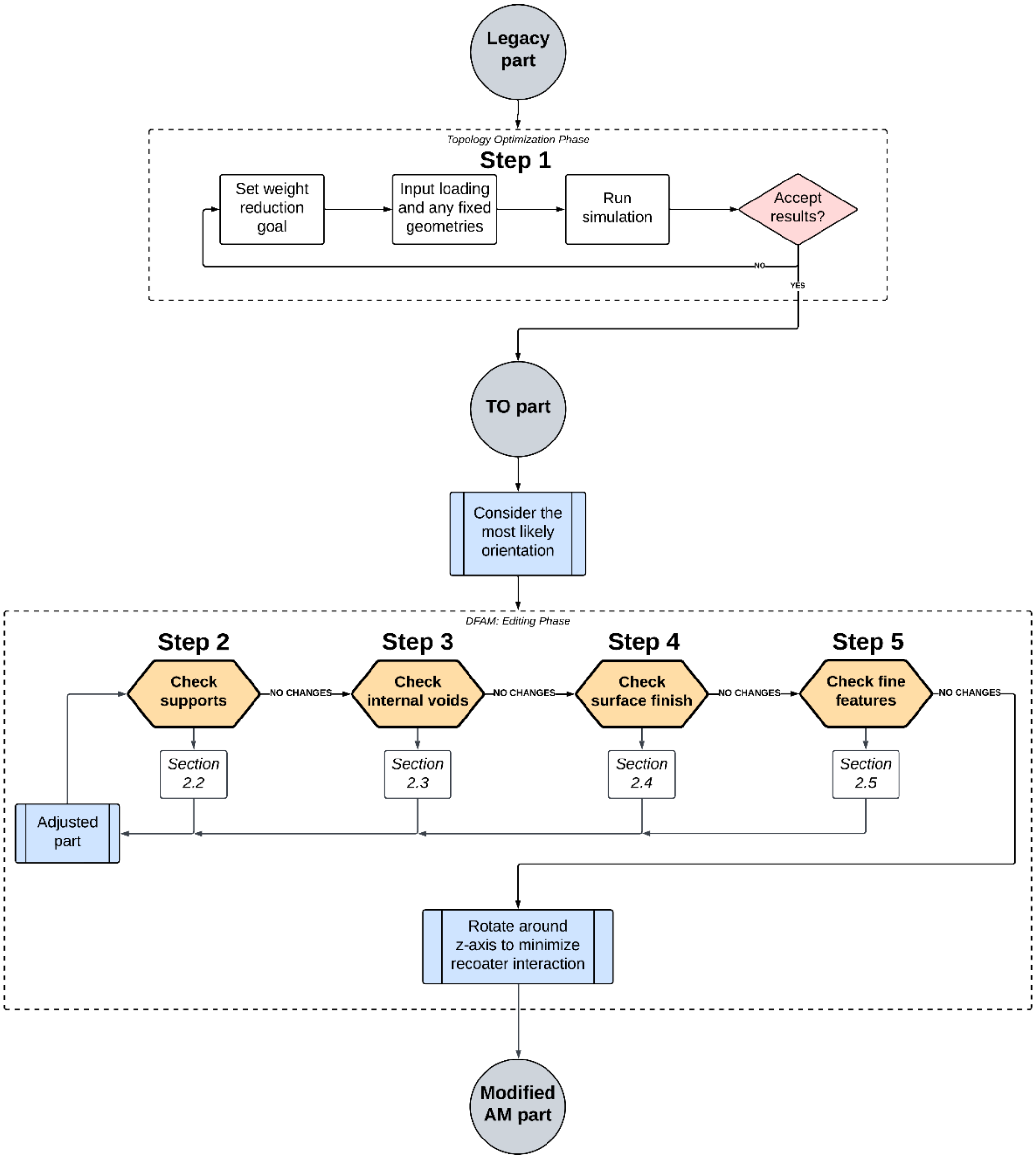

Figure 1. A simplified version of the entire design guide for legacy tooling redesign. Each step, noted in orange boxes, has its own subtree(s) shown in the corresponding Figures 2 through 5.

2.2. Checking Supports

Supports are a necessary component of AM, but inevitably waste material, degrade surface finish, and increase post-processing time after the printing process is complete. Therefore, reducing support material use will typically make the part more easily manufacturable. Some TO programs will have the option to minimize support material prior to generating a design, but this decision framework aims to assist a designer who needs to alter support material manually. As a general rule, surfaces that have an overhang less than 30-45° in the ZX or ZY plane will require support material beneath it to print [12, 24]. TO simulation results often include such overhangs, unless AM rules are incorporated into the algorithm. The three subcomponents in this design step are eliminating support interfaces with ES, reducing the amount of support needed, and ensuring the supports can easily be removed after printing.

Eliminate Support-ES Interfaces. The first stage in the DfAM process is to check if support is interfacing with ES. It will be difficult to completely remove these supports after printing, which will disrupt the functionality of the ES. Since these surfaces cannot be redesigned, the only option is to reorient the entire part [12]. The designer should check to ensure this reorientation does not place the part out of bounds of the print volume [19]. If it does, a different reorientation should be attempted. In cases where support cannot be eliminated from the ES, a designer should aim to remove as much support material as possible via reorientation in this iterative manner.

