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Title: Automated Rapid Manufacturing Feedback for Design Considering Advanced Joining Processes

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As manufacturing advancements continue to develop, designers must be able to consider these technologies during the design process. Unfortunately, many of these new technologies, such as additive and advanced joining, have many nuances that require expert knowledge to effectively apply. Additionally, new design techniques, such as topology optimization, allow users to create geometries that are traditionally not manufacturable. The approach presented in this thesis bridges the gap of expert knowledge between component design and a new advanced manufacturing technique, specifically linear friction welding to form monolithic components from multiple individual raw material blanks. The first step of the approach analyzes a part geometry to determine the unmachinable regions. This is done by converting an input tessellated shape into a voxelized solid and analyzing different axial cutting tool approach directions that could occur during a milling operation. Areas that the tool cannot access remain, which indicate regions of unmachinable solids. These solids are then used to determine areas where pre-joining machining could occur, taking advantage of the capabilities of linear friction welding. This is done using an existing part decomposition method while using a two-objective search optimizing total cost of manufacturing and total unmachinable volume. Decomposition configurations yield new set-ups of individual sub-volumes to determine unmachinable volume remaining and manufacturing plans are created by rebuilding the configurations to determine total cost of manufacturing. Results of the work demonstrate the ability to determine manufacturing plans and the potential tradeoffs of complex geometries, processing, and costs.

AUTOMATED RAPID MANUFACTURING FEEDBACK FOR DESIGN CONSIDERING ADVANCED JOINING PROCESSES

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CONTRIBUTION OF AUTHORS

Chapter 3: Manuscript 1

Prof. Matthew Campbell was integral in the development of the voxelization library and provided feedback regarding functionality of the library within the machining analysis. Prof. Karl Haapala provided input on the model functions to accurately represent machining capability. Both contributed in writing of this conference article and provided input and direction to the work.

Chapter 4: Manuscript 2

Prof. Matthew Campbell contributed to the development of the multi-objective optimization and voxel solid tracking within the manufacturing plan search. Prof. Karl Haapala provided guidance and assistance in creating the process and cost models used in the manufacturing plan creation. Both contributed in writing this journal article and provided input and direction to the work.

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1 INTRODUCTION

This chapter will present and introduce the research developed herein. An overview of the research area and background of research topics are offered. Furthermore, the research objectives, tasks, and outline of the thesis are detailed.

1.1 Overview

Keeping up with the advancements in manufacturing technologies is becoming an increasingly difficult task for engineers. For example, over the past half century, engineers in the aerospace industry have developed expertise in machining monolithic parts from a single workpiece – often using hard metals, such as titanium and stainless-steel alloys. However, these methods produce significant volumes of waste material, resulting in hidden environmental and economic costs to industry and society. Developments in advanced additive and joining processes can allow manufacturers to save significant amounts of material in comparison to traditional subtractive methods [1]. Additionally, these new processes can allow new geometries to be manufactured that could not be made with subtractive processes alone.

While manufacturing technologies have progressed, new design methodologies have also come about. Advancements in topology optimization allow designers to create parts that can withstand the near-exact load case while minimizing the mass of the part. A key challenge, however, is that the parts generated by these optimizations exhibit complex geometries, making them difficult or impossible to manufacture through conventional methods, such as forging and machining. Attempts have been undertaken to implement manufacturability constraints into the optimizations, but the search for a robust consensus solution to the problem has had limited success.

Design methodologies and manufacturing technologies are advancing rapidly, and the expertise required to effectively apply these developments is becoming increasingly cumbersome for design and manufacturing engineers. In short, the knowledge gap between product design and manufacturing is growing. This knowledge gap can be addressed through more automated manufacturability analysis.

Manufacturability analysis systems can allow design engineers to receive rapid feedback early in the critical design stage so that final manufacturing process design can be done more easily [2]. The methods discussed in this thesis attempt to bridge the expanding knowledge gap between the two fields by providing designers with manufacturing plan feedback that can be used iteratively in the design stage. Manufacturability analysis is not a new concept; currently available solutions employ identified features in the design to determine machining operations [3]. The method developed and presented here utilizes a tessellated shape to implement an entirely featureless approach to manufacturability analysis. Thus, the method is not tied to a specific computer-aided design (CAD) program to present manufacturing analysis results to the design engineer. The presented results will allow designers to correlate part geometries and complexities to costs and processing required to manufacture the part. This rapid feedback with cost, processes, and design changes will allow designers to justify designs or change specific features early in the design process.

1.2 Background

In aerospace manufacturing of titanium alloy (Ti-6Al-4V) aerospace parts, machining has traditionally been the primary method of fabrication. Aerospace components undergo rigorous testing and validation to be qualified for use on aircraft

[4,5]. Material properties driven by metals manufacturing processes can dictate whether or not a part is airworthy. Their relatively new technical development and rapid technology change puts additive and advanced joining techniques in a difficult position to be able successfully penetrate the industry. Some new technologies, such as linear friction welding, have been demonstrated to provide material properties that are close to the parent materials in the join [6,7]. This offers an advantage over conventional production since it has the potential to create parts that can compete with forged components. Creating a manufacturability analysis system for titanium components considering linear friction welding and machining can aid the development of cost-effective aerospace components with geometries not achievable using the conventional forging and machining route.

1.3 Problem Overview

While new manufacturing technologies, such as linear friction welding, have emerged to enable more rapid and cost-effective production, aerospace component designers face difficulties in considering these new manufacturing technologies when creating parts. In particular, designers familiar with subtractive processes often do not have the expert knowledge to effectively apply and understand the capabilities of linear friction welding into the design process. There needs to be a way for designers to rapidly query manufacturing feedback on their early parts designs, so they can evaluate cost and manufacturability in an efficient manner.

1.4 Research Objective

The objective of this research is to provide aerospace component design engineers a way to quickly evaluate design alternatives on the basis of cost and manufacturability when using advanced (linear friction welding) and conventional (machining) manufacturing processes. In this research, the raw material forms considered are plate, rectangular and circular bar stock, and closed-die forgings. Design will be evaluated based on the feasibility of manufacturing as well as estimated production cost. The work herein will provide automated rapid manufacturing feedback for design considering advanced joining processes.

1.5 Research Tasks

To decrease the manufacturing knowledge gap for designers, a manufacturability analysis system will be implemented using an initial machinability analysis and manufacturing plan search employing a part decomposition technique. The search will be multi-objective, considering both cost and input part design fidelity.

The first task is to develop a machinability analysis model to provide a single set-up baseline. Subtasks include understanding the capability of machining processes, creating a geometric representation library that can represented solids (this methodology will use voxels), developing functions for operating on the solids that can adequately represent machining capabilities, and developing a useful way to return results of the machinability analysis.

The second task is to develop a multi-objective optimization that considers the estimated production cost of a part and how closely the manufacturable part geometry matches the initial, tessellated part geometry (termed "part fidelity"). Subtasks include conducting background research on hard metal machining and linear friction welding, creating a measure for part fidelity, creating an objective function considering manufacturing cost and part fidelity, using the objective function to implement a manufacturing plan search, and exploring the tradeoff between cost and part fidelity under different weighting scenarios.

1.6 Thesis Outline

The research herein is presented in the manuscript format consisting of five chapters. Chapter 1 provides an overview, motivation, objective, and research tasks. Chapter 2 provides a literature review on work done in manufacturability analysis, linear friction welding modeling, manufacturing plan modeling, topology optimization manufacturing constraints, and multi-objective modeling in manufacturing.

Chapter 3 is a conference article to appear in the *Proceedings of the ASME 2018 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference (IDETC/CIE 2018)* and is titled "Machinability Analysis Using Voxelized Solid Models." This article reports on the development of component machinability analysis using voxelized solid models.

Chapter 4 is a journal article to be submitted to the Journal of Manufacturing Science and Engineering and is titled "Automated Manufacturing Plan Generation for Parts with Poor Machinability." This article demonstrates an automated manufacturing plan generation technique that can be used to inform designers on geometric feasibility and processing cost. The manufacturing plans will consider the capabilities as a driver to reduce geometric infeasibilities from the initial design.

Chapter 5 offers a summary, conclusion, research contributions and limitations, and potential avenues for future work. No appendices containing program code are provided due to intellectual property concerns, but all public libraries (e.g., TVGL [8]) used are cited in the bibliography.

2 LITERATURE REVIEW

This chapter will consider prior research done in manufacturability analysis systems and presents the limitations with regards to assessing with considerations to additive and advanced joining processes.

2.1 Manufacturability Analysis and Design

Research in manufacturability analysis is incredibly widespread due to the nature of the problem. The term manufacturability is difficult to quantify because it is entirely dependent on the resources available. Being able to consider technologies in the design process as they become available without the use of expert knowledge is a broad area of research, depending on the perspective taken. Some sub-topics that can be found in this area of research include manufacturability analysis systems, knowledge-based engineering (KBE), and manufacturing based design automation techniques.

The closest and most current related work to the manufacturability analysis developed herein is a software called ANA developed by Hoefer et al. [9–11]. This software takes in a tessellated shape and provides a machining analysis by returning a heat-map of the tessellated shape highlighting areas that are difficult to machine. This manufacturing analysis does not consider costs of the processes used and only considers single process setups. Work done by Kerbrat and co-workers [12–14] does consider additive processes within the manufacturing plan and uses an oct-tree representation to determine the complexity of a part's surface. The oct-tree representation of the parts is then used to determine manufacturing complexity. Neither Hoefer et al.'s work on ANA nor Kerbrat's and co-workers' work returns costs nor complete ordered processes.

The work of manufacturability analysis has also been explored using feature-based approaches. Molcho and co-workers [15] have developed similar work with a methodology dubbed CAMA (computer-aided manufacturability analysis). The CAMA methodology consists of taking the features identified in a CAD program and applying manufacturing rules to those features based on manufacturing processes that could be used to manufacture the feature. Similarly, a machining and tooling analysis based on part features is used by Ong and Chew [16]. Their work considers machinability and complexity of tooling based on each individual feature of a part and gives the designer a quantitative metric for consideration and interaction through the design process. Work done by Tedia and Williams [17] applies a voxel technique to model additive manufacturing and support material required. With this technique, they are also able to identify angle of overhangs and optimize build orientation.

KBE and artificial intelligence techniques have also been used to determine manufacturability. These software approaches use knowledge of processes and products to help the engineering process. Work by Humpa and Köhler [18] uses a KBE approach to determine the geometry of spiral milled parts based on toolpath sweep knowledge, virtual tool shapes, and known manufacturing capabilities in spiral milling. Their work also requires the use of features gathered from a detailed CAD file. Kulon and co-workers [19] use KBE to design forgings, taking into account machine, material, and forging specific data. Johansson [20] uses KBE from a Finite Element Analysis (FEA) approach where he presents a method to automate an FEA to determine preparedness for rotary draw bending.

Approaches for manufacturability can also be seen from the design side. Topology optimizations in particular have attempted to apply manufacturing rules to generate more producible shapes. Sigmund [21], for example, created a robust topology optimization process to obtain more manufacturing tolerant designs. Sigmund applies filters that thicken or thin bodies and re-analyzes the mesh to help correct single node connected elements ("checkerboarding"). Other topology optimizations consider additive manufacturing techniques specifically and constrain the design based on support material or overhang feature limitations [22–24]. Still, parts from these optimizations are difficult to manufacture and would require significant smoothing and redesign to be done after the fact by a designer, without knowledge of the potential cost to manufacture. The designer can see load paths and potential design, but does not get a lot of feedback on how to improve the manufacturability of the part.

2.2 Capabilities of Linear Friction Welding of Ti-6Al-4V

The research herein is based on the concept that linear friction welding can enable the production of new and more complex geometries that were not previously manufacturable. This would be done by machining blanks prior to joining with linear friction welding. Additionally, linear friction welding is superior to additive manufacturing techniques in aerospace applications due to the more reliable material characteristics of joined versus printed parts. Linear friction welding is a proven technology and is currently used to add blisks onto fans and compressors for titanium airplane engine parts [25].

In a literature review of solid state joining, including both rotary and linear friction welding, joining metals, such as Ti-6Al-4V, using these technologies yields parts that have material characteristics near parent material [6,7,26]. This indicates that should the blanks chosen for joining have reliable material characteristics, the joined part would also have those characteristics. With aerospace qualification for airworthiness being a stringent and lengthy process [5], using parts that will have similar reliabilities as forgings, which are currently qualified, can help make that process easier.

