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Knowledge-based decision support in CAM for additive manufacturing: A rules mathematization approach.

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Mouhamadou Mansour Mbow. Knowledge-based decision support in CAM for additive manufacturing: A rules mathematization approach.. Computer Aided Engineering. Université Grenoble Alpes [2020-..], 2020. English. NNT: 2020GRALI082 . tel-03173667

HAL Id: tel-03173667

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THÈSE

Pour obtenir le grade de

DOCTEUR DE L'UNIVERSITÉ GRENOBLE ALPES

Spécialité : GI : Génie Industriel : conception et production

Arrêté ministériel : 25 mai 2016

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préparée au sein du **Laboratoire des Sciences pour
la Conception, l'Optimisation et la Production de Grenoble**
dans l'**École Doctorale I-MEP2 - Ingénierie - Matériaux, Mécanique,
Environnement, Energétique, Procédés, Production**

**Aide à la décision basée sur l'expertise métier
dans le domaine de la FAO pour la fabrication
additive : une approche par mathématisation des
règles.**

**Knowledge-based decision support in CAM for
additive manufacturing: rules mathematization
approach.**

Thèse soutenue publiquement le **11 décembre 2020**,
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Dedicated to,

Dédié à,

May na ko,

Khalifa Babacar, Soda, Alioune, Oumou, Aïda, Youssoufa et Fatim

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Abdou Kane, Aïda Hann, Malick Tall

...

Acknowledgments

I would like to begin by thanking my supervisors Frédéric Vignat, Philippe Marin and Nicolas Perry for giving me the opportunity to do this thesis work in the laboratories G-SCOP in Grenoble and I2M in Bordeaux. This, through the COFFA project funded by the French National Research Agency (ANR) that I thank for the financial support of this thesis. Thanks to the time spent with the actors of this project, I learned a lot of things in rich and varied fields. I would like to express my gratitude to Philippe Marin and Franck Pourroy for having introduced me to the basics of research work during an internship prior to this PhD.

I am particularly grateful to Frédéric Vignat for his supervision and for the fact that he always pushed the work further, in order to have better results. I am grateful to the following people for their invaluable help in carrying out this work: Christelle Grandvallet, Guy Prudhomme, Marco Montemurro, Jérôme Pailhes, Gilles Foucault.

I would like to thank my parents Khalifa and Marème Soda, all my family in Senegal and my uncles Malick Tall and Abdou Kane for their support throughout my studies. I cannot thank enough my very dear Maoude who has been present during these three years to encourage and listen to me. Thank you for this attention. I am also grateful to my friends Mohamed Dieng, Nafissa Dia, Ibrahima Fall and Cheikhna Seck.

This work also went well thanks to the good mood of the colleagues at work and thanks to the music sessions of the Coffi-Coffa Band. I think especially of Akram, Manoch, Supasit, Cédric, Pierre Thomas, Vo Hoang, Amer, Rafael, Yohannes, Pascal, Clément, Matthieu, Nicolas, Maxime, Giulia and Soukaina. Finally, I would like to thank Alain Bernard, Lionel Roucoules and Nabil Anwer for having accepted to be members of my thesis jury.

Remerciements

J'aimerais commencer par remercier mes encadrants Frédéric Vignat, Philippe Marin et Nicolas Perry de m'avoir donné l'occasion d'effectuer ce travail de thèse au sein des laboratoires G-SCOP de Grenoble et I2M de Bordeaux. Ceci à travers le projet COFFA financé par l'Agence National de Recherche (ANR) que je remercie pour l'accompagnement financier de cette thèse. Grâce au temps passé avec les acteurs de ce projet, j'ai appris beaucoup de choses dans des domaines riches et variés. Je témoigne d'avantage ma reconnaissance à Philippe Marin et Franck Pourroy pour m'avoir initié aux bases d'un travail de recherche lors d'un stage précédent ce doctorat. Je remercie particulièrement Frédéric Vignat pour l'encadrement et pour le fait d'avoir toujours poussé plus loin les travaux, afin d'avoir de meilleurs résultats. Je suis reconnaissant aux personnes suivantes, pour leur aide inestimable dans la réalisation de ces travaux : Christelle Grandvallet, Guy Prudhomme, Marco Montemurro, Jérôme Pailhes, Gilles Foucault.

Je remercie mes parents Khalifa et Marème Soda, toute ma famille au Sénégal et mes oncles Malick Tall et Abdou Kane pour leur soutien tout au long de mon cursus d'études. Je ne saurai remercier assez ma très chère Maoude qui a été présente pendant ces trois années à m'encourager et à m'écouter. Merci pour cette attention. Je suis également reconnaissant à mes amis Mohamed Dieng, Nafissa Dia, Ibrahima Fall et Cheikhna Seck.

Ce travail s'est également bien déroulé grâce à la bonne humeur des collègues au travail et grâce aux session de musique du groupe Coffi-Coffa. Je pense spécialement à Akram, Manoch, Supasit, Cédric, Pierre Thomas, Vo Hoang, Amer, Rafael, Yohannes, Pascal, Clément, Matthieu, Nicolas, Maxime, Giulia et Soukaina. Je finis par adresser mes remerciements à Alain Bernard, Lionel Roucoules et Nabil Anwer d'avoir accepté d'être membres de mon jury de thèse.

Abstract

Pre-processing or CAM operations in additive manufacturing (AM) by powder bed fusion (PBF) include complex actions such as the definition of part orientation, the design of support structures, the nesting of parts, etc. The definition of the parts orientation in the manufacturing build space is the first step and several studies have shown that all of the remaining steps depend on it as well as the quality, cost and production time of the part. Its definition is given by only two rotation angle parameters in the global machine reference, but their definition is complex and requires strong skills in the field. Studies in the literature have shown that industrial users rely on their knowledge or expertise of the process to achieve this. Today, despite the technical advances, there is still a lack of tools or methods to take into account this formalized expertise. In this context, this thesis (from ANR COFFA project) proposes methods and tools to efficiently include the formalized knowledge of experts in the decision making process of CAM parameters, in PBF and AM in general.

As a first step, the review of methods to use expertise in decision making in traditional manufacturing CAM is presented in order to find the disadvantages and possibilities for integration in AM. Secondly, an investigation of the types of knowledge that can be used for decision support is carried out. This part of the work also explores the knowledge resources available for the definition of part orientation in the research literature but also in the industrial practice. The third part of the work presents a new approach for transforming knowledge of action rule type into desirability functions. This approach allows in particular to evaluate these action rules on parts and to obtain a quantitative appreciation which is considered as the level of respect of the rule (when the CAM parameters applied to the part). Then, this approach is applied to the action rules found in the second part of the work to establish quantitative models for the calculation of orientation desirability. Finally, a tool for the calculation of this orientation desirability and decision-making support is presented. The use of the tool is illustrated through case studies of industrial parts benchmarked with commercial tools, and through tests carried out with engineering school students.

The main output of this project is the provision of numerical means to assist CAM operators in their decision-making on optimal manufacturing parameters based on the company expertise. In addition, the approach presented offers the possibility of redesigning parts by targeting surfaces that have a low desirability with respect to the part orientation.