Reducing General Support Use. Now that supports on the ES have been taken care of, the designer can begin reducing the overall volume of support material across the entire part. Reorientation is typically the quickest, most intuitive route to save material, since it does not involve an extensive redesign of the part [12]. Reorientations should aim to maximize the number of surfaces that are at or above a 45° angle with the build plate, since these will not require support material. After reorienting, it is important to check that the part remains inside the build volume and that the reorientation did not cause supports to interfere with any ES. If the newly oriented part cannot fit in the build volume or it now has support-ES interfaces, a new orientation should be attempted. The designer should attempt another orientation to further reduce the support material until no more improvement in support volume reduction is seen. A new reorientation would entail checking again if the part is outside the build volume and if supports interfere with an ES.

The designer then reaches the decision of whether a part redesign would reduce support use. If the part cannot be redesigned, the designer should follow the arrow that exits Step 2 and returns to the main four steps in the DfAM portion of the flowchart. If these overhangs can be redesigned, the designer should decide between either adding or removing material in the following ways: the angle of the surface in the ZX or ZY plane can either be adjusted so it is greater than the minimum self-supporting angle or the material beneath it can be filled in. Increasing the angle of the overhang will generally reduce both the mass of the final part and its stiffness, while filling in the area beneath the overhang will increase both. While reducing the part mass would better fit with the overall goal of the TO of the part, it may not always be possible, which is why the designer is presented with this choice.

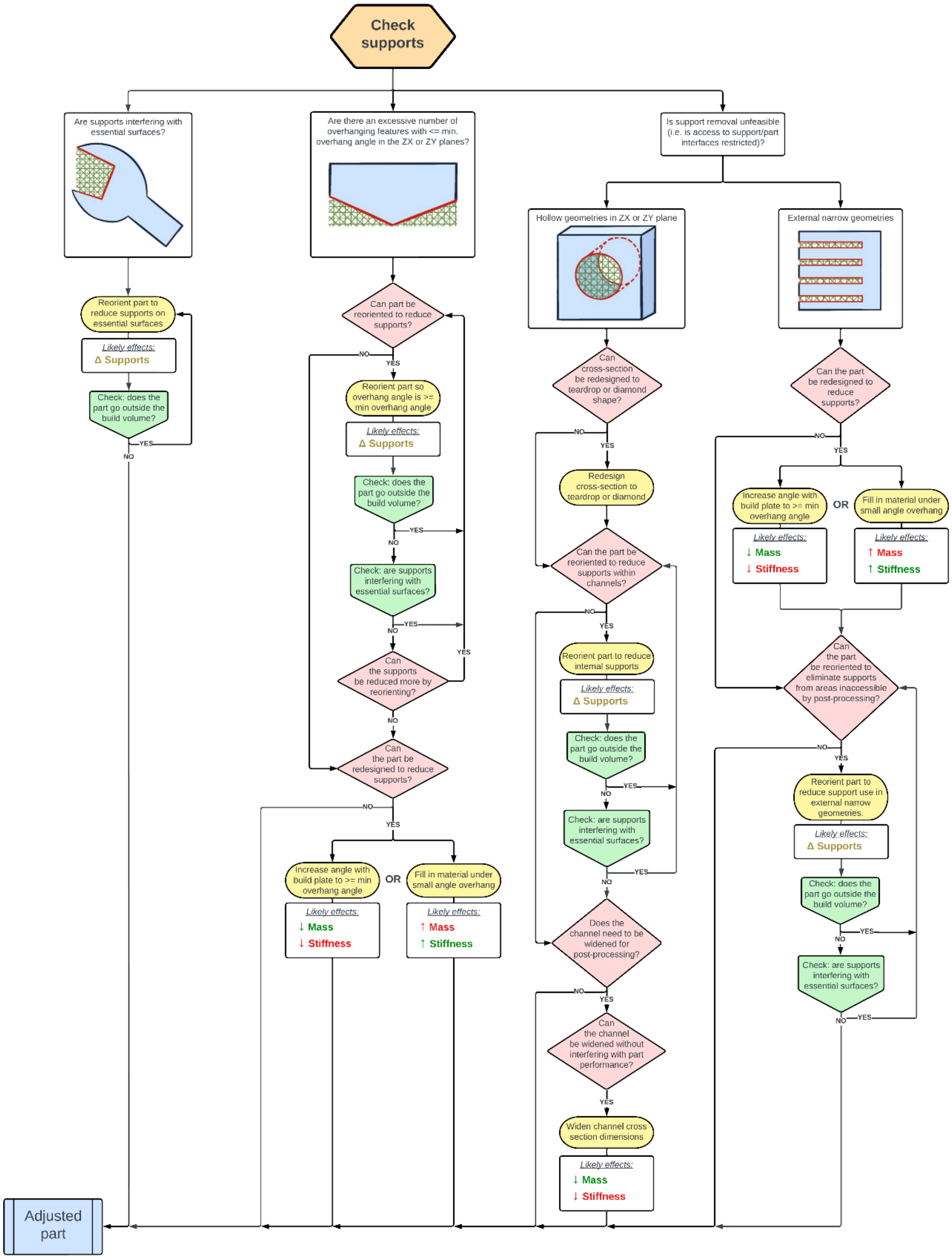

Figure 2. Fully detailed sub-trees for Step 2: Support Removal.

Facilitating Support Removal. Being able to remove supports from a part is crucial as they are intended to be temporary and may interfere with part performance if left in place. The general concepts in this section are to avoid support use internally, where it would be difficult or impossible to access them, and to ensure external support is accessible to support removal tools.