Linear friction welding is highly accurate at placing welds in their correct area. In a presentation by Steve Dodds of The Welding Institute, he states that there are machines able to place welds at less than 0.05 millimeters from the desired location with repeatability at 0.025 millimeters [26]. This level of accuracy allows pre-join machined parts to make aerospace geometric tolerances.

2.3 Limitations of Prior Research and Research Question

The main research limitations seen in literature herein is related to the exploration in advanced joining methods. Although advanced joining analysis is available, machining and additive analysis is more prevalent. Additionally, cost is not a consideration in these manufacturability analyses while it is the primary measure used in industry. These limitations beg the question, "How can a manufacturability analysis system be designed to consider linear friction welding and total cost of manufacturing such that a designer can use the results to better inform component design?"

The work presented in this thesis attempts to answer this question by proposing an automated manufacturing plan creation methodology that uses a multi-objective search. This methodology can be broken up into two specific capabilities. The first capability will tackle the initial single set-up machinability analysis to establish a baseline for the part design. The second capability will decompose the part using a multi-objective beam search so that joining based manufacturing plans can be considered.

Chapter 3: Assessing Component Machinability using Voxelized Solid Models

by
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Submitted to the 2018 International Design Engineering Technical Conference
Quebec City Convention Center, Quebec City, Canada

3 ASSESSING COMPONENT MACHINABILITY USING VOXELIZED SOLID MODELS

3.1 Abstract

New automated approaches in design often generate non-manufacturable component geometries. Improved machinability of topology optimized parts, for example, has been under exploration for over a decade with limited success. Recent work is pursuing novel design approaches enabled by developments in voxel-based representation and advanced process technologies. Research reported here suggests a featureless approach for analyzing the machinability of a given geometry using voxels. The input is a tessellated shape, which is converted into a voxel representation. The voxelized shape is then filled in the orthogonal toolpath directions defined by the minimum bounding box to approximate the reach of the cutting tool in each part orientation. The filled shapes are intersected with each other to achieve a solid representation that can be readily accessed by a cutting tool. Overlaying this solid shape against the original tessellated shape will highlight the non-machinable regions of the part when visualized. The volume of non-machinable material can be estimated and used to inform a larger search process for separating and adding part features together to improve component manufacturability.

3.2 Introduction

As new processing techniques for monolithic component production become available, designers need to be able to react to those changes quickly to take advantage of new geometries that can be manufactured. Additionally, designers are using more sophisticated methodologies for designing parts including topology optimization.

These parts are usually comprised of features that can be difficult or impossible to produce using traditionally subtractive techniques.

The pace at which manufacturing technologies are advancing makes it increasingly important for designers to receive rapid feedback on their part designs, so they can take advantage of state of the art resources at their disposal. As hybrid manufacturing (additive and subtractive) methods gain traction in the metals product manufacturing industry, the tools used to model the processes need to keep pace with this demand for more rapid, more accurate, and more informative analysis. Hybrid manufacturing techniques most often terminate with a machining operation. Thus, critical part features must be machinable.

To provide machinability information to the designer, there needs to be an understanding of what features of a geometry can be machined and when machining operations occur in the overall production flow. These operations can be final machining or may be intermediate – before joining (e.g., fusion welding or friction welding). The research presented herein provides a featureless voxel-based approach to analyzing machinability and visualizing the non-machinable features. This approach can be developed to be used within a standalone analysis tool or eventually embedded into computer-aided design (CAD) software to offer real time feedback to designers as they iterate through geometries. Further, this approach can be implemented into larger automated manufacturing planning tools to analyze how to expose areas that are non-machinable by dividing a single part into smaller parts.

3.3 Related Work

The work most closely related to the presented approach is that of Hoefer and co-workers in their manufacturability analysis tool, ANA [9]. Machinability analysis presented in the ANA tool breaks machinability into four categories: visibility, reachability, accessibility, and setup complexity. The work reported by Hoefer and co-workers weights the different categories of machinability and provides a score which is then distributed as a heat map across the part. The methodology presented here visualizes the material that is inaccessible. The approach developed determines the areas are not machinable and fills in the material to present the closest material shape and volumes added to the designer. Li and co-workers presented machinability analysis for 3-axis flat end milling that parallels this research as well [27]. Both works stem from research at Iowa State University, with Hoefer's work applying some of Li's methods for machinability analysis. Jang and co-workers modeled multi-axis computer numerical control (CNC) processes using voxel-based geometry representations [28]. Their work focused on tool path modeling and material removal rate simulations given the velocity of the tool. Prior work has not developed models that elucidate material accessibility in machining. The simulation approach presented by Jang and co-workers requires geometries to be finalized, whereas the methodology reported herein would be used primarily in the design iteration stage.

3.4 Methodology

The approach developed and reported here aims to assist designers in quickly analyzing parts for machinability by automatically identifying and highlighting features that are non-machinable. Further, it approximates the material to be added to an optimized geometry make part manufacturing feasible. This section will describe the process taken to analyze an arbitrary geometry. This process can be divided into five steps (Figure 3.1): inputting the shape, voxelizing, toolpath filling, intersecting, subtracting, and returning/visualizing results. Each operation performed in this methodology and the 3D visuals accompanying them are generated using the Tessellation and Voxelization Geometry Library (TVGL) [8]. The following subsections discuss the key steps in greater detail.

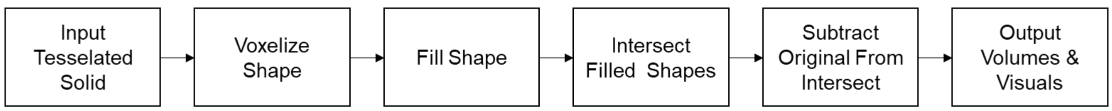

Figure 3.1: Methodology flow chart

3.4.1 Voxelizing the Shape

Since the algorithm starts with an arbitrary tessellated shape as an input, the representation is first converted to voxels. The voxel representation used in this analysis is a hierarchy that increases resolution at each level. The largest voxels have an edge length equal to 1/16th of the longest dimension of the bounding box given for the shape. The longest dimension of the bounding box of the input geometry defines the default side length of the bounding cube used for voxelization. Then, the vertices, edges, and faces of the tessellated input shape are interrogated to determine what voxel they occupy.

Each voxel in the bounding box space is defined as one of three types to represent the geometric solid: full, partial, or empty. A full voxel is considered to be solid material and an empty voxel is representative of empty space. A partial voxel a mixture of empty and solid space and is brought to the next level in the hierarchy to increase the resolution for analysis. Partial voxels have their edges segmented another 16 times per side of the larger voxel cube (equating to 4,096 sub-voxels) to create another level of resolution. This hierarchical or sparse voxel representation is inspired by OpenVDB [29]. The approach is also similar to octrees, which use a smaller division of eight sub-voxels per larger voxel instead of 4,096 [30]. The voxels that the vertices, edges and faces of the tessellated shape pass through are all considered as partial voxels. These are then used to fill in the remaining interior space with full voxels.

The final level of the hierarchy may have partial voxels as well but will be assumed to be full in the final representation. The size of the voxel at the final level is the resolution limit. Figure 3.2 shows a tessellated pump housing and that same pump housing represented using voxels with two levels. This part will be used to illustrate the steps in this methodology.

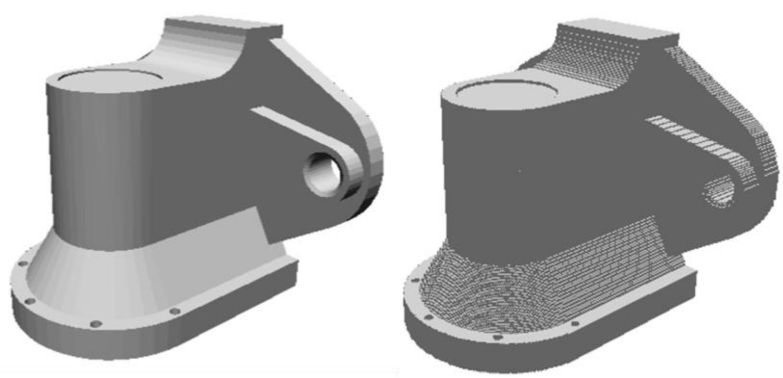

Figure 3.2: Original tessellated shape (left) and voxel solid converted shape (right)

3.4.2 Toolpath Filling

After the shape has been voxelized, the material accessible to a machine tool is represented using a toolpath fill function. The fill will be done along a direction that represents the approach of a cutting tool. Layers of voxels in each direction are observed and use to modify the subsequent voxel layers. If a voxel is full in the preceding layer, the voxel following it along the toolpath direction will also be full. If a voxel is empty, the voxel immediately following it will be unchanged and maintain its status from the original voxelization. If a voxel is partial, then the process recurses to the finer level of included voxels and the filling process repeats. As stated earlier, at the lowest level in the hierarchy, partial voxels are treated as full voxels. These iterations will proceed through the end of the bounding box defining the voxelized shape. An example 2D toolpath fill can be seen in Figure 3.3.

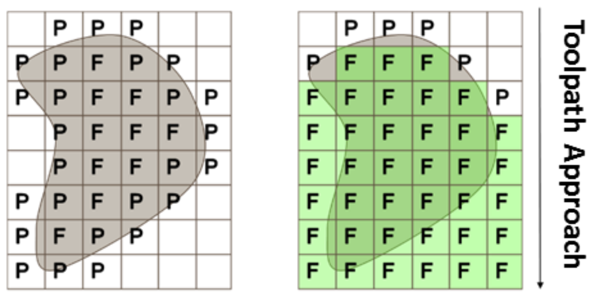

Figure 3.3: 2D example with original shape (left) and toolpath fill functionality (right)

The figure shows an original shape and a filled shape with inaccessible material highlighted in green. Partial and full voxels are denoted with "P" and "F" respectively. A result for toolpath filling a 3-D shape can be seen in Figure 3.4. The part represented using voxels is filled in with an indicated toolpath direction. The new material added is highlighted as green voxels. This operation is repeated six times to represent the tool

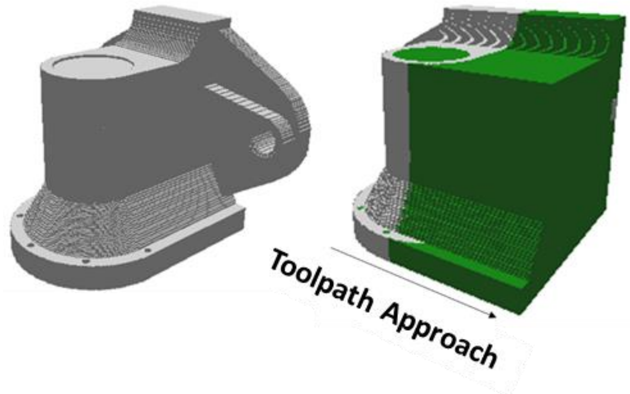

Figure 3.4: Starting geometry (left) and toolpath filled shape with tool approach in the x-positive direction (right)

approaches along all six orthogonal cardinal directions. Filling the part in all those directions will yield the geometries that are presented in Figure 3.5.