Résumé

Les opérations de préparation ou de FAO en fabrication additive (FA) par fusion sur lit de poudre (FLP) consistent en des opérations complexes telles que la définition de l'orientation des pièces, la conception des supports, l'imbrication ou le nesting des pièces, etc. La définition de l'orientation des pièces dans l'espace de production est la première étape et plusieurs études ont montré que toutes les étapes restantes dépendent d'elle tout comme la qualité, le coût ainsi que le temps de production des pièces. Sa définition n'est donnée que par deux paramètres d'angle de rotation dans la référence globale de la machine, mais leur définition est complexe et nécessite de fortes compétences dans le domaine. Des études dans la littérature ont montrées que les utilisateurs industriels se basent sur leurs connaissances métier pour y parvenir. Aujourd'hui, malgré les progrès techniques, il y a encore un manque d'outils et de méthodes pour prendre en compte cette expertise formalisée. Dans ce contexte, cette thèse (dans le cadre du projet ANR COFFA) propose des méthodes et des outils pour intégrer efficacement les connaissances formalisées des experts dans le processus de prise de décision sur les paramètres de la FAO dans le domaine de la fabrication additive.

Dans un premier temps, la revue des méthodes d'utilisation d'expertise dans la prise de décision en FAO de fabrication traditionnelle est présentée dans le but de trouver les inconvénients et possibilités pour une intégration en FA. En deuxième lieu, une investigation des types de connaissances pouvant être utilisés pour l'aide à la prise de décision est effectuée. Cette partie du travail explore également les ressources en connaissances disponibles pour la définition de l'orientation des pièces dans la littérature mais aussi dans la pratique industrielle. La troisième partie du travail présente une nouvelle approche pour transformer les connaissances de type règle d'action en des fonctions de désirabilité. Cette approche permet notamment d'évaluer ces règles d'action sur des pièces et d'obtenir une appréciation quantitative qui est considérée comme le niveau de respect de la règle (lorsque les paramètres de la FAO s'appliquent à la pièce). Ensuite, cette approche est appliquée aux règles d'action trouvées dans la deuxième partie du travail pour établir des modèles quantitatifs destinés au calcul de la désirabilité d'orientation des pièces. Enfin, un outil de calcul de cette désirabilité d'orientation et d'aide à la décision est présenté. L'utilisation de l'outil est illustrée par des études de cas de pièces industrielles dont les résultats sont comparés à ceux d'outils commerciaux, et à travers des tests réalisés avec des étudiants en écoles d'ingénieurs.

La principale sortie de ce projet est la fourniture de moyens numériques pour ai-

der les opérateurs de FAO à prendre des décisions sur les paramètres de fabrication optimaux en fonction de l'expertise de l'entreprise. De plus, l'approche présentée offre la possibilité de re-concevoir des pièces en ciblant les surfaces qui ont une faible désirabilité par rapport à l'orientation de la pièce.

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Glossary

AHP: Analytical Hierarchy Process

AM: Additive Manufacturing

AR: Action Rule

CAD: Computer Aided Design

CAM: Computer Aided Manufacturing

COFFA: Design and Shape Optimization for Additive Manufacturing (FR: Conception et Optimisation de Forme pour la Fabrication Additive)

DF: Desirability Function

DMLS: Direct Metal Laser Sintering

EBM: Electron Beam Melting

FDM: Fused Deposition Modeling

KM: Knowledge Management

MA: Manufacturability Analysis

NURBS: Non-Uniform Rational Basis Splines

PBF: Powder Bed Fusion

SLA: StereoLithography Apparatus

SLM: Selective Laser Melting

SLS: Selective Laser Sintering

STEP: STandard for the Exchange of Product model data

STL: STereoLithography

TO: Topology Optimization

Introduction

Thesis Context and COFFA Project

The question of product design customization has increasingly become a major concern for manufacturing industries that are facing an exigent demand. From the customer design specifications to the finished parts, the traditional methods of fabrication (milling, turning, casting, forging, etc) usually require the development of special individual tooling for each family of product. However, with the implementation of additive manufacturing (AM) and particularly the metal additive manufacturing methods such as the powder bed fusion (PBF), the development of new parts or assemblies has become faster. In the present industrial context, AM processes are gaining more and more importance thanks to their capability of producing various shapes from the simplest one to the most complex that were formerly difficult or impossible to manufacture with existing means. This large freedom in design made possible the development of more flexible design approaches such as the function based design (Klahn et al. (2015)), which allows generating products that are more competitive, lightweight and more suitable with their function. At their beginning, additive manufacturing technologies were limited to prototyping purposes, but nowadays they are extended to the manufacturing of end user products (e.g. parts for automotive industry, medical implants, etc). Nevertheless, despite the advantages, the parts made with PBF systems recurrently suffer from issues related to quality and performance including lead time and cost (Metal AM Vol4, N°3, (2018)). The latter are actually causing production repeatability and reliability problems hindering the prompt progress of PBF techniques for some industrial applications. Owing to the high cost of AM processes, products need to be well designed and well manufactured from the first time in order to alleviate the material waste.

Throughout the design process of a part, a designer must take advantage of

the AM shape freedom, while taking into account the limitations related to the manufacturing resources. Today, the design based on topology optimization (TO), consisting of finding the right material distribution inside a given design space in order to meet targeted requirements: mass, stiffness etc (Costa et al. (2019)), is one of the most popular approaches. However, either using classical CAD tools or TO tools, the designers as well as the manufacturing preparators or CAM operators (those who adjust the manufacturing parameters) must consider the process constraints in order to make possible the right production from the first trial. Thus, they are confronted to recurrent decision making about the design and the manufacturing parameters. Today, this remains a complicated task since in AM not only little data about manufacturability criteria and indicators are available, but also, the commercial design solutions do not usually include the manufacturing constraints. Therefore, most of the industrial users, only rely on their knowledge (expertise). To leverage that expertise from the different actors of the value chain (design, preparation, manufacturing, post-processing) to assist the daily decision making, there is a need of formalization and modeling tools.

In the view of this, the COFFA project (Design and Shape Optimization for Additive Manufacturing) proposes to assist the actors along the value chain of AM by providing interactive CAD and CAM tools. This project funded by the French National Research Agency (ANR) gathers two laboratories namely G-SCOP (Grenoble INP) and I2M (ENSAM Bordeaux) both located in France. The scope of COFFA is limited to two powder bed fusion systems (electron beam melting EBM, and selective laser melting SLM). COFFA works in close collaboration as illustrated by Fig. 0.1 with KAMLAB project (Knowledge Aided Manufacturing) funded by DP Research Institute and the ANR GeoCAM project (Geometrical Control of parts produced by Additive Manufacturing) which is also led by I2M and G-SCOP laboratories. KAMLAB proposes a set of tools to acquire and formalize expert knowledge for manufacturing. GeoCAM studies the geometrical defects of powder bed fusion parts. In the present work, the results from these projects will be referred by the following references: Grandvallet et al. (2020) and Ghaoui et al. (2020).

The main objectives of COFFA are as follows:

1. The integration of manufacturing constraints in the topological optimization process – this part of the project aims at taking over some feasibility criteria early in the design stage.