Hollow geometries in the ZX or ZY plane, such as internal channels or holes, can be difficult to access after the part has been built. However, they can be redesigned to have diamond or teardrop shaped cross-sections, which don't require support material [12, 24]. If the hollow geometry cannot be redesigned to have an alternative shape for the cross-section, the entire part should be rotated so the cross-section of the hollow geometry is parallel to the build plate. Once again, any reorienting should include a check that the part does not exceed the build volume and does not add support material to ES. If it does either of these, a different orientation should be attempted. The hollow geometry should also be wide enough to post-process for an improved surface finish, i.e., with bead blasting or a small file, if that is necessary for the part to function (i.e., fluid flow). If the hollow geometry is an ES, allowing post-process access is vital. If the channel is too narrow to accommodate post-process tools, it should be widened. External features should also be far enough apart that support material between them can be removed; this will depend on how the supports are intended to be removed after printing. For example, needle-nose pliers will not need as much space to remove supports as regular pliers. The external features should first be redesigned, if possible, to accommodate post-processing. If the part cannot be redesigned, the designer should attempt rotating if it will reduce support in the region in question. However, rotation should be a last resort by this point to avoid adding in support elsewhere, as this stage should already have minimized support use across the entire part and ES.

2.3. Checking Internal Voids

In L-PBF, it is important to avoid voids that have no outlet to the external environment surrounding a part. Since the powder feedstock is present in every layer and only solidifies where the final part will be, powder will get trapped inside voids that are completely enclosed [12]. The way to avoid this is to put in drainage holes, so the powder can be poured and vacuumed out of the part once the build has finished. So, if the part has any fully enclosed surfaces, drainage holes should be added to allow the powder to escape. The drainage holes should be designed with a cross-section that does not interfere with prior decisions, such as internal channels in the ZX or ZY plane requiring diamond or teardrop shapes. The size should be several times larger than the largest particle diameter noted on the powder size distribution (PSD) for the feedstock that will be used to create the part. A suggestion would be five times, or greater, than the maximum of the PSD or the focus diameter of the machine in question, whichever is larger. This ensures that the machine can still create the holes and that powder should pass through them without a problem.

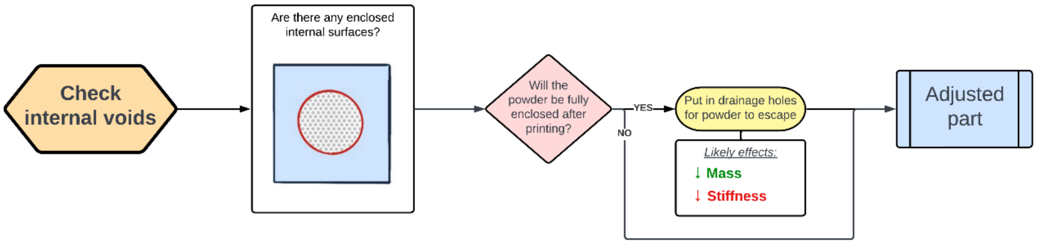

Figure 3. Fully detailed sub-tree for Step 3: Checking Internal Voids.

2.4. Checking Surface Finish

Surfaces that are printed on downward facing overhangs are called downskin, and they typically have a poorer surface finish than upskin surfaces since they meld with some of the loose powder beneath [12]. Therefore, if the part has any ES printed as downskin, the designer should evaluate whether this is acceptable [24]. Some factors that go into this decision may be whether the surface finish of these downskin sections can be improved by post-processing and whether enough of the ES is printed with downskin that it will present a problem.