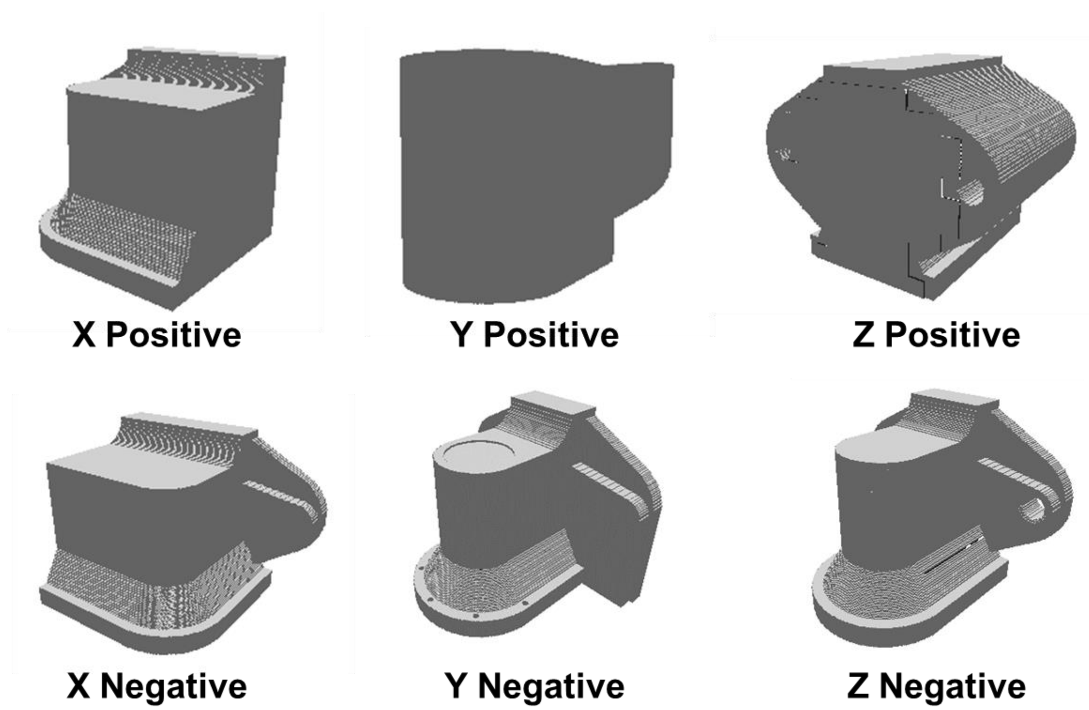

Figure 3.5: Filled shapes in the six orthogonal directions

Given our focus on rotating milling cutting tools, it is understood that interior corner features are limited by the radius of the cutting tool. A minimum feature size algorithm needs to be applied to smooth features below the tool radius limit and capture these non-machinable geometries. One approach to define this limit is to modify numerous two-dimensional cross-sections from the original tessellated shape. From the original tessellated shape, any cross-section generates one or more polygons. For each polygon, an offset is applied to enlarge the polygon by an amount equal to the minimum radius of a feature. This process is conceptualized in Figure 3.6. It is straightforward to translate the lines of the polygon outward, but a more complex algorithm is needed to extend the lines to join points and remove intersections. However, this can be done

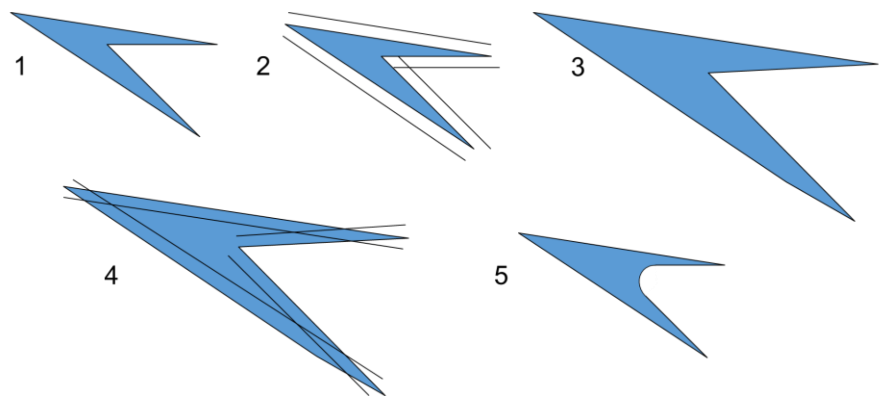

Figure 3.6: Polygon offsetting steps: (1) Original polygon with internal features, (2) Original lines offset out from the original shape, (3) Extending lines to fill gaps, (4) New shape's lines offset in, and (5) Adding radius to fill gaps

quickly for even large polygons as the operation is completed in linear time. The process is then applied in reverse as a new polygon is defined by offsetting inward the same amount. The result of this outward, and then inward offsetting is simply to round any internal features to a specified radius. The polygon operations described follow the approach used by Hoefer and co-workers as part of their machinability analysis approach for accessibility. Following the double offsetting approach, the edited polygon is redefined as voxels and the inaccessible voxels at each layer of the toolpath filling process are filled in as shown in Figure 3.7. The voxels that changed from the original shape are bolded and underlined.

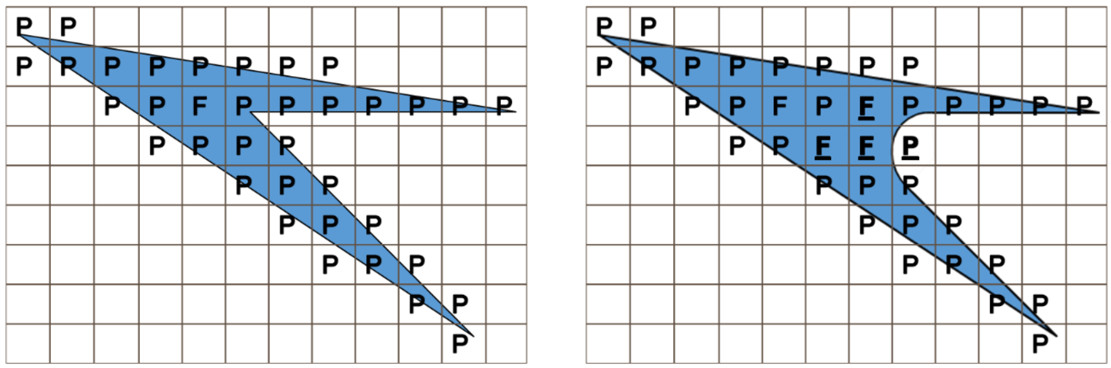

Figure 3.7: Voxel layer before feature smoothing (left) and after (right), where changed voxels are underlined

3.4.3 Intersecting and Subtracting

Once all toolpath orientations have been filled, the algorithm creates a new geometry from the intersections of all the toolpath filled geometries. Voxels from all six shapes with identical locations are compared against each other. As this is a six-way intersection operation, the resulting voxel state is defined as a conjunctive expression of each of the voxels from the six directions. If all six voxels are full, then the resulting voxel is full. If one is empty, then the result is empty (accessible). If no voxels are empty, but one or more are partial, the algorithm will recurse to lower levels in the voxel hierarchy. The expectation is that at minimum, all the voxels from the original shape will be retained.

After the intersected shape is created, the original voxel shape is subtracted from it. Any remaining solids are voxels that were added because the machine tool is unable to access those areas. A shape that is completely machinable will return no new solids after the subtraction. The pump housing used to illustrate voxelization and toolpath filling is entirely machinable, so it returns the original shape after intersecting, and nothing after the subtraction.

3.4.4 Displaying Results

Once all operations are performed, the shapes that are used to display the results are the original tessellated solid and any voxel solids left after intersecting and subtracting. The tessellated solid is visualized with the voxel solid overlaid on top. The solids created from intersecting and subtracting are displayed with a contrasting color to clearly show the areas that need to be redesigned for the part to be a machinable.

Additionally, an estimated volume of material needing to be added is also tracked and can be returned to the designer. This is done by summing all voxels that are full or partial at the highest resolution and multiplying by the volume of a single voxel. The accuracy of the volume returned is based on the voxel resolution used. An entirely machinable part, like the part used to illustrate the steps of the methodology (shown in Figure 3.2) will return only machinable solids. Figures showing results from examples that are non-machinable will be shown in the following section. The volume of non-machinable voxels can provide a useful metric to fabrication planning methods that are seeking to minimize the difference between final part shape and the design part shape.

3.5 Machinability Analysis Results

This section presents the machinability analysis methodology described above for three arbitrary part geometries. The first geometry has features that are non-machinable, while the second is the result of topology optimization, exhibiting poor machinability. The third part is the machinable part previously shown but is presented here to explain setup complexity analysis capabilities. All three parts are analyzed using a two-level hierarchy for voxel resolution.

The first part is a rectilinear bracket with internal features. The original part is presented in both tessellated and voxel form in Figure 3.8 and Figure 3.9, respectively. In Figure 3.10, the results are shown with the original part along with the representation of non-machinable regions in the part highlighted as pink fill material. The cylindrical pocket on the bottom of interior has no access points for a tool to approach it and, thus, is filled in.

This result does not include the smoothing step defined above. Using the double offsetting simplification methodology previously mentioned, there would also be some added material to round out the corners in the main cavity of the part. The areas which would result in fill material are circled in Figure 3.11.

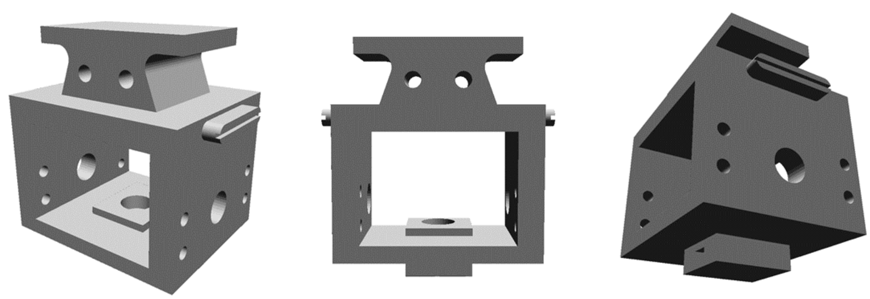

Figure 3.8: Rectilinear bracket as tessellated shape

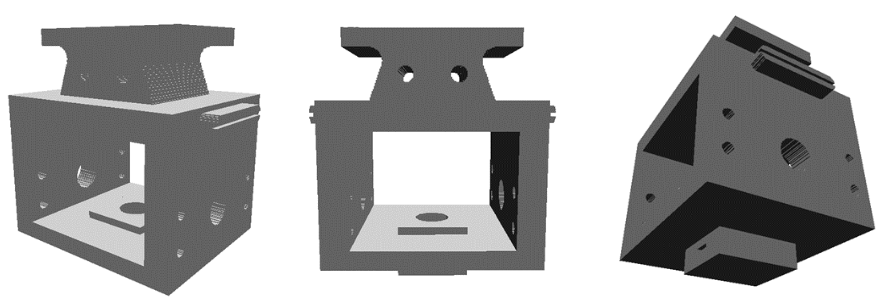

Figure 3.9: Rectilinear bracket as voxelized shape

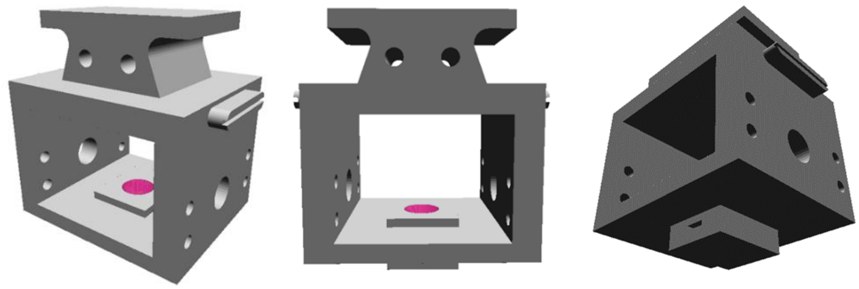

Figure 3.10: Rectilinear bracket results with non-machinable area highlighted

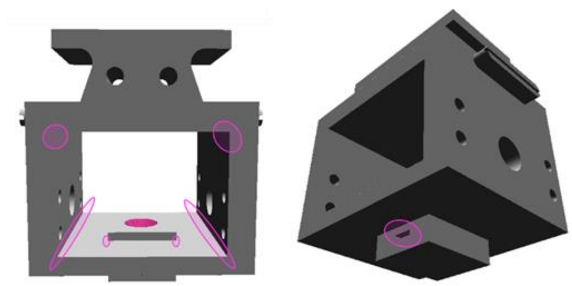

Figure 3.11: Rectilinear bracket with additional non-machinable regions that would occur with offset rounding

The second part analyzed is a support plate that has been topology optimized using the ParetoWorks software [31,32]. Figure 3.12 and Figure 3.13, respectively, show the original part as a tessellated shape and a voxel representation. The curvature of this part makes it difficult to manually define non-machinable regions, but in the voxel version, pockets and indents are more apparent with clear voxel ridges. The part has a large internal area where it is difficult to gage if a cutting tool would have difficulty accessing