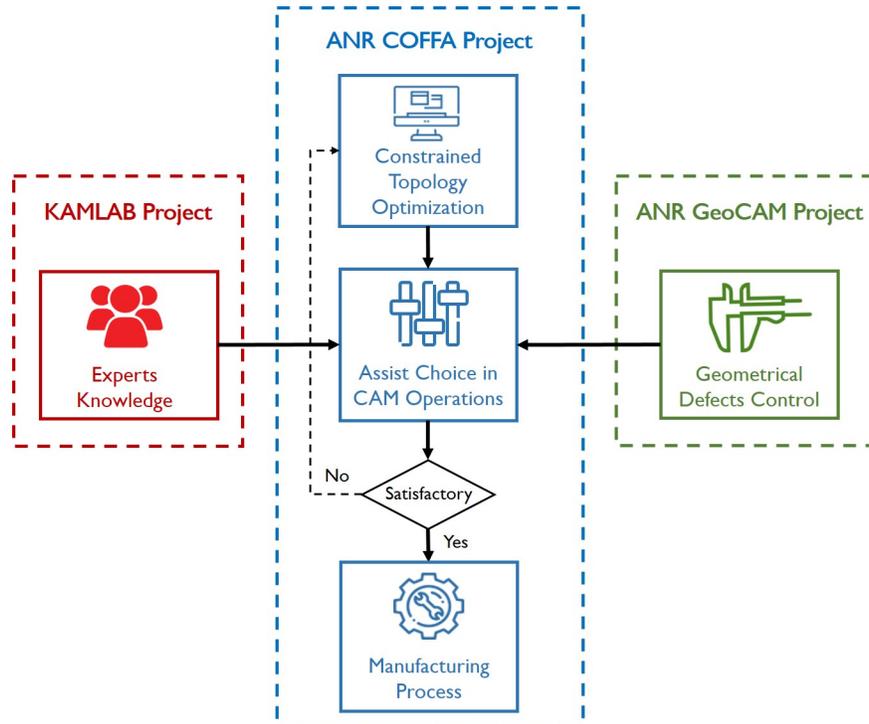


Figure 0.1: Collaborations between COFFA, KAMLAB and GeoCAM

2. The implementation of an automated surface reconstruction tool after topology optimization in order to get geometrical entities as output.
3. The development of an approach to integrate experts knowledge in the assistance of the decision making on CAM parameters (manufacturing set of parameters comparisons for optimal choice).
4. The proposal of an approach to redesign parts by basing on the knowledge-based manufacturability assessment results.

For a given product to design and produce, the approach of COFFA is to first perform a topology optimization process including some manufacturing constrains. Secondly, the CAM parameters for manufacturing the part resulting from the topology optimization are determined based on experts formalized knowledge. Then, if the found set of manufacturing parameters are not satisfactory a re-topology optimization is achieved to solve the issues related to the geometry.

This thesis will focus on the construction of a methodology to use as efficiently as possible the knowledge of experts in the PBF domain for supporting CAM decision-makers. The approach of this work is mainly centered on the assistance of the CAM actors in the choice of the right manufacturing parameters. The content of this document will discuss the methodologies and approaches executed to reach this objective.

The Powder Bed Fusion Process Chain and Pre-processing Issues

PBF Techniques

In metal AM, Powder Bed Fusion (PBF) systems are today known as efficient ways to get end-user parts. They are based on the melting or sintering of powder layers by using the power of laser or electron beam. Three technologies namely the Direct Metal Laser Sintering (DMLS), the Selective Laser Melting (SLM) and the Electron Beam Melting (EBM) are dominating the market (Additive Manufacturing Market, web site 1). Fig. 0.2 shows a schematic description of the powder bed principle. Firstly, a rake spreads the powder in question on the build plate, then the beam melts or sinters the appropriate zones corresponding to the targeted shape. The possibility of handling thin layer thicknesses makes it possible to manufacture high resolution geometries and even very small features. A Swedish company named ARCAM is the only manufacturer of EBM machines (Frazier (2014)), while a set of companies around the world are making SLM and DMLS machines such as SLM Solution, AddUp, Renishaw, Realizer, Concept Laser, EOS etc. This thesis focuses more on the EBM technology, nevertheless, most of the approaches that will be presented are also valid for SLM technology.

Value Chain & Pre-processing Issues

Owing to the technological shift between the traditional methods of manufacturing and the additive manufacturing, a significant difference can be noticed in the value chain of products acquisition. In AM, a product classically has to pass through several stages from its design to its quality control as shown in Figure 0.3 (taken from works of Grandvallet et al. (2020)). In the industrial practice, as well as in

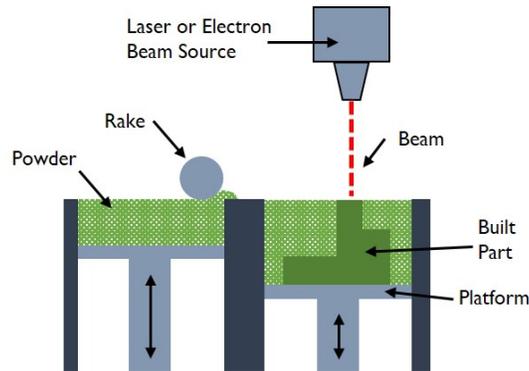


Figure 0.2: Powder bed fusion process

the academic research, these stages have been reported to be highly governing the production quality, repeatability and efficiency (Metal AM Vol4, N°3, (2018)).

For the PBF systems (similarly to the other AM techniques), the numerical chain begins with the *design* point, where the part's shape is developed by design engineers based on specifications; the output is usually a CAD model in either native or standard formats. Today, two main design approaches can be used, namely the designer-driven shape (the shape is entirely made by the designer in a classical CAD environment) and the process-driven shape such as the TO (the shape generation is automated) (Hällgren et al. (2016)). Later on, the designed product is transferred to the *pre-processing* stage in which, the CAM operators adjust the manufacturing parameters and eventually suggest re-design options if non-conformance with the process capabilities occurs. The part is then processed by the PBF system and sent to the *powder* and *support removal* stages before engaging the *post-processing* in which, operations like finishing or polishing are achieved. Finally, a *quality control* is performed for the validation of customer requirements. All of these phases must be conveniently managed in order to obtain good quality products.

One of the pivot boxes making the interest of this thesis is the pre-processing of the parts, also known as CAM operations. It clusters different sub classes of operations to perform in order to adequate the designed geometry to the process and post-process specificities. The CAM operations mainly intend to setup the manufacturing parameters taking into account the limitations and intricacies of the available resources. Steps as orienting the part, defining the regions to support, designing the support structures, associating a build strategy and nesting (if more

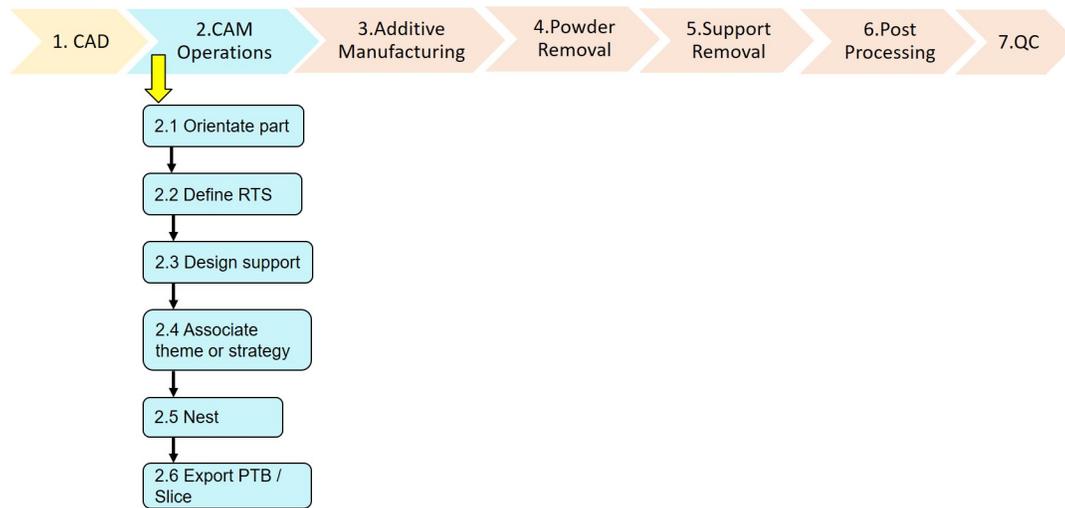


Figure 0.3: Powder bed fusion value chain and process preparation operations

than one part) have to be managed in the CAM software.