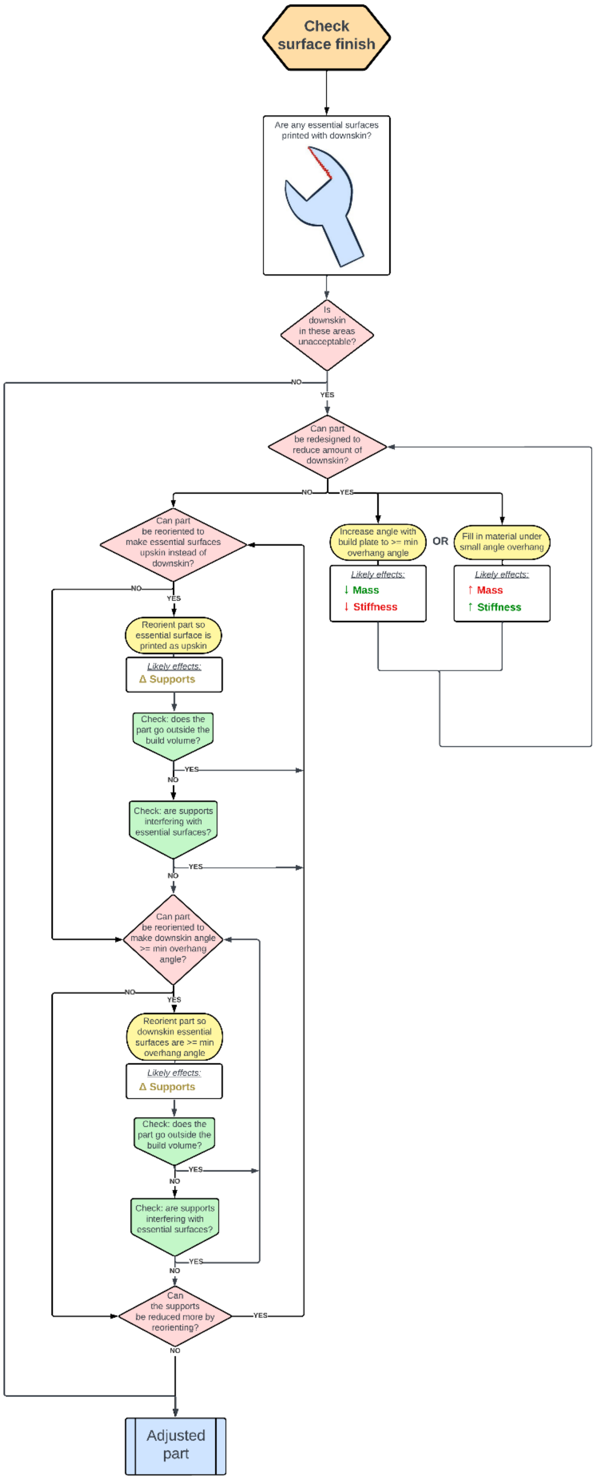

Figure 4. Fully detailed sub-tree for Step 4: Checking Surface Finish.

If only a small portion of the ES will be downskin, it may be acceptable to achieve the desired surface finish with special post-processing. If it is not, the designer must decide if the part can be redesigned to reduce the amount or increase the angle of downskin. If the part can be redesigned, the designer should attempt one of these methods. If the part cannot be redesigned to reduce the downskin of ES, the designer may try reorienting. However, this should typically be a last resort. Generally, it is more time and cost-efficient to select an orientation that best reduces the support volume rather than prioritizing reducing the downskin in ES; the latter may result in a large volume of support waste and may affect more of the surface finish on the rest of the part. If the designer decides that the downskin of the ES is unacceptable, the part may be reoriented so that the ES is printed as upskin.

2.5. Checking Fine Feature Resolution

At this point, there should be no further large changes to the part design; this stage should be minimal adjusting of fine features. One of the limitations of any AM process is its feature resolution. For L-PBF, this is reliant upon the laser spot size, which is the diameter of the laser where it contacts the substrate. Commercial printers typically have the minimum feature size, which is the solid feature measurement that can be printed with as few consecutive laser passes as possible, listed as part of its specifications. Negative spaces between adjacent features and the size of positive features need to be considered for the laser resolution to achieve final part accuracy.

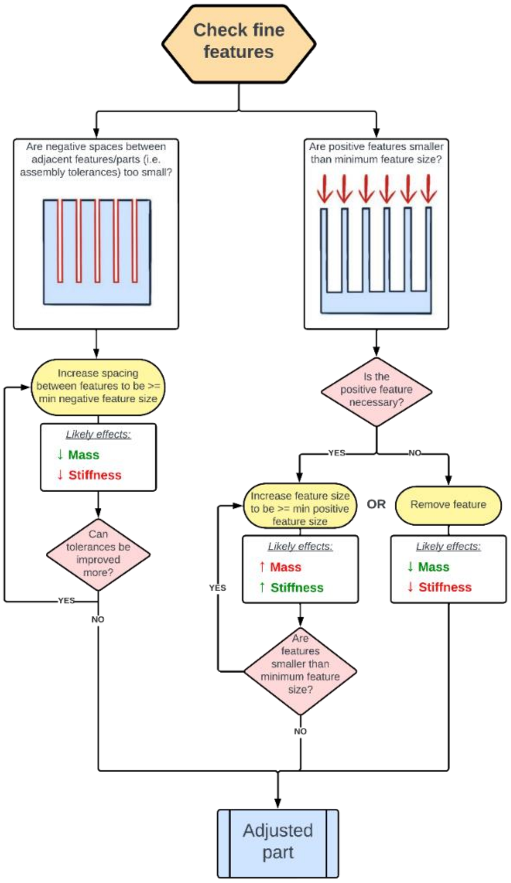

Figure 5. Fully detailed sub-trees for Step 5: Checking Fine Feature Resolution.

Adjusting Positive Features. If there are small positive features, there is a chance they may not print [12, 24]. If the features are smaller than the prescribed minimum feature size, they must either be eliminated (if deemed unnecessary) or thickened to match the minimum positive feature size. TO simulations often result in symmetric parts, either due to symmetric loading conditions or an intentional design constraint, so features that are asymmetric could potentially be considered for elimination. When stiffness is used as the TO objective, the designer can also observe if these features only connect to the part on one end. In such cases, features that protrude from the part and truncate before connecting somewhere with the part again do not add strength to the part and can be eliminated.

Adjusting Negative Features. If the negative spacing between adjacent features is too close, the printed material will sinter together [12, 24]. The features will not be distinct as they were designed to be. This can be avoided by increasing the spacing between adjacent features to be at least the minimum negative feature size. Once again, for symmetric design spaces undergoing symmetric loading, the symmetry of the part can be used as a guide to determine the necessity of these negative spaces. These negative spaces can also be considered unnecessary if the volume they take up is reasonably small. A sample metric for this could be if the negative space is less than or equal to five times the minimum positive feature size. If the designer decides that the spaces are unnecessary based on such a metric, the negative space can be intentionally filled in with material.