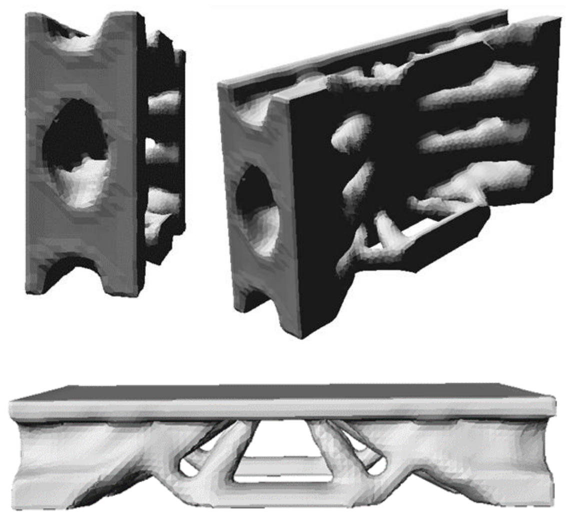

Figure 3.12: Topology optimized fixture as tessellated shape

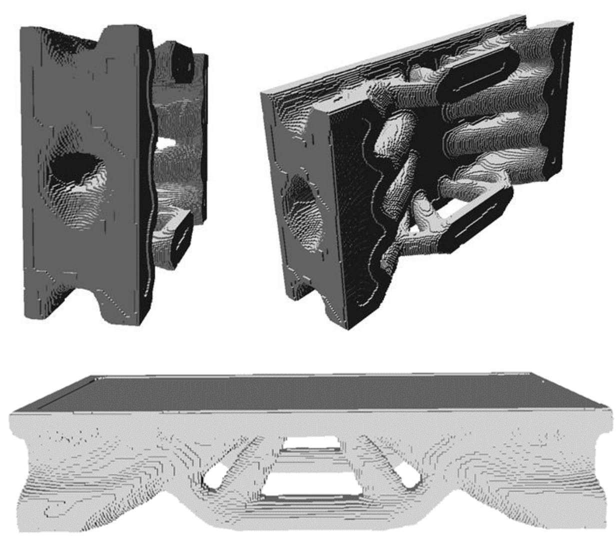

Figure 3.13: Topology optimized fixture as voxelized shape

material to be removed. The machinability analysis presented can make those areas where a machine tool could not get access clearer. In Figure 3.14, the results from this topology optimized part are shown with the non-machinable areas clearly highlighted. The part's internal pockets are filled along with areas that curve towards the interior of the part. If produced using machining, the non-machinable areas would add about 14% of material to the original tessellated shape.

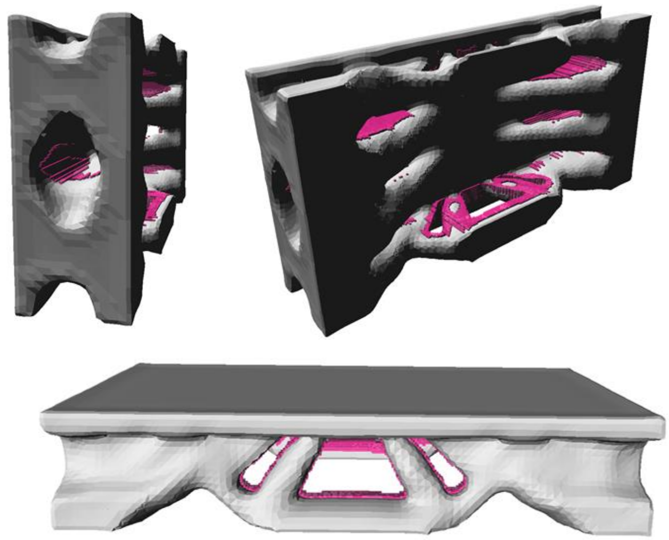

Figure 3.14: Topology optimized fixture results with non-machinable areas highlighted

Lastly, additional analysis is performed using the pump housing previously shown in the methodology section. The original geometry can be seen in Figure 3.15 (left). This part is entirely machinable when analyzed from the six orthogonal directions but does not actually require access in all directions to be entirely machinable. The part can be completely machined using four setups with tool approaches from the Y-positive, Y-negative, Z-positive, and Z-negative directions. Additionally, the part can sacrifice a minor feature and be machined with three setups with tool approaches from the Y-negative, Z-positive, and Z-negative directions. The results from the three-setup analysis can be seen in Figure 3.15 (right) with the minor feature unable to be machined highlighted in pink. This analysis shows that the methodology can be used to find machining processes with lower cycle times and fewer setups. While the full designed geometry is not achieved, this allows design engineers to explore tradeoffs between part geometry and manufacturing process complexity.

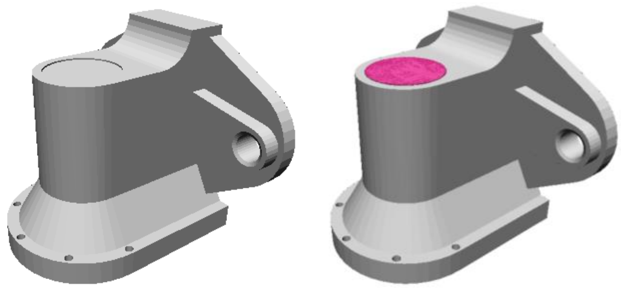

Figure 3.15: Original part (left) and part with non-machinable areas using three-setups (right) indicated

3.6 Future Work

In its current state, the implemented approach can represent the abilities of three-axis milling well, with setups oriented in alignment with the bounding box. However, as a result of this simplification, the algorithm developed has trouble with features that are not exposed via the orthogonal directions. If holes and pockets are set at an angle to the orthogonal directions, for example, the algorithm will consider that feature to be at least partially filled in. Figure 3.16 illustrates the cross-section of an angled hole, which is found to be partially inaccessible, though it could be readily drilled using a simple angle vise.

A possible solution is to repeat the methodology as before on a voxelized version of the part transformed into a new orientation. After an initial toolpath fill, the original part and any non-machinable solids would be rotated and filled again. The process for this approach would be iterated until all desired orientations are explored. Iterative analysis will require the tessellated shape to be rotated and voxelized in each new orientation, so the voxels are aligned properly for filling. A separate geometric analysis would be desirable to limit the number of orientations explored before terminating the analysis and returning results.

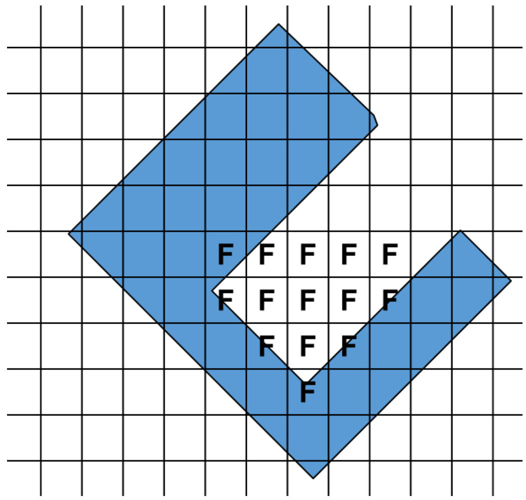

Figure 3.16: Angled pocket limitation in 2D

Another improvement could pair this machinability analysis approach with a decomposition methodology similar to that presented by Massoni et al. [33]. In that work, a search is performed to decompose, or divide, a monolithic part into smaller sub-volumes that are produced individually and then assembled into a rigid structure. Such a decomposition methodology could expose internal pockets for machining prior to assembly (e.g., using fasteners or advanced joining techniques).

For example, if a cutting plane were placed through the square support part as shown in Figure 3.17, a majority of the non-machinable regions would become accessible to a cutting tool (e.g., endmill). The two sub-volumes generated by the cutting plane would be analyzed independently for machinability. The results from the independent analysis can be used to define a process plan.

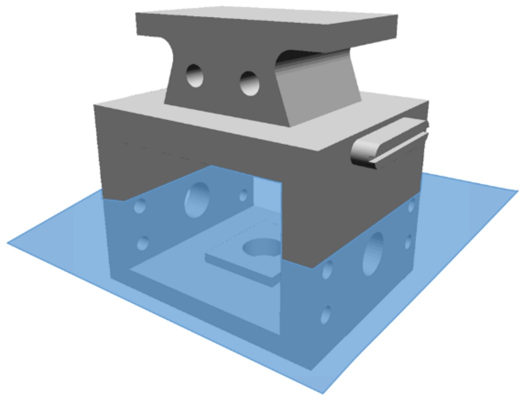

Figure 3.17: Rectilinear bracket with slicing operation along indicated plane

3.7 Conclusion

This paper has presented a featureless methodology to analyze the machinability of components using voxelized solid models. The part is first filled along the orthogonal toolpath directions and then the resulting shapes are intersected. Material remaining after intersection will indicate either non-machinable regions or the final geometry desired to be generated by machining. An application of the presented methodology showed the machinability results using a shape with non-machinable features and a topology optimized part with poor machinability. Additionally, the example analysis explored a part that could be machined using fewer toolpath directions to illustrate how a designer could use this approach to evaluate and reduce setup complexity through part redesign.

Development of the presented methodology is ongoing. It is demonstrated that three-axis milling along orthogonal tool path approaches using a flat endmill can be accurately analyzed. The analysis results provide designers with a visual representation of the material and features needing to be edited. Additionally, the volumes and material added can be used to inform an automated cutting plane search and enable pre-joining machining of stock blanks to a near-final shape prior to assembly.

3.8 Acknowledgements

The authors would like to acknowledge the Boeing Company and the Oregon Metals Initiative (OMI) for their support of this research. The authors would also like to thank Prof. David Kim and Brandon Massoni, of Oregon State University, and Matthew Carter, Eric Eide, and Rob Tsunehiro, of Boeing, for their guidance and assistance as part of the larger research team.

Automated Manufacturing Plan Generation for Parts with Poor Machinability

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4 AUTOMATED MANUFACTURING PLAN GENERATION FOR PARTS WITH POOR MACHINABILITY

4.1 Abstract

New automated approaches in design often generate geometries that are not manufacturable. For example, improved machinability of topology optimized parts has been under exploration for over a decade with limited success. The development of joining techniques, such as linear friction welding, provides the opportunity to explore monolithic part geometries not manufacturable in single setup machining. The approach developed here uses voxelized solid models to analyze a part and determine a manufacturing plan that takes advantage of advanced joining techniques. The manufacturing plans returned are optimized to minimize the difference between the input design and the final part geometry achieved, as well as the total cost of manufacturing. This is done using a weighted sum objective function that allows the designer to weight the two objectives based on personal preferences and goals. Additionally, regions that are not manufacturable in a certain configuration will be highlighted and returned to the designer so that they can better design the component. The results of this search will allow designers to determine the tradeoff between their design geometries and the cost to manufacture the designs in question.

4.2 Introduction

Manufacturability of complicated geometries is a difficult measure. Given advancements in additive and advanced joining processes, material reduction, cost savings, and new geometries can be taken advantage of by adopting novel additive and advanced joining processes. The difficulty in adopting these advances though, is that these technologies all require expert knowledge that designers may not necessarily have. Knowing the technologies that are in practice is what allows designers to stay ahead of the curve and design more optimal parts. Developing these manufacturing analysis systems is difficult [2].

Aerospace industry, for example, machines many titanium forgings, but could potentially save money by creating parts using linear friction welding and simpler raw material forms [1]. Aerospace components go through rigorous qualification processes to determine that a part design and its manufacturing produce airworthy parts. This requires manufacturing techniques that produce high quality material characteristics. Linear friction welding of metals produces material characteristics close to the parent material of the join [6,7] and has the capability to produce airworthy parts.

Design techniques such as topology optimization have had a difficult time creating parts that are manufacturable. Although manufacturing constraints must be considered within the topology optimization process if an optimal part design is the desired outcome, a manufacturing plan search considering multiple raw material forms and processes, such as the one presented, would require excessive computational power. The method shown will provide a manufacturing plan search that will attempt to manufacture the part as close to the input design as possible such that it minimizes deviation from an optimized shape.

The research presented herein builds upon our previously published work. A machinability analysis was developed to determine the unmachinable solids of a part design [34]. This machinability analysis returns a voxelized solid representing the unmachinable regions. In the methodology presented here, the unmachinable solid is used to determine how to best create the part using linear friction welding. This is done using a method similar to the one presented by Massoni and co-workers [35]. The pre-joining machining operations on specific blanks and joining operations are then calculated to return cost.