- The *part optimal orientation* in the machine's build space is one of the most important steps. Its determination is a complex task, which has significant impact on the product quality as well as on the build duration and cost (Pandey et al. (2007)). A particular attention will be given to this step in this document.
- The definition of the *regions to support* consists of detecting zones of an oriented part needing to be supported, these include the overhanging areas, and also zones that are likely to deform. In AM, support structures are currently used to anchor the part (Calignano (2014)) and help solving problems related to the distortions of the products as well as avoiding the collapse of overhanging surfaces during the fabrication.
- Following the definition of regions to support, the *support structures are designed* by respecting a certain number of rules related to their height, distribution, density, fragmentation, etc. As the support structures do not belong to the targeted part, one must have in mind their removability while designing them.

- The *association of theme or strategy* – allows defining volume attributes which can be either porous or compact.
- *Nesting* step is usually required when different parts must be built at the same time. This operation is about finding an optimal way to position the parts relatively to each others, in order to maximize the quantity built simultaneously, and thus reduce build time and cost.
- *Exporting part to build* allows storing and transferring the manufacturing required data containing for instance, the main geometry, the support structures, the manufacturing parameters etc.

In spite of the scientific and technical advances, PBF products still exhibit a set of defects related to characteristics as geometry and strength (Frazier (2014)). The freedom in shape design offered by these technologies leads to think that every design can simply and successfully be materialized. In contrast, whatever the design method used, the geometry must comply with the capabilities of the manufacturing resources.

In the daily practice, for additive manufacturing, these are not trivial to take into account. On the one hand, the designer (in some cases, communicating with the manufacturing agents) might be able to analyze the feasibility for simple geometries, but when the complexity increases, it becomes less and less realizable for him. On the other hand, the topology optimization process uses intricate algorithms in which it would be difficult to add all of the manufacturing constrains, as they have to be expressed mathematically and with some constrains such as derivability, continuity etc. Some of the manufacturing constrains are made up by the CAM operations to prepare stable manufacturing. The different CAM steps requirements might suggest re-design proposals so that the product returns to the designer with recommendations related to the manufacturability and eventually highlighting the problematic elements of the design. Setting up the CAM parameters in additive manufacturing requires a certain level of skills about the process. From a study led by Grandvallet et al. (2017) alongside an industrial manufacturer using PBF technologies, it can be seen that the CAM operators mainly use the know-how or expertise of their company when preparing parts. When formalized, this company expertise can be used to assist the determination of optimal manufacturing parameters that lead to the demanded quality, production cost and time.

Research Question and Motivation

The formalized knowledge for CAM operations can be seen as rules that must be tested on a given geometry to check whether they are compliant or not and to what extent. For instance, CAM experts could recommend this rule for orienting a given part: “Orient the functional surfaces of the part close to the vertical”; in this case a good orientation of the part is the one that puts the maximum of its functional surfaces close to the vertical. This compliance assessment is not an easy task since, not only the geometries are usually complex in AM, but also the knowledge in its literal form is difficult to quantify. Moreover, if a couple of rules are considered, the complexity of the problem amplifies, making it difficult to handle manually. These requirements lead to a main question which is: *How to Integrate the Experts Knowledge in the Assistance of CAM Operations for the Powder Bed Fusion Additive Manufacturing?*

In this study (as detailed in Chapter 1), the investigation of the methods used for assisting CAM activities by using knowledge has shown that for PBF no solution is available. For that reason those from traditional manufacturing have been reviewed in order to check what can be adapted to the present need. The methods found mainly consist of inference engines, and they are usually based on feature recognition (decomposition of CAD parts) which is not suitable for the complex shapes involved in the additive manufacturing. A review of the knowledge types used by industry practitioners to select CAM parameters (presented in Chapter 2) has shown that action rules (e.g. “minimize the support marks on non-machined surfaces”) are mainly used. According to experts, the action rules are simultaneously applied to see how extent they are compliant with the CAM parameters applied to the geometry of interest. For this reason, inference engines would not be suitable for the evaluation of the compliance level (quantitative values) of the action rules. At this time, it is difficult to find tools supporting this kind of evaluation for additive manufacturing. The quantitative evaluations pass through the mathematical representation of the rules. In regard of this, the central research question of this work is:

How to Mathematize Action Rules from Experts to Assist Decision-making in Powder Bed Fusion CAM operations?

One of the main aim of the present work is to fill the gap between rules, expressed in natural language, and their evaluation on geometries regardless their complexity. A precedent work led by the same research team has gathered a set

of useful knowledge resources about CAM for PBF systems (Grandvallet et al. (2017; 2017; 2020)). Following up, the present work aims at investigating a way to make use of that knowledge to support decision-making. This passes through being able to compare the scores (i.e manufacturability criterion) of multiple set of parameters.

Thesis Approach

According to what is aforementioned, different steps will be needed to respond to the research question. The points cited below describe the main approach of the present thesis.

1. Investigation of the methodologies used for computing part manufacturability in the traditional and additive manufacturing domains in order to find out which of them could help comply the present requirements.
2. Secondly, an investigation of the available formalized knowledge resources for AM CAM operations is performed. To this end, a brief review of the literature is carried out to find the already elicited knowledge and how, today, industry practitioners make use of that capitalized knowledge.
3. Construction of a novel modeling approach, which is able to transform formalized knowledge into mathematical models usable in computational systems. This constitutes the pivotal element to the transition from the literal nature of expressed knowledge to quantitative formulation.
4. Proposition of a method of assessing knowledge (in the form of rules) onto geometries. Beyond the modeling of knowledge, this work also aims at providing a methodology to assess rules given by experts on geometries. This methodology must be able to handle any geometry from the simplest to the most complex one, and provide compliance level for each prescribed rule.
5. Design of decision making assistance tools in order to facilitate the analysis of the results from the evaluations. The decision assistant intend to provide operators a scale to compare different scenarios of processing parameters.

Manuscript Content

One of the major objectives of this work is to support the CAM activity in AM based on the formalized knowledge of the experts in the domain. To get to this, the knowledge has first to be acquired from experts through elicitation process, then formalized to infer action rules and finally translated from its literal form to something that can easily be evaluated on geometrical entities. The knowledge acquisition (elicitation) is not in the scope of this work, thus, knowledge resources available in the literature are used. Detailed analysis of all of these elements will be provided in the different chapters of this work. The document will thus be organized as follows:

Chapter 1 presents a review about pre-processing operations in PBF and part manufacturability assessment methodologies in traditional manufacturing and in additive manufacturing. Then, a discussion about knowledge leveraging methods in manufacturing pre-processing and their limitations is carried out.