2.6. Rotating Part to Minimize Recoater Interaction

In L-PBF, the powder feedstock is spread over the build plate by a long, thin recoating mechanism at the start of each layer. Since the layers are on the micron scale, the recoater comes very close to the part on the prior layer and can cause friction if there are any discrepancies in the height of the solid part. Therefore, a common practice to reduce friction with the recoater is to rotate parts around the z-axis, typically so they are approximately at a 45° angle with the recoater blade [12].

3. Wrench Case Study

In this section, the workflow from Section 2 is demonstrated as applied to a simple wrench design. This legacy part was chosen because of the large amount of solid material that can be used as a design space. It has historically been created with traditional manufacturing methods, but a fast turnaround rate to replace a broken or lost part by quickly printing a new one would be valuable. A weight reduction will improve the ease of use for the end user and ensure a more efficient build. The legacy part has two holes that interface with other parts, which must be excluded from the design space, and since the part is not flat, it will require adjustments to reduce support material that will showcase the decisions made through following the design guide. The original part is shown in Figure 6. The part is fixed at the square end with an assumed torque of 34 Nm applied on the interior of the circular end. A plain alloy steel was used for the sample material.

3.1. Topology Optimization of Legacy Design

Using SolidWorks 2022, the TO simulation was set up with the goal to reduce the part weight by 85%. The raw output of this simulation is shown on the right side of Figure 6. This aggressive goal was chosen to account for some material that may have to be added back in during the DfAM adjustment phase. The two ES of this part are in the interior of the circular and square cut-outs, which is where the part will interface with other tools. Since these surfaces are assembly interfaces, their geometry must be as close to the CAD model design as possible. Note that the middle of the part is not intended to be a handle, and therefore is not considered an ES.

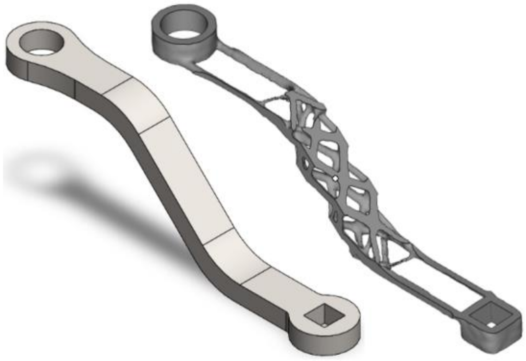

Figure 6. Legacy (left) and raw TO (right) wrench designs.

3.2. Checking Supports

Before beginning the DfAM portion of the flowchart, the raw TO part must be imported into slicing software that has support-generating capabilities. Materialise Magics 26.0 was the program used for this case study, and an EOS M280 profile (including build volume size) was chosen. Note that each orientation/edited part has been placed on the build plate with the software's "default position" translation operation. This places the part as close as possible to the origin on the build plate and raises it half an inch above the build platform. Supports will be generated to fill the void between the part and the build plate to ensure the part is not damaged during removal post-print. Figure 7 shows the automatic part orientation with non-solid supports shown in blue. The support volume use, 0.1683 in^3 in this case, is noted for comparison in potential future orientations.

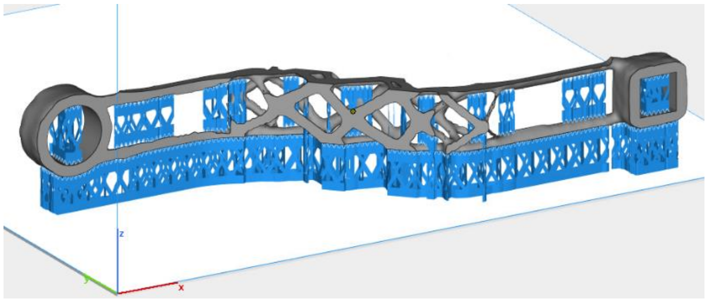

Figure 7. Wrench imported to Materialise Magics in automatically generated orientation. Supports are shown in blue.

Eliminate Support-ES Interfaces. Following the flowchart, the first support sub-tree is concerned with supports interfacing with ES. The automatic orientation in Figure 7 places supports inside the circle and square cutouts on either end of the part. These are ES and therefore cannot have support interfaces, so another orientation should be tried. The most apparent orientation to reduce support use in ES is to rotate the part 90° around the x-axis so it stands upright, as in Figure 8. The user should check that the part is still within the build volume and is the appropriate distance from the build plate for removal after printing. This satisfies the ES preservation sub-tree, and the user can move onto the next sub-tree, noting that the support volume has now increased to 0.3512 in^3.

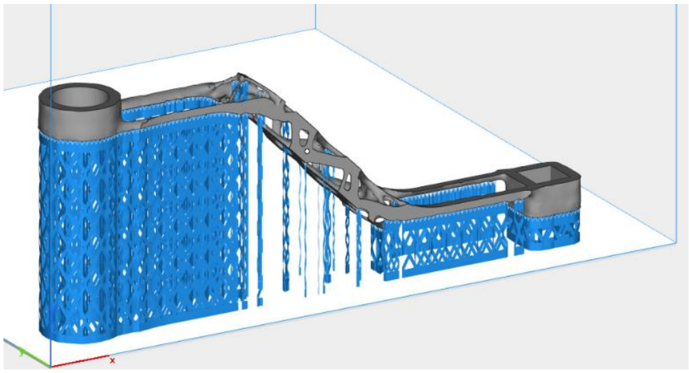

Figure 8. Wrench rotated to eliminate support use interfacing with ES.