Section 4.3 introduces related work as well as techniques that have been gathered and used in the development of this methodology. Section 4.4 delves into the details of the search used and the analysis done on the sub-volumes to track unmachinable regions. Section 4.5 presents a demonstration using the methodology described in Section 4.4. The demonstration will include a simple prismatic part as well as a topology optimized part and will show results by varying the weights within a multi-objective function. Section 4.6 discusses opportunities for future work to improve or build on the methodology described and Section 4.7 presents the conclusions and final discussion points.

4.3 Related Work

Work related to design for manufacturing analysis can be divided into two main topics. First, are manufacturability analysis systems, which look at a given part design and present any found manufacturing constraints. Second, are design automation techniques, which attempt to apply manufacturing constraints such that resulting parts are manufacturable.

Work presented by Hoefer and co-workers analyzes component geometry and a set of manufacturing techniques [9]. This work does not consider additive and joining techniques. Work presented by Kerbrat and coworkers explores manufacturability by looking at subtractive and additive processes [12]. Kerbrat uses an oct-tree representation for geometric representation and uses the levels of the oct-tree to determine part complexity. Both Hoefer and coworkers' and Kerbrat and coworkers' work analyze the "difficulty" of manufacturing the part. The method presented in our earlier work returned an unmachinable solid, which is used to inform a decomposition [34]. The presented method tracks the unmachinable solid returned by the voxel based machinability analysis and decomposes the part using the technique developed by Massoni and co-workers [35]. This decomposition for efficient manufacturing opens up avenues for analyzing pre-joining machining operations to determine new machinable regions. The combination of machining and advanced joining in the manufacturing plan search after decomposition aims to address the lack of research in manufacturability analysis with considerations to advanced joining. Returning full manufacturing plans will allow designers to determine the tradeoffs between design complexity and cost.

In the design automation work, authors like Sigmund have created manufacturing tolerant topology optimizations. Sigmund uses filters to prevent holes and non-manufacturable designs [21]. Other topology optimization approaches consider additive manufacturing techniques, specifically, and constrain the design based on support material or overhang feature limitations [22–24]. Still, parts from these optimizations are difficult to manufacture and require significant post-processing by a designer without knowledge of the potential cost to manufacture. The designer can analyze load path compliance and glean design inspiration from a topology, optimization, but does not receive feedback on how to improve the part manufacturability from a processing and cost perspective.

4.4 Methodology

This section presents the steps required in the decomposition and manufacturing plan search as well as the concepts used and developed for this. The high-level steps for this search can be seen in Figure 4.1. They include inputting the shape, determining the unmachinable solid regions, determining the candidate list of cutting planes, decomposing the part using multi-objective beam search, and outputting results. Methods for determining cutting planes will be described in Section 4.4.1. The beam search's objectives are the remaining unmachinable volume on a part and total cost of manufacturing. The objective function will be described in further detail in Section 4.4.2. The unmachinable solid regions are tracked during the decomposition to determine which sub-volume the unmachinable solid belongs to and how the unmachinable solid could potentially be reduced. This method will be detailed in Section 4.4.3. In the multi-objective beam search, there is a nested manufacturing plan optimization that determines the manufacturing plan to determine total cost of producing a part for a given decomposition configuration. This manufacturing plan creation along with how results will be returned will be explained further in Section 4.4.4

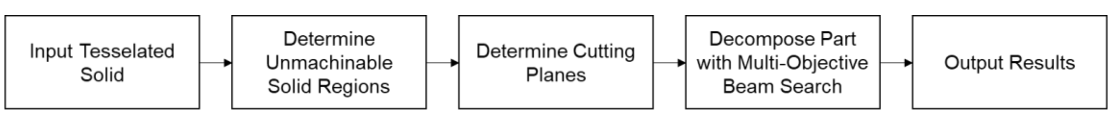


Figure 4.1: Manufacturing search process flow chart

4.4.1 Evaluating Cutting Planes

To determine a feasible manufacturing plan, the part needs to be decomposed into smaller sub parts that can be joined back together. This decomposition requires the identification of planes to separate the part, which are found and using methods presented by Massoni [33]. Not all cutting planes will provide improved manufacturability for the part through pre-join machining. To help make sure the cutting planes applied have high potential for exposing previously unmachinable areas, a heuristic check to see how many voxels can be accessed from the cutting plane is implemented.

This heuristic method loops through all the voxels and projects multiple lines from the center of the voxel. The line directions considered are the voxels' orthogonal directions and the cutting plane normal direction. If a line projected from the center of the voxel never intersects with the cutting plane, it is not considered. A 2D example in Figure 4.2 shows a voxel projection with five separate line segments: the voxel orthogonal directions and the cutting plane normal. Only the line segments projected in the cutting plane normal and two of the orthogonal direction intersect with the cutting plane.

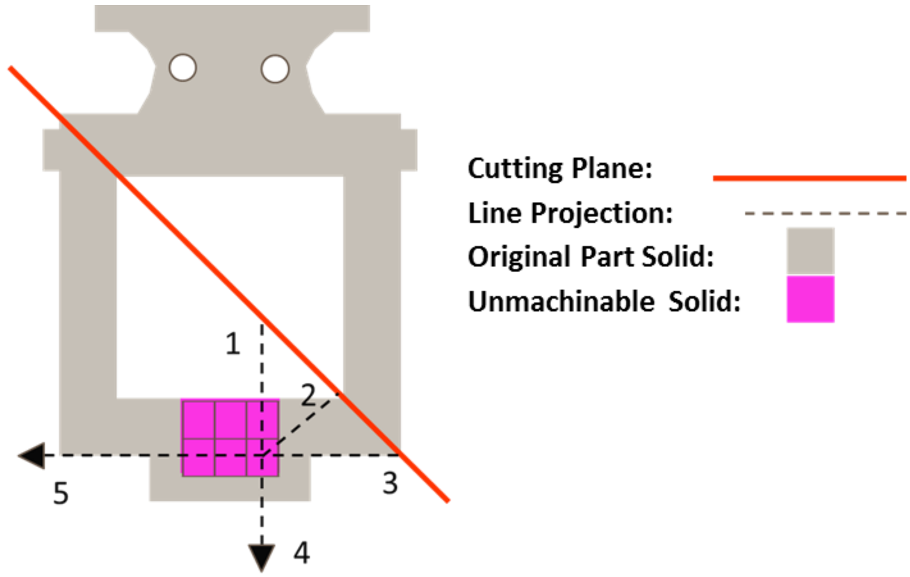


Figure 4.2: Voxel projection along five directional line segments (1-5). Segments 1, 2 and 3 intersect with the cutting plane so they are considered. Segments 4 and 5 will be ignored since they do not intersect with the cutting plane.

Once line segments of interest are isolated, the line segments are checked to see if any intersect with the original part solid. If any line segment projection for a given voxel does not intersect with the original part solid, then the voxel is determined to be machinable and it is removed from the solid part. If all of the line segments from a given voxel intersect with the original part solid, then the voxel is not reachable, and it must be added to the final part. Voxels like this are summed to create the aforementioned voxelized unmachinable solid that will be presented in the next section. The unmachinable volume is also gathered from this unmachinable solid. A 2D example of a voxel intersection check can be seen in Figure 4.3. The voxels in the part on the right shows all line segment projections intersecting with the original part solid while the voxel in the part on the left shows a line segment that reaches the cutting plane without intersecting the original part solid.

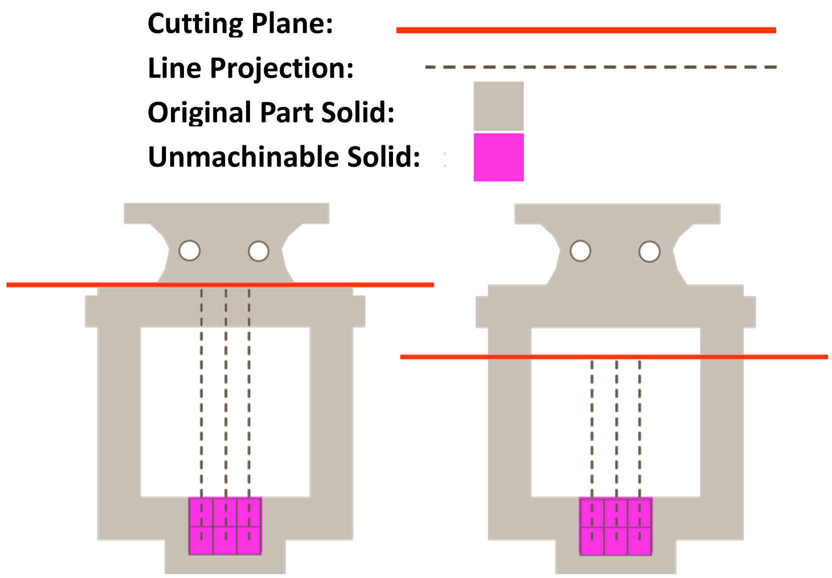


Figure 4.3: Voxel projections intersecting the original part (left) and intersecting the cutting plane prior to the original part (right)

There are added complications for final sub-volume machinable material analysis. For example, a given cutting plane may divide a given part into more than two sub-volumes. In such a scenario, the separate setups of the sub-volumes may allow a machine tool to approach from a direction that was once not accessible. The 2D example in Figure 4.4 shows such a part. As you can see, all the sub-volumes would be entirely machinable given individual setups even though the unmachinable region of sub-volume A would not have been identified as machinable using this heuristic. This method can eventually be used to generate cutting planes automatically, but is currently used to evaluate a potential list of cutting planes. This allows designers to determine which cutting planes they would like to consider.

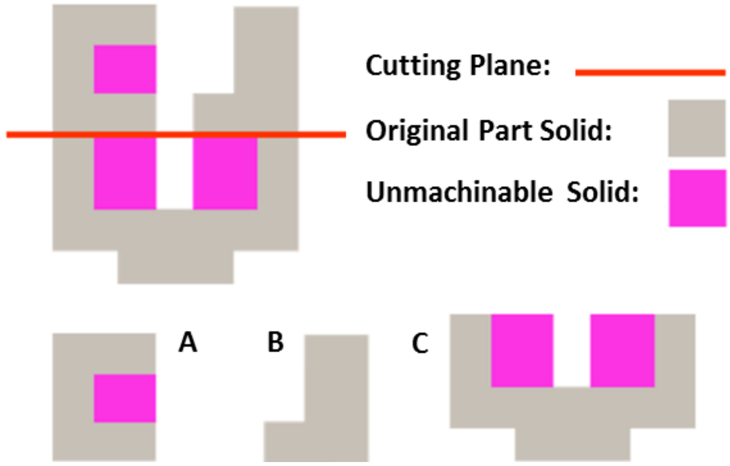


Figure 4.4: Cutting plane that creates multiple sub-volumes (top) with all three resulting sub-volumes, A, B, C, shown (bottom)

4.4.2 Multi-Objective Beam Search

This section will describe the beam search method used in the decomposition of the part geometry and how the search determines which configurations to pursue. A beam search is a tree search algorithm that only seeds the next depth of the tree from a limited number of nodes [35]. This number of nodes constitutes a beam width. For example, if the beam width were two and a given depth of the tree had five nodes, only the top two nodes would be used to create the next depth of the tree. Traditionally, a beam search tree continues until it reaches a complete solution, but each node of the tree in this implementation is a complete solution. To prevent excessively large trees, a depth limit is implemented. Figure 4.5 provides a visual representation of a hypothetical search tree with a beam width of two and a depth limit of three trying to minimize the node values.