Chapter 2 presents some of the knowledge typologies that can assist CAM as well as the type of knowledge that interests this work. This chapter will also investigate the available knowledge resources in AM research literature and industrial practice for part orientation.

Chapter 3 proposes an approach to the quantitative modeling of a targeted knowledge type namely the *Action Rules*. Here, all the required stages allowing the transformation of the rules from literal to mathematical formulation (by using desirability functions) are discussed.

Chapter 4 exposes an application of the modeling approach to the computation of part orientation desirability. In this part, a set of rules from industry practitioners about the good practices for orienting parts, are transformed into mathematical functions. The algorithms used for the evaluation of the rules on geometries are also presented for each action rule.

Chapter 5 presents the COFFA tool made for computing part orientation desirability. Here are also exposed a set of tools for decision making assistance and case studies of some industry parts.

Chapter 1

Review of CAM Systems & Use of Knowledge for Assistance

Introduction

In the manufacturing domain, CAM systems have been used to ensure successful production for decades. Usually defined as numerical control programming tools (to generate toolpath), the CAM systems have today various meanings and usefulness. The different operations in CAM job intend to prepare the manufacturing process with the required parameters. Here, all the pre-processing steps between the design and the manufacturing stages are grouped in the CAM operations as depicted by Fig. 1.1. Preparing parts for manufacturing requires the selection of the best set of parameters that would allow getting optimal cost, production time and required quality. Hence, in order to reduce manufacturing cost due to useless iteration and time to market, decision making about those manufacturing parameters needs to be efficiently assisted. To do so, some tools are needed. Primarily, the comparison between scenarios (manufacturing parameters, design) is carried out on the basis of the feasibility or the so-called manufacturability evaluation. Then, a measure that can be qualitative or quantitative is used to benchmark and make strategic choice among different solutions.

Usually complex, manufacturability analysis (MA) task requires solid skills about the manufacturing system of interest. For this reason, the intervention of experts usually is vital to the achievement of those analyses as well as to the decision making. Fig. 1.1 illustrates a kind of loop that many companies use to store feed-backs from CAM operations and quality control teams in the form of knowl-

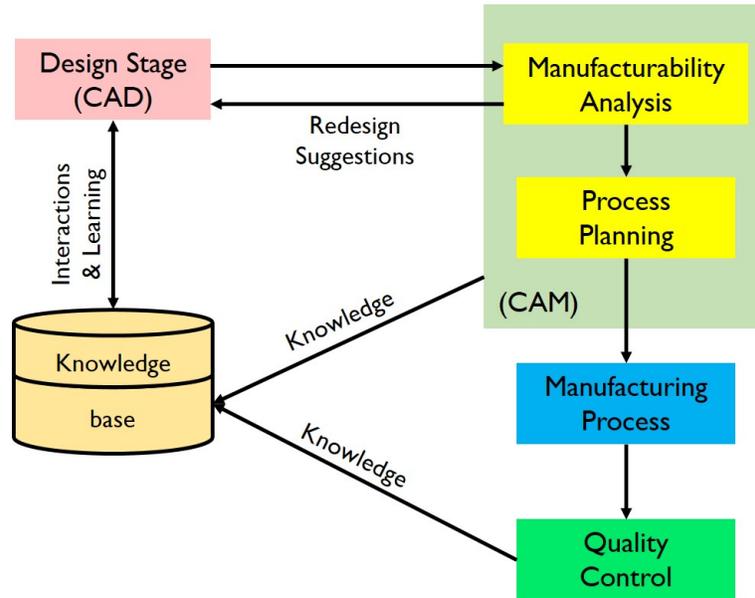


Figure 1.1: Classical scheme from design to manufacturing of components and manufacturing knowledge acquisition (adapted from Molcho et al. (2008))

edge resources (examples of quality knowledge extraction are available in Wang et al. (2007)). Those are most of times transformed into rules that can be used in future projects to design or analyze manufacturability (the present context). As said by Shukor and Axinte (2008), the manufacturing analysis systems offer various advantages such as:

- Recommending better designs,
- Generating process sequences,
- Helping the selection of suitable parameters, processes and materials,
- Assisting designers lacking of in-depth knowledge about the process of interest.

In traditional manufacturing (including machining, casting and other techniques), various works have already been led to propose different manufacturability analysis methods or tools. They are usually based on rule bases arising from the capitalized

knowledge. Comprehensive methods have been implemented into CAD/CAM algorithms for the traditional machining to evaluate the fitness of multiple parametric scenarios in order to generate re-design suggestions, process planning, process selection and materials (Sánchez et al. (1997), Capodiecici et al. (2004)). In contrast, owing to its young age, in AM, not many tools intended to define manufacturing attributes based on expertise are available. It is then worth checking how knowledge has formerly been used in production in order to implement it as efficiently as possible to AM CAM. As a reminder, note that this thesis aims at proposing expertise-based assistance of parameter choice for AM.

In this brief review chapter, AM CAM operations as well as the concept of manufacturability analysis in traditional and additive manufacturing are investigated in sections 1.1 and 1.2 respectively. The section 1.3 will discuss the use of experts knowledge in the assistance of feasibility analysis.

1.1 Additive Manufacturing CAM Operations

The developers of new products must have in mind the restrictions and allowances of the downstream process that will be used for the elaboration of the products. That is the reason why every single step preceding the manufacturing process must be conveniently executed to ensure reliable production. In additive manufacturing numerical chain seems simple, but the steps inside require a particular attention. The design stage remains complex due the wide design space which is the consequence of the shape freedom. Hence, researchers concentrated many efforts on proposing design methodologies and standards of assistance for the various processes.

The AM CAM operations differ from those of the traditional manufacturing. The usual elements are the part orientation, the definition of the regions to support, the design of the support structures, the choice of the build strategy (not presented here) and the nesting. These operations have great impact on the production output. As stated by Arndt et al. (2015), the only prerequisite to the economically feasible utilization of AM technologies is the best manufacturing preparation. In the following sub-sections these pre-processing operations are detailed.

1.1.1 Part Orientation

This operation opens the pre-processing steps. It has been seen as one of the activities that have the greatest impact on the manufactured part geometrical and mechanical qualities. The orientation of the parts can be defined by two angles α and β in the global reference (o, x, y, z) as illustrated in Fig. 1.2. And those two parameters alone can have a huge impact on the desired process duration (thus, the time to market), the quality expected by the customers and the production cost Köhler (2009). Today, it is well known that all of the downstream CAM steps depend on the build orientation. Hence, ensuring the product's conformity starts by defining the right orientation.