Reducing General Support Use. The next sub-tree is concerned with general support volume. The second orientation, while eliminating the amount of support material that interfaces with ES, has increased the overall support volume. The first question is whether the part can be reoriented without interfering with the goals of prior reorientations. If so, multiple reorientations should be attempted until the support use has been minimized. Figure 9 shows the result of these iterations, where the part is now angled on the build plate. Each reorientation should be checked to ensure it still fits within the build volume of the machine. The reorientation found to be the most helpful was a rotation of 50° around the x-axis from the original raw import. The support volume is now 0.1032 in^3, which is a 70.62% reduction of material from the second reorientation.

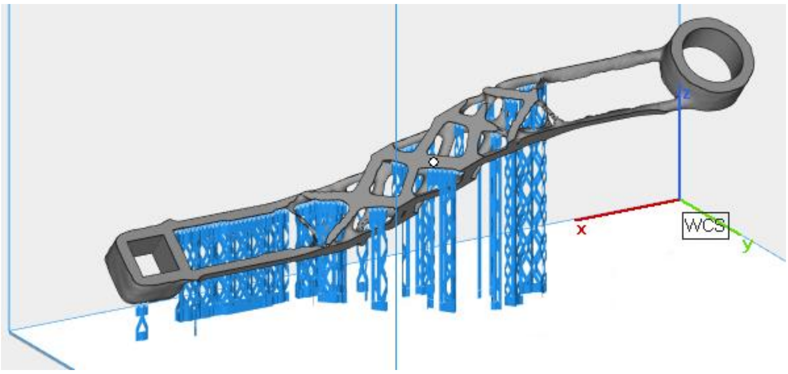

Figure 9. Wrench rotated to reduce support use across the entire part and on ES.

Now that the part has been reoriented as much as possible to reduce support use without interfering with the ES, the designer can attempt to redesign part surfaces to reduce support use. There are small areas where the overhang angles might be altered to reduce the use of support material beneath them. These are numbered in Figure 11A. The areas were identified because they use a large, typically tall, amount of support material. These overhang angles could either be increased or decreased, as shown in Figure 10, which displays a closeup of Area 2 in Figure 11A. However, if the angle is decreased, the supporting member that comprises the overhang will be cut off and eliminated, which is undesirable. Major changes to the TO like this could have a negative impact on the strength of the final part. Therefore, the blue arrow in Figure 10 should be chosen to increase the angle of overhang for Area 2, which will add part material to reduce support material. This same scenario presents itself for Areas 1, 3, and 4, and material was added in all four situations to reduce the support use. The result of these changes is shown in Figure 11B, which reduced general support use by about 6.5% from the orientation chosen in Figure 9.

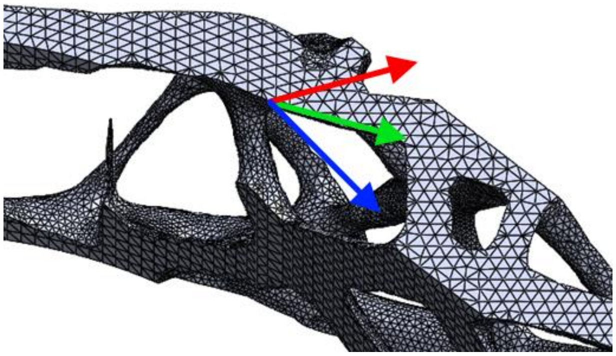

Figure 10. Diagram of potential fixes to improve support use on a member. The angle of the overhang (shown in green) can either be increased (blue) or decreased (red).

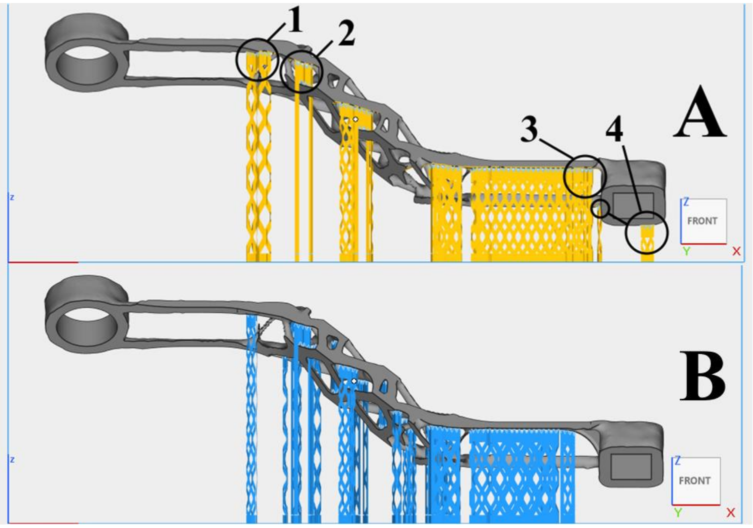

Figure 11. Wrench geometry after completion of major reorientations from front before (A) and after (B) redesigning to decrease overall support volume. Multiple annotated supports are noted in A that were removed or lessened in B.