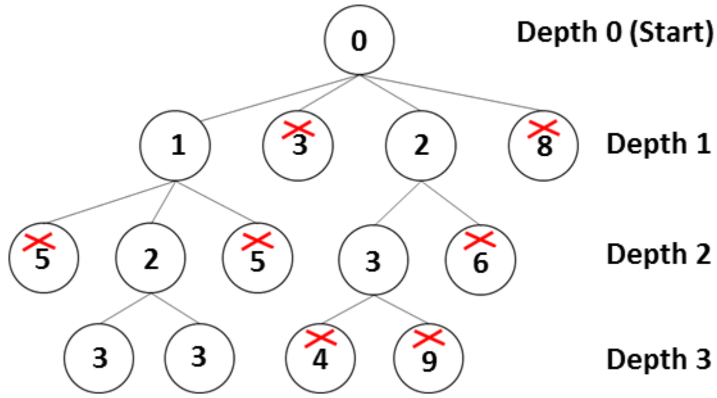


Figure 4.5: A minimization beam search tree with beam width of two and depth limit of three

The two objectives used to evaluate a given configuration are total cost of manufacturing and total volume of part created. The objective function used for the beam search is a simple weighted sum of the two objectives [36]. Each of the objectives, cost and volume, are analyzed independently at each depth to determine the optimum value for each at a given depth. The objectives are normalized with their optimum values, weighted, and summed to determine the value for each node. The equation is shown below in Eq. 4.1.

$$Minimize\ Z = w_1 \cdot \frac{C_{Mfg}}{C^*_{Mfg}} + (1 - w_1) \cdot \frac{V_{Total}}{V^*_{Total}} \qquad \text{Eq. 4.1}$$

The variable C_{Mfg} is the total cost of manufacturing for a given configuration while the variable C^*_{Mfg} is the cost of the cost optimal configuration at the given depth of the tree. Note that in typical search scenarios, it does not make sense that the normalization factor should change. However, in a beam search, “survival” in the search is dictated only by the limited spots in the beam, which is reset at each depth in the tree. This means for the set of solutions evaluated by Eq. 4.1, at least one will have its C_{Mfg} equal to C^*_{Mfg}. All the other solutions will be above one.

The variable V_{Total} is the total volume of the part that can be manufactured for a given configuration and is made up of two components as can be seen in Eq. 4.2.

$$V_{Total} = V_{Unmachinable} + V_{Part} \qquad \text{Eq. 4.2}$$

The variable V_{Part} is the volume if the original tessellated shape input and is a constant. The variable $V_{Unmachinable}$ is the volume of the unmachinable solid, or inaccessible voxels founded from the method presented in Section 4.4.1. The variable V^{*}_{Total} is the lowest volume that can be produced at the given depth of the beam search tree. The reason total volume is used instead of just unmachinable volume is because unmachinable volume can reach zero and would not be useful as the normalizing factor. The variable w_1 is the weight of the cost in the objective function and can be set between zero and one depending on the tradeoff in the resulting solutions that the designer is considering. The weight for the volume is simply $1 - w_1$.

The number of configurations chosen to seed the next depth level of the tree is based on the beam width set by the designer. The maximum total number of cutting planes considered in a configuration is defined by the depth limit. A beam width of five and depth limit of three is used for the demonstration in Section 4.5. This particular beam search would return the manufacturing plans found at each depth, so the designer can see all the alternatives and the varied amount of processing. All the manufacturing plans returned have their objective function values re-calculated against the global minimum for volume and cost before being returned. The global minima are gathered from the minimum values of each from the roster of configurations returned at the end of the search. The designer can also adjust beam width and depth to increase the search space of the beam search. Increasing the beam width and depth causes the runtime and memory to increase.

4.4.3 Sub-Volume Machinable Material Analysis

As cutting planes are applied and the part gets separated into multiple sub-volumes, the unmachinable solid also needs to be separated and assigned to a specific sub-volume. This allows the manufacturing plan search to determine which sub-volumes require pre-join machining. This is done by identifying which voxels are within the sub-volume's minimum bounding box by looping through all voxels in the unmachinable solid.

Once a sub-volume and its original unmachinable solid are determined, the unmachinable solid must be updated for the new machining setup. This is done by projecting the voxel center to each bounding box face individually and checking with intersections with the original sub-volume solid. If all the directions of the voxel projection intersect with the sub-volume solid, the voxel remains full or partial depending on its current indicator. If there is a voxel projection that does not intersect with the sub-volume, then the voxel is set to empty. A 2D example can be seen in Figure 4.6 where grey represents the original sub-volume and pink represents the unmachinable regions. The top sub-volume shows a projection from the center of the voxel to all the minimum bounding box faces. All the projections intersect the original sub-volume, so the voxel will remain full or partial. The bottom sub-volume shows a projection from the center of a voxel in all directions, but the projection to the right has no intersection with the sub-volume original part solid. This voxel will be changed to empty and updated in the unmachinable solid.

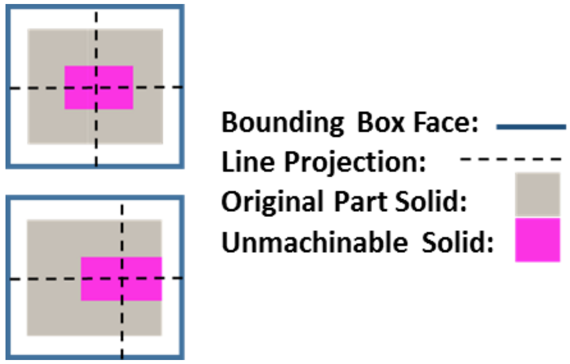


Figure 4.6: Sub-volume voxel projection – intersections with the original part in all directions (top) no intersection on the right projection (bottom)

It should be noted that this analysis is entirely independent of manufacturing processes and blanks chosen, so it only needs to be done once at each node of the search tree. The volumes gathered from this are used to determine the part fidelity measure of the beam search. In Eq. 4.2, the volume is determined as the sum of all unmachinable solids remaining and the original tessellated shape volume. This is divided by the optimal at that depth of the tree.

4.4.4 Manufacturing Plan Creation and Presenting Results

This section will present the methods used to search and determine the optimal manufacturing plan given a specific configuration. The manufacturing plan search is nested within the multi-objective beam search explained above and is the driver of the cost portion of the objective function. This manufacturing plan search is done using a cost first search where blanks are chosen first in the upper layers of the tree and then joining operations are chosen afterwards. In Figure 4.7, an example configuration is shown. A manufacturing plan search tree for that configuration is shown in Figure 4.8. The configuration consists of three sub-volumes from a single cutting plane. The first three depths of the search tree will decide on the blanks. The subsequent levels choose the joining operations. For each joining operation, the search will take into consideration the associated auxiliary processes. This includes required material handling, non-destructive testing, dimensional testing, and flash removal. All manufacturing plans are considered to begin in warehouse inventory, where blanks are stored, and to finish with final machining, heat treat, and engineering quality assurance.

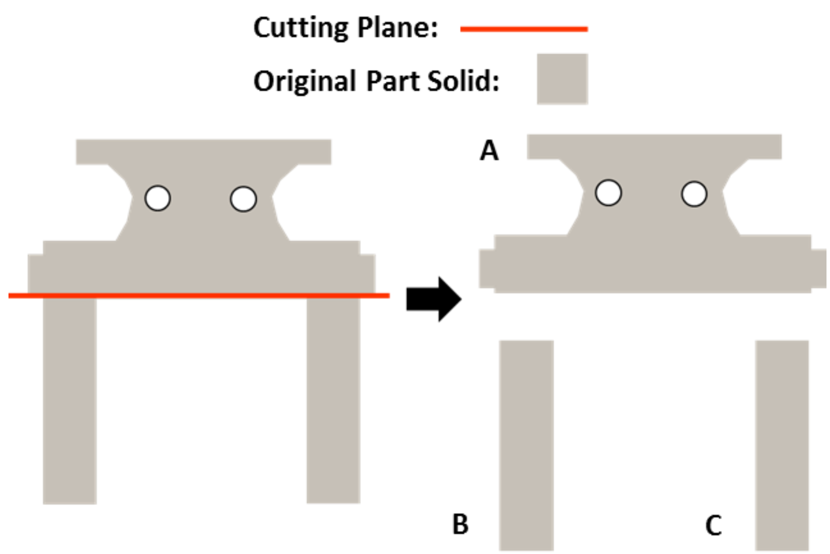


Figure 4.7: Part configuration example – cutting plane would result in three sub-volumes (A, B, C)

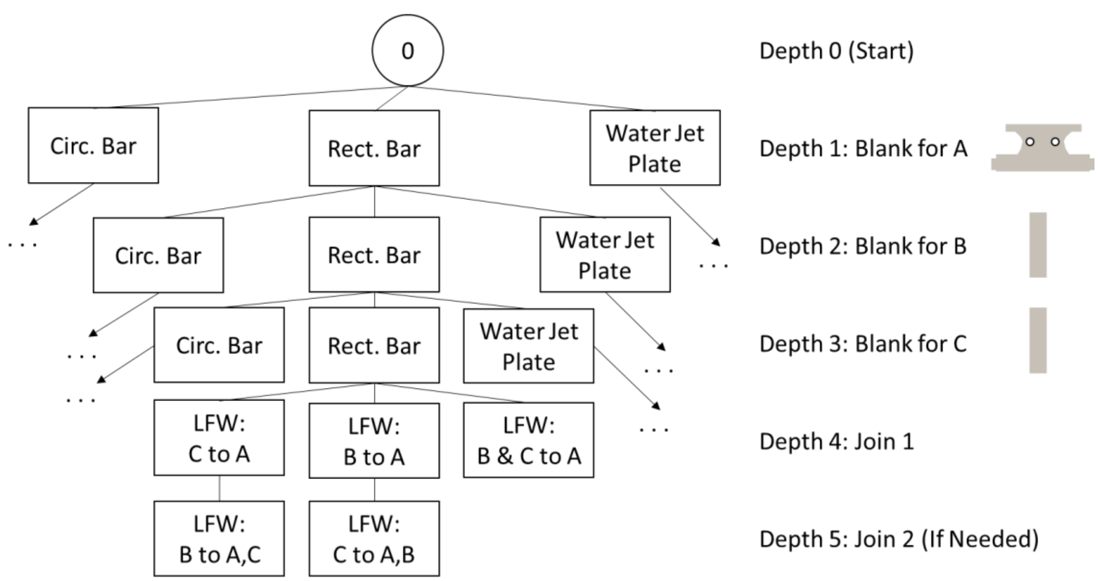


Figure 4.8: Manufacturing plan search tree for configuration shown in Figure 4.7

In Section 4.2, Dodds states that linear friction welding can weld with high accuracy and repeatability [26]. Machining before a join can take advantage of this accuracy and enable the creation of shapes that were not before considered. Since it is known which sub-volumes have unmachinable solids, this allows the search to choose the lowest cost blanks for pre-join machining, which eliminates other blank combinations be considered. Once all blanks are chosen, different joining combinations are considered including joining multiple blanks in a single setup to determine the lowest cost approach for joining all the blanks together.

The blanks considered for manufacturing plan creation in this work are rectangular bar stock, circular bar stock, waterjet plate, and closed-die forgings. Closed-die forgings are only considered at depth zero and are not a candidate for joining. Additionally, the geometry and cost of forgings are determined using the forging estimation approach reported by Massoni and Campbell [37]. Linear friction welding limitations, including join area minimum and maximum, minimum feature size, minimum distance between join areas, and weld envelope size, are modeled in this manufacturing plan search. If it is determined that there is no possible way to join the blanks for a given configuration, the configuration will be removed from consideration. In manufacturing plan generation, it is assumed that all blanks requiring pre-join machining will be machined before any other operation, all blanks required for production will move as a kit, and all operations are done sequentially.

The first complete manufacturing plan reached is the manufacturing plan that is returned. The cost measure is merely a summation of the process costs and blank decisions made at one level of the tree are independent of the other decisions. This independence assumption is what allows the search to declare that the first returned complete manufacturing plan is the optimal. Due to the proprietary nature of the cost models used to determine process and blank costs, the equations making up the models are not reported in the methodology demonstration. The general cost modeling methodology used is reported by Malshe [1]. The total cost of manufacturing plans as well as the blanks and ordered processes are presented.

4.5 Methodology Demonstration

A demonstration using two example parts is presented in this section. The parts include a rectilinear bracket and topology optimized flat fixture. Both of these parts are assumed to be made of Ti-6Al-4V. The manufacturability of the parts is evaluated by considering linear friction welding and machining as the two main processes with potential blanks including waterjet plate, rectangular stock, circular stock, and closed die-forgings. Closed die forgings will only be considered for manufacturing plans that do not contain linear friction welding. Auxiliary processes, such as flash removal, material handling, non-destructive testing, heat treat, dimensional testing, and final quality assurance are considered in the cost, but are not explicitly called out in the descriptions of ordered processes for simplicity.