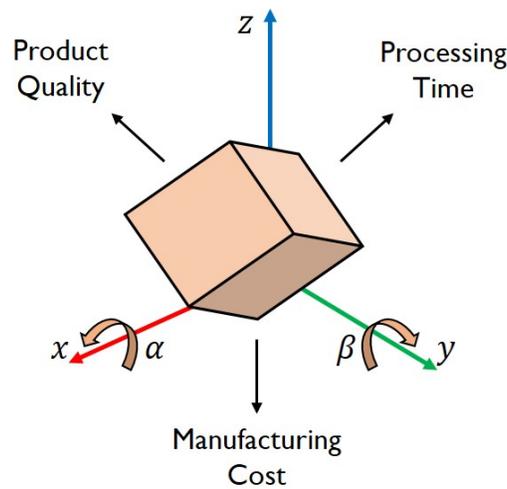


Figure 1.2: Example of part orientation definition

However, optimally defining the handles α and β , requires a certain level of skills about the AM system of interest (Grandvallet et al. (2020)). In PBF systems such as electron beam melting, things are even more complicated cause of the process specificities. Another issue in AM is that the criteria for orienting parts largely vary from one process to another. For instance in FDM, it is usually preferable to orientate the part such that its largest flat surface is in contact with the building plate to ensure the process stability (Hur and Lee (1998)). In contrast, for EBM, the engineer should better avoid large horizontal melted areas in order to prevent the part from geometrical distortions (Danjou and Köhler (2009)). Moreover, the

stability in EBM process is by default ensured by the surrounding powder in the machine vat.

Despite the advances made, existing pre-processing tools do not still fully assist operators in the choice of convenient orientation where experts are not available to intervene. Based on the investigations achieved here, no tool including expert knowledge in the determination of α and β has been found. From the works led by Grandvallet et al. (2020), it can be clearly seen that in the industrial context, people have many good practices and it is possible to formalize rules arising from their daily activity. Particular specifications can be found in that work. For instance, they differentiated the different surfaces of the part and classified them into categories. Among those are the post-machined surfaces, the priority surfaces and the machining datum surfaces. Each class of surface must be oriented in a specified way according to the experts. The governing rules are not simple to evaluate on complex geometries. So far, none of those kind of rules are integrated in software or algorithms to solve orientation problems; this is of great need and requires research efforts.

1.1.2 Definition of Regions to Support

Owing to the orientation, there might be some surfaces of a geometry that directly rely on the powder during the manufacturing. Those surfaces need to be supported during the layer by layer stacking. Support structures have multiple functions. They can play the role of heat sink (Järvinen et al. (2014)) especially in metal fusion, where heat rate is relatively high. They also play the role of anchors that hold the part to prevent from distortions (Hussein et al. (2013), Bobbio et al. (2017)). Defining regions to support is an important step in AM. For example, in EBM it is not recommended to start melting material directly over the powder (this can cause dross effects as described in Calignano (2014)), thus support structures are needed. Today, the criterion mainly used to define regions to support (on surfaces) is the overhanging, which is governed by the angle of the surface from the horizontal. However, one should go further in considering criteria such as support removability or their ability to mechanically stand process induced mechanical stresses due to temperature gradient during solidification.

1.1.3 Design of the Support Structures

Designing support structures involves complex criteria linked with their distribution, density, shape, orientation, required resistance and so on. They have to be robust enough to absorb the thermal stresses, and soft enough to be post-processed. A common practice is to connect the support and the main body with spaced teeth (Fig. 1.3); this eases the removal. Authors have proposed in some ways, algorithms or methodologies to help the strategic design of support structures. Calignano (2014) worked on the optimization of the supports to reduce manufacturing and post processing efforts in SLM technologies. He used Taguchi's method to experimentally determine which topology of support would prevent from warping and would be easy to break.

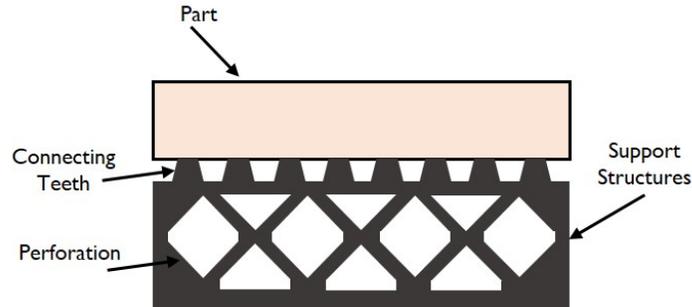


Figure 1.3: Support teeth and perforation

As a result teeth dimensions, perforation type and other geometrical specification could be proposed. Vaidya and Anand (2016) proposed a way to optimize support made of unit cells of various geometries (that can be hollowed) distributed by using Dijkstra's shortest path algorithm.

In order to ensure the efficient thermal conduction of the support structures, Zhou et al. (2019) reported an optimization approach for laser PBF. They implemented a transient heat transfer model into a gradient-based topology optimization to find the convenient material distribution. Additionally, to also ensure support's resistance, some authors investigated their mechanical strength for powder bed fusion (Bobbio et al. (2017)). Although commercial tools for automated support generation exist (e.g. Amphyon by Additive Works), some practitioners still prefer achieving support design semi-manually using tools as Magics (by Materialise).

1.1.4 Nesting

When making multiple parts, it is better to find a way to maximize the number of components in the production batches in order to minimize time to market and extra costs. Indeed, for powder bed fusion techniques the time to prepare the machine (fill the powder tank, calibrate the plate, make vacuum if needed, and preheat the chamber) is not negligible and must be achieved for each new production batch. To avoid repeating these setup times, an efficient way is the nesting optimization, which allows putting as many parts as possible in the build space. A nesting method combined with production scheduling has been proposed by Chergui et al. (2018) for electron beam melting. Different methodologies are available in the literature (Canellidis et al. (2013), Wang et al. (2019), Wodziak et al. (1994)).

It has to be kept in mind that the nesting needs to be operated with consideration of some important points such as guarantying the optimal orientation. In this context, Zhang et al. (2015) worked on a parallel nesting scheme based on 2D projection profiles. They first find out the optimal orientations for each part by using feature-based method, then, they used a parallel layout searching algorithm to determine the best projected 2D layout. For further efficiency, Arndt et al. (2015) worked on three dimensional nesting that also examines the optimal orientation of each part in the build space. For these methods, various commercial solutions are being developed since the additive manufacturing market is facing a fast economical growth.

1.2 Manufacturability Analysis

Faced with a more and more pressing demand and a strong competition, companies have to reduce manufacturing costs, leading times and provide good quality products. To achieve this, products must be compliant from the first production attempt to avoid time useless consumption and material waste i.e. their manufacturability has to be ensured starting from the design stage. For this reason, the concept of DFM has been largely used over the last decades to tackle the feasibility issues due to the gap between the designed and the manufactured products Shankar and Jansson (1993), Gupta and Nau (1995), Sánchez et al. (1997). In the classical scheme of manufacturing companies, the product designers do not have much information about the capabilities of the available machinery, and do not have enough feed-backs from the manufacturing teams (Ong and Chew (2000)).

Thus, during the product development life cycle, many iterations are performed to finally determine the best feasible design (Shukor and Axinte (2008)). This has justified the need of developing manufacturability analysis systems that allow matching the design requirements with the manufacturing process properties. In next sub-sections, reviews of some MA methods in traditional and additive manufacturing are presented.