Facilitating Support Removal. The next sub-tree in the chart is to consider the feasibility of support removal. While there are no hollow geometries in this part, there are many external narrow geometries within the lattice that will need support material to be removed after printing. Several examples of this are pointed out in Figure 12A. Following the flowchart, the part can be redesigned to improve the use of support material in these locations. The roughly square-shaped cutouts created by the lattice (see Areas 1, 2, and 3 in Figure 12A) can be considered the overhangs, which means that they can either be manipulated so the angle with respect to the build plate is 45° or greater, or the material can be filled in completely. Similar to the changes made in the general support sub-tree, if the angle of the overhang were to increase, it would reduce the member above it to a thickness smaller than the minimum feature size or eliminate it entirely. Since this member was identified as necessary by the TO simulation, removing it is not an option. Instead, material should be added to fill in the space beneath the overhang, as shown in Figure 12B. Recall that the aggressive weight reduction goal in the original TO simulation allows for adjustments like this to be made. Note that the supports on Area A3 were not eliminated, but the supports that connected that overhang to the rest of the part have been made unnecessary.

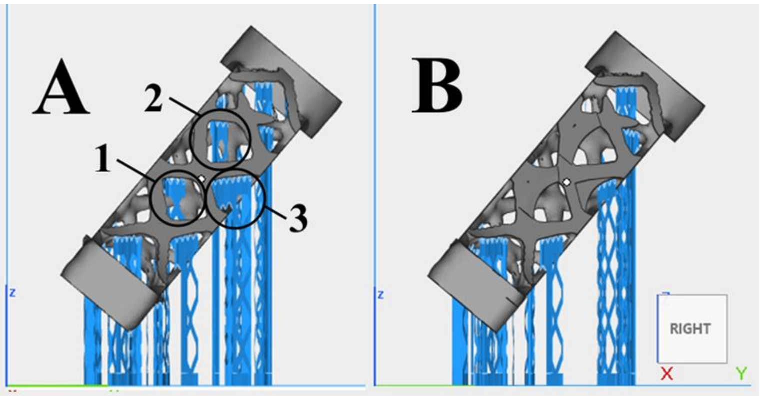

Figure 12. Comparison of support use in internal lattices before (A) and after (B) adding material.

3.3. Checking Internal Voids

The next step in the flowchart is to ensure internal voids have powder drainage holes. This part has no true internal voids, but the interior of the lattice can be considered such for the purposes of the case study. The EOS M280 has a laser focus diameter of 100μm [25], so if a sample PSD ranges from 20-80μm [26], the designer should create drainage holes of diameter 0.5mm, based on the five times rule suggested in Section 2.3. The large cut-outs in the lattice are more than sufficient for powder drainage purposes, so no drainage holes need to be added to the part.

3.4. Checking Surface Finish

There are portions of the ES that will be printed with downskin in the current orientation, which can be a concern for surface finish. If this is unacceptable, as the flowchart prompts, the designer would need to choose a different orientation. In this scenario where the downskin is unacceptable for the ES, the designer would return to the second orientation (Figure 8) and then proceed back through the support redesigning stage with that as the permanent orientation. However, the geometry of the ES in the wrench is very simple and could easily be machined in post-production if the tolerances were extensively disrupted in those areas. Therefore, the current orientation will be retained for the duration of the case study, since the designer is aware of the downskin but has decided it is acceptable not to prioritize.

3.5. Checking Fine Feature Resolution

The final design step is to consider minimum feature size. A sample laser resolution of 500 microns was used to test minimum feature size, so positive features cannot be smaller than this and negative spaces between features cannot be closer than this.

Adjusting Positive Features. The two yellow highlighted regions in Figure 13A show positive features that were measured with the Evaluate tool in Solidworks and found to be much too small for the laser to resolve with a resolution of 100μm. Area 1 is an incomplete strut, which is a common occurrence in TO simulations. This appears to be an inconsequential artifact left over from the simulation. It is not load-bearing, as it does not connect anywhere, and it is not mirrored on the other side. Therefore, it appears to be safe to say that this member is not necessary and can be eliminated. Conversely, the member highlighted in Area 2 is connected to multiple other portions of the part and has a strut that mirrors it on the other side of the part. Thus, this member is a necessary feature, and was consequently thickened.

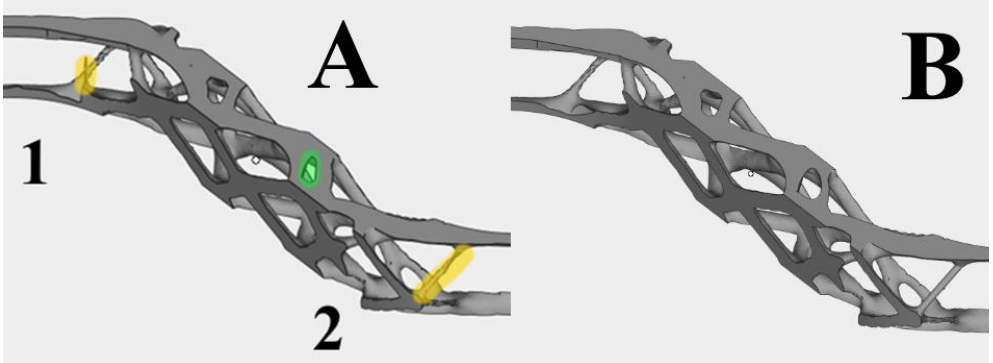

Figure 13. Wrench with yellow highlighted areas indicating positive features and green indicating negative features that are too small to resolve before editing (A) and after editing (B).