The rectilinear bracket will consider the cutting planes shown in Figure 4.9. These cutting planes have been identified by the designer as having a high potential for linear friction welding or exposing unmachinable regions. The manufacturing plan search was run with a beam width of two and depth limit of three, so the manufacturing plan created will have at most three cutting planes applied to it. Additionally, the as-designed part volume is 11,238 cm^3.

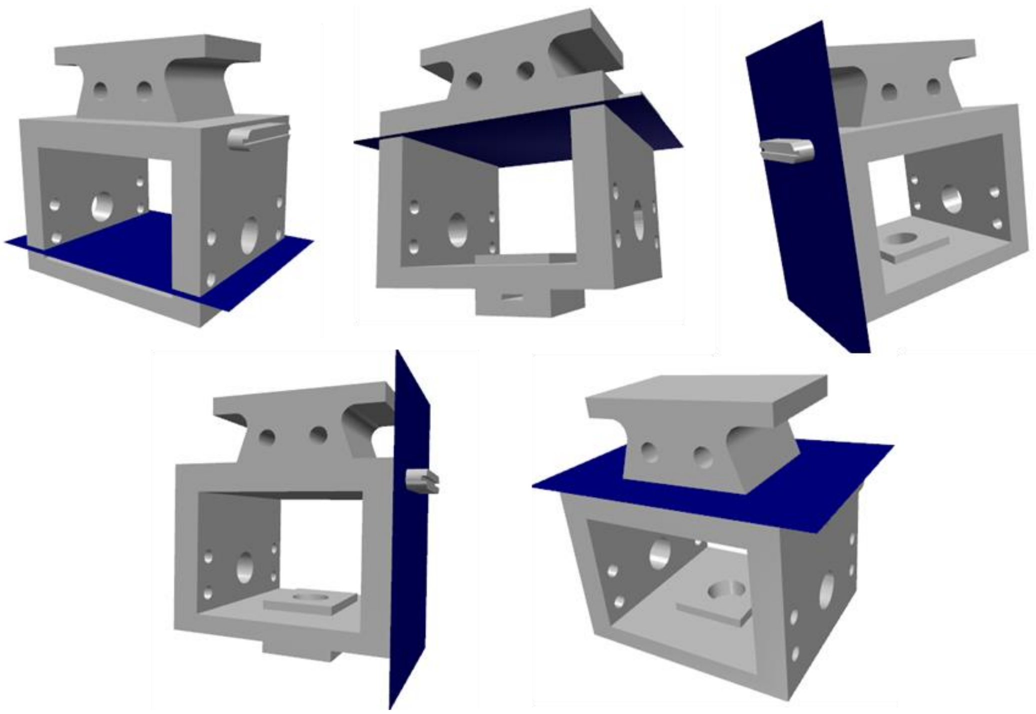
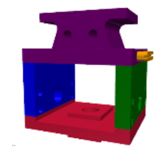


Figure 4.9: Selected cutting planes for the rectilinear bracket manufacturing plan generation and search

The search was run five times with various weights to demonstrate the effect of weighting on tradeoff. The search is run once considering only cost ($w_1 = 1.0$), once where cost was weighted at 80% ($w_1 = 0.8$), once where cost and unmachinable volume were weighted equally ($w_1 = 0.5$), once where unmachinable volume was weighted at 80% ($w_1 = 0.2$), and once where only unmachinable volume is considered ($w_1 = 0.0$). The optimal result from each search is summarized in Table 4.1.

Table 4.1: Rectilinear bracket manufacturing plan search results (w_1 is the weighting used for the objective function)

	$w_1 = 1.0$	$w_1 = 0.8$	$w_1 = 0.5$	$w_1 = 0.2$	$w_1 = 0.0$
Image					
Total Cost	\$5346	\$5346	\$5346	\$5346	\$6505
Blanks	Closed-Die Forging (Red)	Closed-Die Forging (Red)	Closed-Die Forging (Red)	Closed-Die Forging (Red)	Rectangular Stock (All 5)
Unmachinable Volume	54.33 cm^3	54.33 cm^3	54.33 cm^3	54.33 cm^3	0 cm^3

The result from the cost only search resulted in a single piece machining operation that would result in the same amount of unmachinable solid as the initial design. The part will be made from a closed-die forging and will just require a single machining operation. This will cost a total of \$5346 and will have 54.33 cm^3 of volume on top of the as designed input from unmachinable areas. The unmachinable regions left in those manufacturing plans can be seen in Figure 4.10.

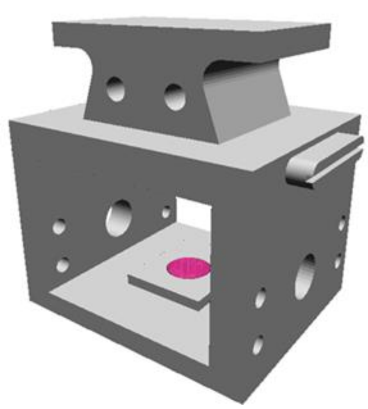


Figure 4.10: Unmachinable region remaining shown in pink

When the search adds in the measure of volume, the results are the same as the cost only search due to how small the unmachinable material is and how much the cost difference is. It is only in the search where objective function is entirely weighted on volume that a result that incorporates linear friction welding is the optimal. The search where $w_1 = 0.0$ returns a manufacturing plan that consists of five blanks, all of which are rectangular stock. The base piece, seen in Table 4.1 in red, is machined prior to join to access the unmachinable region. The joins are a single piece linear friction weld joining the purple and yellow blanks, then the green and blue are simultaneously joined via linear friction welding to the purple and yellow joined assembly, with the red piece being joined last to the complete sub-assembly at the green and blue blanks. The point where the single piece manufacturing plan is no longer the optimal is between $0.03 < w_1 < 0.07$. The weights used are sensitive to the part size and the ration of unmachinable volume to input part size. Each part will require some fine tuning to determine the optimal weights for interesting results.

This search can also be run for topology optimized parts that are more difficult to identify the best areas for joining and exposing the unmachinable areas. The part used to demonstrate this is a flat table fixture. The cutting planes used to decompose this fixture can be seen in Figure 4.11. This manufacturing plan search was run with the same variation of weights as the search for the rectilinear bracket and also used a beam width of two and depth limit of two. The input part has an as-designed volume of 3945 cm^3.

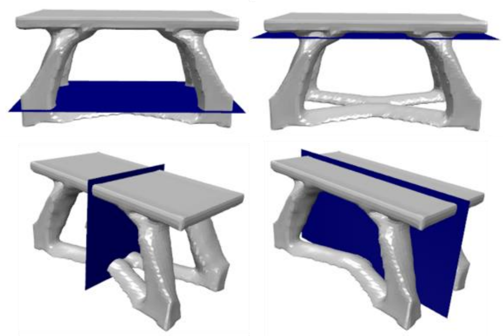


Figure 4.11: Selected cutting planes for topology optimized part manufacturing plan generation and search

For the topology optimized part, the configuration that exposed the most material was also the cheapest manufacturing plan. Thus, the weights are inconsequential for final evaluation. That being said, the solution has two cutting planes applied. If the beam width did not capture the first cutting plane due to the weights, this configuration and manufacturing plan would not have been found. The configuration can be seen in Figure 4.12. The green sub-volume is made from rectangular bar stock while waterjet plate is used for the rest. All the blanks are pre-join machined due to fact that all carry some unmachinable solid. The original unmachinable solid amount and the remaining can be seen in Figure 4.13.

Figure 4.12: Configuration for topology optimized part consisting of six blanks - rectangular stock is used for the green sub-volume and waterjet plates are used for the five other sub-volumes

Figure 4.13: Unmachinable solid shown in pink over the as-designed part from a single piece (left) and using the optimal manufacturing plan (right)

The initial analysis on the left side of Figure 4.13 closes off some of the interior areas of the legs due to the difficult angle for a cutting tool. The left side shows nearly no pink areas. The manufacturing plan for the single piece would be a single machining operation from a closed-die forging. This would have a cost of $4757 and would leave 82 cm^3 of unmachinable material. The optimal manufacturing plan indicates pre-join machining for all six of the blanks, joins for all four legs simultaneously to the green portion, and then a join for the red base onto the legs of the joined assembly. This manufacturing plan has a cost of $3348 and only leaves a calculated 2 cm^3 of unmachinable material. This remaining material is likely in small pockets within the optimized shape that would be difficult to expose and identify.

From these results, it is shown that this methodology is a useful way for identifying part machinability while considering linear friction welding capabilities. An area of interest that would be thought-provoking is a method for determining proper weighting as there are vast differences on the effects of weights based on the two example parts. Both searches however succeeded in finding manufacturing plans that would improve the manufacturability of the part as well as considered costs.

4.6 Future Work

The research shown herein provides designers a way to evaluate part designs considering machining and linear friction welding joining processes for Ti-6Al-4V parts. Designers are offered a way to determine the trade-off between cost and part design complexity and can see the specific processes used to create such a part. The work developed and shown has a lot of exciting potential for future efforts.

Improvements to the original voxelization and unmachinable solid analysis would make this search more powerful. The addition of improved voxel resolutions would allow the method to achieve a higher fidelity to the original tessellated shape and model a finer unmachinable voxel solid. Also, the ability to search along multiple directions outside of the orthogonal directions in the initial machinability analysis would aid in a more accurate modeling of the machining process.

As manufacturing technologies develop, the ability to add additional materials and processes into the manufacturing plan search would be an area of interest. Comparing these advanced joining-based systems to an additive model would be a subject of interest and could be useful to industries that may not have as stringent of requirements as aerospace.

As mentioned at the beginning of this paper, an interesting continuation of this work would be to introduce this search nested within a topology optimization as a multi-objective search. Although the computational requirement is large, it would guarantee an optimal solution that considers mass of the part, cost, and feasibility of manufacturing. It would also be interesting to look at additional multi-objective optimizations so that the volume measure is better represented if a designer is not sure what weights are appropriate. This large scale nested optimization may not be feasible in the short term but would be an exciting area of research as technology develops.

4.7 Conclusion

This paper has presents a method which allows designers to receive feedback on the manufacturability of a part design considering linear friction welding and machining. This is done by returning manufacturing plans with determined unmachinable regions, which is done using a decomposition of a part while tracking the unmachinable regions from an initial analysis within the created configuration of sub-volumes. The sub-volumes are then used to do a manufacturing plan search that chooses which blanks will be used and when joining operations will be applied. The decomposition for choosing cutting planes is done using a multi-objective beam search heuristic that measures both total cost of manufacturing and the remaining unmachinable material. The cost portion is calculated by generating a manufacturing plan which is compiled doing a cost first search by choosing the blanks and then the joining processes.

The results from the research show a promising method to analyze manufacturability while considering linear friction welding and machining for Ti-6Al-4V parts. The simpler prismatic rectilinear bracket created a manufacturing plan that would make the part entirely manufacturable but increased the cost of manufacturing by $1159 in comparison to a single piece machining operation. These manufacturing plans all had higher costs than the manufacturing plan from a single closed-die forging. The topology optimized part had an optimal manufacturing plan that had both the minimum cost and minimum unmachinable material remaining. This allowed the design to take advantage of the material savings from linear friction welding and the pre-join machining to reduce the area of unmachinable material. The results presented in this method are unique to other analyses because of the unmachinable solid tracked through each iteration. As opposed to giving a feature or face a manufacturability score, it adds the material to the design and returns the solid to make the part machinable. This metric is more visually informative to a designer who can gather ideas from this shape of the unmachinable solid for future design iterations.

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5 SUMMARY AND CONCLUSIONS

This chapter will discuss and summarize the methodologies presented and major conclusions of the demonstrated capabilities. Major academic contributions will be highlighted as well as research limitations and opportunities for future work.

5.1 Summary

In summation, this thesis has presented a methodology that can aid designers with considering advancements in manufacturing technologies in the critical stages of the design process. In Chapter 3, a methodology was presented for assessing a parts machinability using voxelized solid models. This machinability assessment is a featureless method that take designer inputs as a tessellated part file. This allows the method to be agnostic of any CAD software the part was designed in. The method consisted converting the tessellated geometry into a voxel representation and then using a toolpath fill algorithm that showed machinability along a given tool orientation. All the filled toolpath orientations then were intersected leaving just the as designed part and any regions that were not accessible using those toolpath orientations. Subtracting away the original voxel shape from the intersected shape allowed the unmachinable solid to be isolated. Results from this methodology showed the ability to find difficult to reach areas on a simple prismatic part as well as a complex topology optimized part. The voxelized unmachinable solid from the analysis is visualized over the tessellated shape, providing designers with visual feedback of potential problem areas in their design.