1.2.1 In Traditional Manufacturing

The manufacturability analysis can either be introduced in the design or the pre-processing operations. In either situation product modifications can be carried out. For example, for a molded part, the designer has to take account of the parting line of the mold to make possible the extraction. Nevertheless, as mentioned, the inclusion of all constraints is not always possible during the design stage. The concept of manufacturability does not only involve the designed shape but also the manufacturing parameters fitness which have a high impact; sometimes the issues are simply covered by setting up the right process parameters. In traditional manufacturing systems works have been led for decades to implement a variety of manufacturability analysis tools. Gupta et al. (1997) stated that the three main characteristics that differentiate the manufacturability systems are the approach used, the measure of manufacturability used and the level of automation.

According to the review of Shukor and Axinte (2008), the most commonly used manufacturability analysis systems are made of expert systems. They can be based on fuzzy logic, neural networks, rule-based systems (RBS), object oriented techniques, agent-based systems or analytical hierarchy process (AHP). Among the latter, the rule-based systems are likely the most used (Shukor and Axinte (2008)). These systems fully rely on inference engines consisting of IF/THEN rules applied in a procedural manner (Brissaud and Tichkiewitch (2000)) using logical units (*and*, *or*). Chan (2003) reported an ES tool evaluating manufacturability regarding the selection of processes and materials and the production cost estimation. That tool also assist designers through design recommendations. Other examples can be found in the works of Kusiak and Chen (1988), ...

Object oriented techniques are the second most used expert systems (Shukor and Axinte (2008)). In this technique different objects are used to represent the model entities. Each of them contains sub-classes which in turn have other sub-classes and the relationships between them are clearly defined. The objects contain the necessary data and their programming codes as well. Some Illustrations of the

use of such systems are presented in Horvath et al. (1999), Amalnik and McGeough (1996), Giachetti and Alvi (2001), etc.

Following this, the analytical hierarchy process is the third most used method Shukor and Axinte (2008). Analytical hierarchy process is used to assign weighting factors to the features composing a part in order to take account of their importance degree. Ong and Chew (2000) developed a machinability and fixturability evaluation system including a solid modeler and databases containing information about available manufacturing operations, tools, dimensional constraints and process capabilities. The quantitative evaluation of the manufacturability is made on the basis of different metrics related to geometrical attributes (orientation, intricacy, accessibility) and technological attributes (dimensional tolerance, surface finish, etc). They used analytical hierarchy process to combine all the individual metrics into an overall one.

The fuzzy logic based expert systems are usually implemented in a hybrid way. In fact, they combine with the RBS, AHP or neural network systems to facilitate the analysis and decision making process. For instance, Korosec et al. (2005) quantitatively fuzzified machine-technological and geometry-topological parameters in order to evaluate the feasibility by using fuzzy evaluation function based on neural networks. The latter allowed representing the complex inter-relations between the fuzzified feature parameters. As a result, intricacy index is proposed. Ong et al. (2003) also proposed a fuzzy set AHP-based design for manufacturability tool for rotational parts. The fuzzy-based system was used to calculate manufacturability indices regarding part support, clamping and its features. The analytical hierarchy process allowed assigning weights to the features with respect of their importance. Agent-based systems use different agents that can concurrently reason to make decision (Shiau et al. (2000)). For example, design agent (used to refine the design) and manufacturing agent (used to choose process parameters) can be used to cooperate. Medani and Ratchev (2005) reported an early design manufacturability assessment method using collaborative agents to support the design, process planning and facility activities assignment. Each agent has an XML ontology behind to communicate with databases dedicated to its activity.

Globally, in the traditional manufacturing systems, the manufacturability analysis is mainly centered on a feature-based design interpretation (Gupta et al. (1997)). Indeed, the considered geometry is decomposed into basic geometries to make the correspondence with predefined sample features proper to a given process (Salomons et al. (1993), Gao et al. (2004)). For instance, to analyze the manufacturability of the component in Fig. 1.4 it is broken down into simple entities; then,

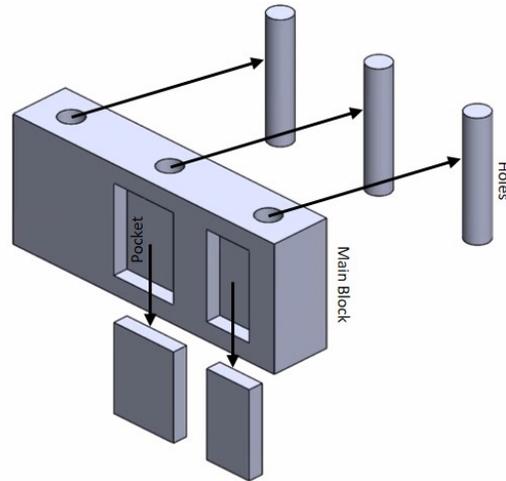


Figure 1.4: Example of geometry decomposition – feature recognition

the manufacturability of each feature is evaluated separately.

The evaluation or measure can be of three distinct types: binary, qualitative or quantitative. In the binary approach the design can only be feasible or not feasible regarding the capabilities of a given process (Sánchez et al. (1997)). For the qualitative methods, grammatical concepts such as “good”, “poor” or “average” are used to rate the manufacturability of a given design. The quantitative methods aim at providing a manufacturability index allowing a user to easily perform comparisons, or an optimization system to find optimum solutions. The present study will particularly focus on quantitative evaluations of manufacturability.

1.2.2 In Additive Manufacturing

In AM, the freedom in shapes generation leads to believe that all geometries are manufacturable while there are restrictions inherent to the processes. Unfortunately, the designed geometry which looks perfect in the CAD software, comes out with different types of defects. Solving these issues either requires modifying the design or setting the right manufacturing parameters and sometimes both of them. So far, different authors attempted to provide design guidelines to help ensuring producible parts, in other words design for additive manufacturing methods (Kranz et al. (2015), Adam and Zimmer (2014), Laverne et al. (2015), Teitelbaum et al. (2009), Vayre et al. (2013), Vaneker (2017)). A few studies based on some of

the guidelines to implement automated manufacturability assessment techniques in AM.

Goguelin et al. (2017) worked on a cloud-based smart manufacturability analysis to assist users of FDM machines. Their methodology consisted of decomposing a part into a series of design features and mapping the FDM machines capabilities (basing on a test part) to analyze the part suitability. As a result, CAD (problematic design features or STL inconsistency) or CAM (machine choice) recommendations are provided to the user. Rosen et al. (2012) presented a tool called AM-Manufacturable that is able to detect small features and can additionally checks whether the part fits in the machine's build space. Any detected small feature like a thin wall is highlighted in red.

A DFAM methodology based on part orientation, functional analysis and manufacturing paths optimization have been proposed by Ponche et al. (2014). The orientation consisted of finding the right position for functional surfaces to help the designer define his design space. The functional optimization then define the design of the part based on its function using topology optimization. Finally, the manufacturing paths optimization finally generate optimum paths regarding the local manufacturing characteristics. Manufacturing program is provided as an output.

Lynn et al. (2016) emphasized that the analysis of manufacturability of parts in AM require the consideration of factors like the build volume, the minimum features size, the estimation of surface roughness, the volume of support and the build orientation. They also affirmed that the five first factors all depend on the last one, the build orientation. They also proposed an analysis of small features by using voxels. Chen and Xu (2010) also proposed a manufacturability analysis based on offsetting methods to find out small infeasible features such as thin walls. Their technique also allowed the part cost evaluation.