Adjusting Negative Features. The green highlighted area in Figure 13A has a lateral width of about 2.4mm, which is approximately 2.5 times the laser resolution. This area is below five times the minimum feature size threshold, and thus should be adjusted. Since it is close to this value and has thick struts around it, the negative feature should be widened. A similar gap is present on the back of the part, but the width of the second gap is only 0.737 mm wide. This gap is much too small to consider keeping, and thus should be filled.

Rotating Part to Minimize Recoater Interaction. Finally, with the major XY reorientations and redesigns completed, the final change to the part must be rotating it 45° about the z-axis. This will be especially important for the top and bottom sections of the part, where there would otherwise be long stretches of the recoater dragging along the part. This change is shown in Figure 14, where the recoater moves up and down, spanning the width of the build volume from left to right.

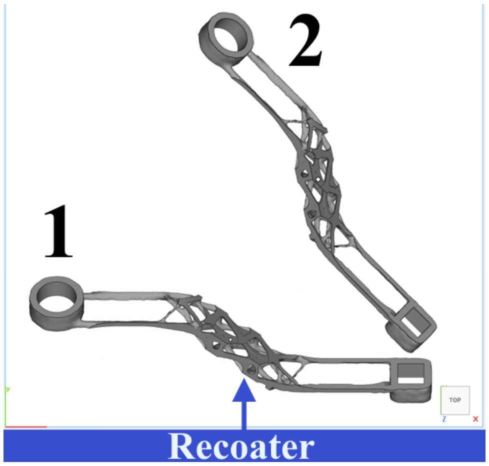

Figure 6. Two orientations of the final modified part in the build chamber. 1 is the original orientation after DfAM and 2 has been rotated to minimize friction with the recoater.

These changes complete the final part build, in Figure 15. Table 1 shows how each major change to the part affected the volume of itself and of its support. Note that only 3% material has been added to the final part, while the support volume has been reduced by more than 50%. The figure numbers in the first column of the table direct the reader back to the relevant image in this paper.

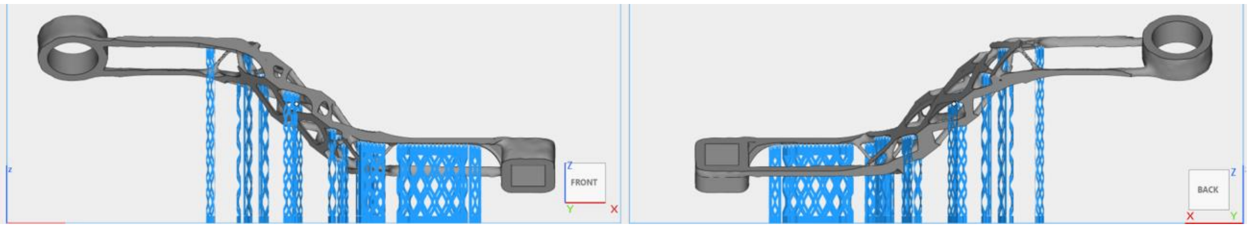

Figure 75. Supports necessary for final, DfAM-optimized wrench geometry.

Table 1. Changes in part volume and support volume throughout case study.

Figure	Action	Goal	**Part**			**Supports**		
			Volume [in^3]	Δ Volume	Δ from Raw TO	Volume [in^3]	Δ Volume	Δ from Raw TO
7	Raw TO	–	0.6916	–	–	0.1683	–	–
8	Reorientation	Preserve essential surfaces	0.6916	0.00%	0.00%	0.3512	108.67%	108.67%
9	Reorientation	Reduce support use	0.6916	0.00%	0.00%	0.1032	-70.62%	-38.68%
11B	Redesign	Reduce support use	0.7029	1.63%	1.63%	0.0964	-6.59%	-42.72%
12B	Redesign	Improve support removal in lattice	0.7127	1.39%	3.05%	0.0840	-12.86%	-50.09%
13B	Redesign	Adjusting fine features	0.7124	-0.04%	3.01%	0.0819	-2.50%	-51.34%

4. Conclusion

Though TO is often used in conjunction with AM, there is still a knowledge gap regarding the DfAM of the TO part. This work has established an initial guiding flowchart for a designer to utilize when transforming a legacy tool design into a topologically optimized, ready-to-print part. A case study was presented with a wrench that followed the flowchart from start to finish, elaborating on crucial steps throughout the process. The final part design and orientation reduced the support material use by more than 50%, with a final support volume of 0.0819 in^3. The final part itself had a little over 3% of the original material volume added to it, for a final weight reduction of 80% from the legacy part.

This guide, while detailed in the areas it does present, is not all-inclusive. The ASTM standard for L-PBF also recommends selecting a build direction with respect to loading conditions, avoidance of large part surfaces to mitigate warping from thermal stresses and minimizing z-height of the part to reduce build time. This design guide is intended to be an educational introduction to DfAM in the context of manually adapting a TO tool. Therefore, its focus is on facilitating a designer's fundamental understanding of basic DfAM principles, and operates under the following assumptions: first, that the printer will not fail during the build and second, that the priorities included in the design guide are more important than minimizing the build time. Additionally, the main macrostructure is determined by the output of the TO simulation, so only minor edits can be made. Future research should elaborate on these other design stages to create a more realistic, comprehensive guide and potentially print and mechanically test parts to document physical progress between the legacy, TO, and DfAM-optimized parts.

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