Chapter 4 uses the unmachinable solid returned by the chapter 3 methodology to explore advanced joining in manufacturing that could make those designs machinable using a combination of advanced joining and pre-joining machining on sub-volumes. The search explores manufacturing plans alternative that attempt to be as close to the original input design as possible as well as cost optimal. The manufacturing plans are based on configurations that are decomposed from the original part design and built back up by choosing blanks, joining operations, and pre-join machining processes. These results show the maximum manufacturability and overlays the remaining unmachinable solid, if there are any. This allows designers to see alternative manufacturing plans and consider potential redesigns based on cost, complexity of design, and total processing.

5.2 Conclusions

In conclusion, this methodology developed has demonstrated a new manufacturability feedback system for designers. This new system is able to consider the cost of the manufacturing plan and includes linear friction welding within the analysis. The baseline analysis presented in Chapter 3 introduced the voxel solid modeling shows how this representation can be used to model linear toolpath directions to determine unmachinable regions of a part geometry. This methodology not only shows the features on a part that are unmachinable, but show the solid material required to be added to make it machinable.

Chapter 4 presented a methodology that showed the ability to access unmachinable areas by decomposing the part and taking advantage of linear friction welding and pre-join machining. This methodology allowed designers to apply expert knowledge of linear friction welding manufacturing processes with ease. The results also enable designers to see the tradeoff between part complexity, processing, and total manufacturing cost. This shortens the feedback loop for designers consulting with manufacturing experts and gives designers a good way to justify and validate geometries for manufacturability.

5.3 Contributions

The academic contributions and innovations developed through the execution of this master's thesis are highlighted in this section. The first contribution that is made is the development of a methodology for determining unmachinable solid regions of a part using a voxelized solid models. This approach differentiates itself from other approaches because other than showing specific features on the design that are unmachinable, it fills the part in to show how much more material would be required to make the part manufacturable. This style of feedback can be more useful as it gives designers more information on how the part could be redesigned.

The research herein also developed a multi-objective beam search for manufacturing plan generation considering both optimality of cost and fidelity to the as designed input using voxelized solid models of unmachinable regions. This search expanded on the manufacturability analysis in Chapter 3 and added considerations to linear friction welding and process ordering. This information adds the ability for parts to be evaluated for manufacturability with new technologies.

The individual analysis above all culminate into a manufacturability feedback system for designers to bridge the gap between design process and advanced manufacturing knowledge. Analyzing a part using embedded expert knowledge for machinability and linear friction welding capabilities in an automated tool can help designers better understand the new technology as well as shorten the feedback loop of contacting an expert. Additionally, the returned ordered processes, costs, and overall part design manufacturability can allow designers to see tradeoffs and gives the designer more information to justify design decisions.

5.4 Research Limitations

Significant background research went into the development of this manufacturing analysis system. However, there are several limitations that this research can address to improve the robustness and increase the amount of feedback presented to a designer. For example, the voxelized solid model library used is young and may not offer ideal resolutions to represent more complex parts. Additionally, the voxel functions developed herein to model toolpath approaches are limited to the orthogonal orientations of the minimum bounding box.

In addition to the limitations of the voxel function, the parts output by the machinability analysis system are not production ready. Additional design edits would be required if a given manufacturing plan is chosen for implementation. The level of involvement required in the design changes would be depended on the initial input design. If this is used with topology optimized parts, it would deviate the part design from the optimal if the part is not entirely manufacturable. Additionally, any part design changes would require the part to undergo loading analysis again.

5.5 Opportunities for Future Work

Based on the limitations stated in the previous section, there are several potential avenues for future work. The main areas being in the development of the voxel library, improving the producibility of output geometries, and guaranteeing an optimal solution in both design and manufacturing.

Improving the voxel library for use in the analysis an area of improvement that would make the search and modeling much more powerful. Increased resolution would allow the part designs and unmachinable solids to be presented with higher accuracy. In addition to resolution, a methodology or function for toolpath approaches outside of the minimum bounding box would allow the machinability modeling to expand from 3-axis milling along the orthogonal to being able to model 5-axis milling.

Combining the final part with the remaining unmachinable solid would also help in the design process. Returning full producible parts would allow the designer to test for load cases immediately if the output passes the “eye test.” This would require a way to convert the voxels to back into tessellated shapes and estimating flat surfaces such that the “stair step” finish would be smoothed.

A stretch goal for this work that would offer solutions that guarantee both optimal manufacturing and design would be to implement the manufacturing producibility search presented within a multi-objective topology optimization. The computational power required would be extensive but results from such a search would be impactful in industry. Such an optimization, if designed modularly, could be a bridge between designers and manufacture. For example more detailed models, like the one built by Grujicic et al. could be used to inform the design automation of specific material characteristics at joining sites [38]. Manufacturers could implement new technological considerations within the manufacturing plan search and designers would be able to implement new metrics into the design portion of the optimization.

6 BIBLIOGRAPHY

[1] Malshe, H. A., 2016, "A Techno-Economic Assessment Methodology for Advanced Additive and Joining Processes," MS Thesis, Oregon State University.

[2] Shukor, S. A., and Axinte, D. A., 2009, "Manufacturability Analysis System: Issues and Future Trends," Int. J. Prod. Res., **47**(5), pp. 1369–1390.

[3] Gu, Z., Zhang, Y. F., and Nee, A. Y. C., 1997, "Identification of Important Features for Machining Operations Sequence Generation," Int. J. Prod. Res., **35**(8), pp. 2285–2308.

[4] Moylan, S. P., 2017, "Qualification for Additive Manufacturing Materials, Processes, and PArts."

[5] 2016, "AS9133A Qualification Procedure for Aerospace Standard Products."

[6] Bhamji, I., Preuss, M., Threadgill, P. L., and Addison, A. C., 2011, "Solid State Joining of Metals by Linear Friction Welding: A Literature Review," Mater. Sci. Technol., **27**(1), pp. 2–12.

[7] Li, W., Vairis, A., Preuss, M., and Ma, T., 2016, "Linear and Rotary Friction Welding Review," Int. Mater. Rev., **61**(2), pp. 71–100.

[8] 2018, "TVGL: Tessellation and Voxelization Geometry Library" [Online]. Available: https://github.com/DesignEngrLab/TVGL. [Accessed: 08-Mar-2018].

[9] Hoefer, M., Chen, N., and Frank, M., 2017, "Automated Manufacturability Analysis for Conceptual Design in New Product Development," *IIE Annual Conference. Proceedings*, Institute of Industrial and Systems Engineers (IISE), pp. 860–865.

[10] Hoefer, M. J. D., "Automated Design for Manufacturing and Supply Chain Using Geometric Data Mining and Machine Learning," p. 58.

[11] Abdelall, E. S., Frank, M. C., and Stone, R. T., "Design for Manufacturability-Based Feedback to Mitigate Design Fixation," p. 18.

[12] Kerbrat, O., Mognol, P., and Hascoet, J., 2010, "Manufacturability Analysis to Combine Additive and Subtractive Processes," Rapid Prototyp. J., **16**(1), pp. 63–72.

[13] Kerbrat, O., Mognol, P., and Hascoët, J.-Y., 2010, "Manufacturing Complexity Evaluation at the Design Stage for Both Machining and Layered Manufacturing," CIRP J. Manuf. Sci. Technol., pp. 208–215.

[14] Kerbrat, O., “A New DFM Approach to Combine Machining and Additive Manufacturing.”

[15] Molcho, G., Zipori, Y., Schneor, R., Rosen, O., Goldstein, D., and Shpitalni, M., 2008, “Computer Aided Manufacturability Analysis: Closing the Knowledge Gap between the Designer and the Manufacturer,” CIRP Ann., **57**(1), pp. 153–158.

[16] Ong, S. K., and Chew, L. C., 2000, “Evaluating the Manufacturability of Machined Parts and Their Setup Plans,” Int. J. Prod. Res., **38**(11), pp. 2397–2415.

[17] Tedia, S., and Williams, C. B., “Manufacturability Analysis Tool for Additive Manufacturing Using Voxel-Based Geometric Modeling,” p. 21.

[18] Humpa, M., and Köhler, P., 2014, “Design Approach for Spiral Milling Parts Using Knowledge Based Engineering,” IOP Conf. Ser. Mater. Sci. Eng., **65**, p. 012001.

[19] Kulon, J., Broomhead, P., and Mynors, D. J., 2006, “Applying Knowledge-Based Engineering to Traditional Manufacturing Design,” Int. J. Adv. Manuf. Technol., **30**(9–10), pp. 945–951.

[20] Johansson, J., 2008, “Manufacturability Analysis Using Integrated KBE, CAD and FEM,” ASME, pp. 191–200.

[21] Sigmund, O., 2009, “Manufacturing Tolerant Topology Optimization,” Acta Mech. Sin., **25**(2), pp. 227–239.

[22] Gaynor, A. T., Meisel, N. A., Williams, C. B., and Guest, J. K., “Topology Optimization for Additive Manufacturing: Considering Maximum Overhang Constraint,” *15th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference*, American Institute of Aeronautics and Astronautics.

[23] Mass, Y., and Amir, O., 2017, “Topology Optimization for Additive Manufacturing: Accounting for Overhang Limitations Using a Virtual Skeleton,” Addit. Manuf., **18**, pp. 58–73.

[24] Mirzendehdel, A. M., and Suresh, K., 2016, “Support Structure Constrained Topology Optimization for Additive Manufacturing,” Comput.-Aided Des., **81**, pp. 1–13.

[25] Hiroshi, K., Koji, N., Tsukasa, W., and Kenji, N., 2014, “Application of Linear Friction Welding Technique to Aircraft Engine Parts,” **47**(1), p. 4.

[26] Dodds, S., “Linear Friction Welding: An Alternative Production Route for Titanium Aerospace Components.”

[27] Li, Y., and Frank, M. C., 2006, "Machinability Analysis for 3-Axis Flat End Milling," J. Manuf. Sci. Eng., **128**(2), p. 454.

[28] Jang, D., Kim, K., and Jung, J., 2000, "Voxel-Based Virtual Multi-Axis Machining," Int. J. Adv. Manuf. Technol., **16**(10), pp. 709–713.

[29] Museth, K., Lait, J., Johanson, J., Budsberg, J., Henderson, R., Alden, M., Cucka, P., Hill, D., and Pearce, A., 2013, "OpenVDB: An Open-Source Data Structure and Toolkit for High-Resolution Volumes," *SIGGRAPH*, ACM, Anaheim, CA.

[30] Meagher, D., 1982, "Geometric Modeling Using Octree Encoding," Comput. Graph. Image Process., **19**(2), pp. 129–147.

[31] Mirzendehdel, A. M., Rankouhi, B., and Suresh, K., 2018, "Strength-Based Topology Optimization for Anisotropic Parts," Addit. Manuf., **19**, pp. 104–113.

[32] "Designing Light-Weight Parts Using ParetoWorks."

[33] Massoni, B., and Campbell, M. I., 2018, "Optimizing Cutting Planes for Advanced Joining and Additive Manufacturing," J. Manuf. Sci. Eng., **140**(3).

[34] Chan, R., Haapala, K. R., and Campbell, M. I., 2018, "ASSESSING COMPONENT MACHINABILITY USING VOXELIZED SOLID MODELS," ASME, Quebec City, Quebec, Canada, p. 8.

[35] Massoni, B. R., and Campbell, M. I., 2017, "A Decomposition Method for Efficient Manufacturing of Complex Parts," Comput.-Aided Des. Appl., **14**(6), pp. 705–719.

[36] Marler, R. T., and Arora, J. S., 2004, "Survey of Multi-Objective Optimization Methods for Engineering," Struct. Multidiscip. Optim., **26**(6), pp. 369–395.

[37] Massoni, B. R., and Campbell, M. I., 2017, "Automated Design of Closed-Die Forgings," p. V02BT03A021.

[38] Grujicic, M., Arakere, G., Pandurangan, B., Yen, C.-F., and Cheeseman, B. A., 2012, "Process Modeling of Ti-6Al-4V Linear Friction Welding (LFW)," J. Mater. Eng. Perform., **21**(10), pp. 2011–2023.