Nelaturi et al. (2015) characterized printing resolution errors by establishing a sort of printability map showing regions below printer resolutions, regions above printer resolutions but below recommended feature sizes and regions above all critical resolutions. They defined the printability map using morphological opening, and identified zones as thin walls, protrusions, bridges or holes needing additional material (for their manufacturability) using medial axis. A voxel-based manufacturability analysis tool consisting in searching thin features and build support structures has been proposed by Tedia and Williams (2016).

Some researchers proposed quantitative evaluations of the manufacturability. In fact, the use of indices makes it possible to benchmark various scenarios, either of design or parameters setting. For the latter the build orientation is usually

varied. Ranjan et al. (2017) proposed a feature graph-based design improvement method using a concept of producibility index for DMLS process. They considered eight factors which are: (1) the total number of sharp corners in slice contours, (2) the number of small holes, (3) the thin regions, (4) the mean cusp height, (5) the area of contact with supports, (6) the support volume, (7) the part height and (8) the part volume. Kerbrat et al. (2011) designed a manufacturing complexity evaluation approach combining machining and additive manufacturing systems to realize parts. The approach is based on calculating manufacturing indexes of the octree decomposition elements (octants) of a given CAD model. Local and global indexes are separately evaluated and combined by using a weighted sum. Zhang et al. (2017) proposed a model optimizing the production manufacturability when combining traditional manufacturing with 3D printing. Their model proposes quantitative evaluation and is also able to include the production batch size.

Another approach, which consists in trying to improve the manufacturability early in design stage by including some constraints in the topology optimization has been proposed by some authors (Mhapsekar et al. (2018), Costa et al. (2017)). In the works of Mhapsekar et al. (2018), two objectives namely the minimization of the number of thin features and the minimization of support volume have been considered. An efficient NURBS-based TO method proposed by Costa et al. (2017) also supports the inclusion of constraints such as minimum and maximum length scale and minimum curvature radius. Mezzadri et al. (2018) also implemented self-supporting structure criterion in topology optimization to produce parts without need of additional support structures. Another approach consists of attempting to predict the quality (even if it remains a challenging task) in order to make suitable design or choose the right processing parameters. For instance, Mokhtarian et al. (2018) proposed a dimensional analysis conceptual modeling framework integrating technology characteristics and the part to build.

In the view of what is exposed in the literature, it can be concluded that no study focused on the use of expert knowledge to support pre-processing operations in the AM and particularly in PBF. The next section presents some tools in additive manufacturing.

1.2.3 Additive Manufacturing Commercial CAM Tools

To date, commercial solutions for AM pre-processing are available on the software market. For instance, tools as Materialise Magics, Amphyon AdditiveWorks, Esprit Additive Suite, 3DXpert, Autodesk NETFABB, ANSYS Additive Prep etc,

propose tools for orienting parts (based on fixed criteria), building and optimizing support structures. These solutions usually provide final proposals considered as optimal solutions (except Amphyon and Additive Prep which display all computation results on heatmaps), whereas the operator does not really master what happens in the back-end. In addition to this, he does not have full control on the inputs basing on his know-how.

Software	Criteria						Functionalities		
	Support Volume	Build Time	Build Height	Material Consumption	Projected Area	Distortions	Multi-Criteria Optimization	Surface differentiation	Heatmap Result Presentation
Magics	x		x		x		x	x	
3DXpert	x	x		x			x	x	
Amphyon	x	x				x	x		x
NETFABB	x						x	x	
Sculpteo AMT	x		x				x		
ANSYS Additive Prep	x	x				x			x

Table 1.1: Criteria used by commercial part orientation software including specific functionalities

Such software do not allow adding parameters as surface specifications or categories except a few of them that allow defining surfaces that should not require support structures. In addition, for the selection of part orientation, they assist the decision-making by evaluating different criteria on the parts (as shown in Table 1.1 for some of them). Those criteria defined by the software editors cannot evolve with the expertise of the company; the experts do not have the possibility to add

new orientation rules or criteria. That is why, there is a great need of developing tools allowing the integration of formalized expertise.

1.3 Knowledge Use in Manufacturing Pre-processing Operations

Let's refer to Fig. 1.5, the classical scheme of knowledge and some of its different ways of use in manufacturing (re-adapted from the works of Kumar (2017)). The first step consists of knowledge resources acquisition, which, can be achieved in different manners.

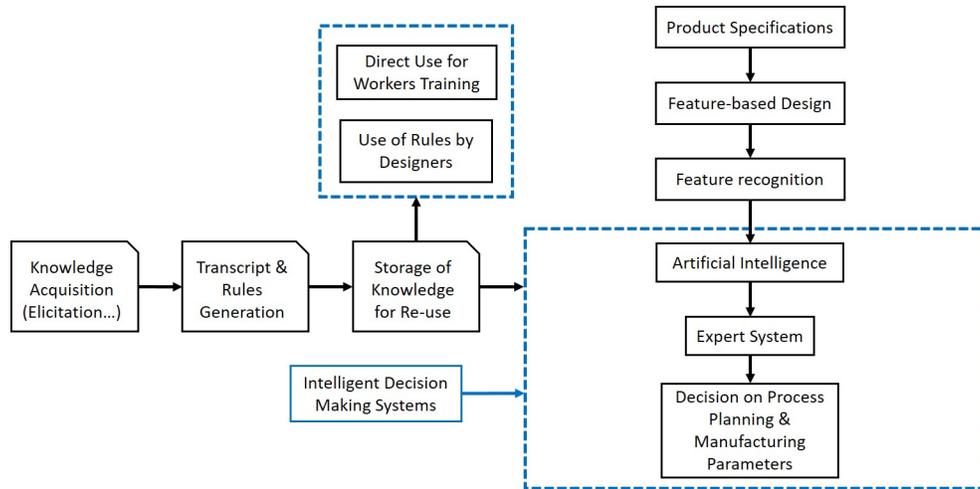


Figure 1.5: Knowledge acquisition, analysis, storage and use in pre-processing (re-adapted from Kumar (2017))

As said in the introduction of this chapter, pre-processing feed-backs in relation with the manufacturing process and post control feed-backs are usually saved in reports to be used in future projects. In the same context, other methods that consist in exploiting machine catalogs and brochures to capture information from manufacturers are also used. Following that acquisition, rules are created. For instance, Kumar et al. (2006) transformed knowledge collected from die designers, product design handbooks, catalogs and brochures into IF (condition) – THEN (conclusion) rules for manufacturability assessment in sheet metal industry (assistance to design engineers and process planners). The program they made scans

information given by a user (through an interface under AutoCAD) and proposes recommendations based on the rules they established. Chen et al. (1995) also worked on such knowledge-based systems, but used object-oriented techniques to assess manufacturability.

Another efficient method for acquiring knowledge, consist in carrying out elicitation sessions. Elicitation processes refer to the methods of “collecting” knowledge assets from human sources as stated by Cooke (1994). Different elicitation techniques, based on observations, interviews or process tracing have been used through years in manufacturing companies (Milton (2007)). The elicitation is usually performed with experts in the domain of interest, that will have the opportunity to explain their knowledge by also providing illustrations. The extracted resources need to pass through various steps in order to be transcribed into something reusable such as rules (in the chapter 2, other types of knowledge will be seen). As an example, in the works of Molcho et al. (2008), assets from periodic questionnaires to manufacturers and from manufacturing post analysis experts were exploited to create rules. The latter were established by respecting a certain ontological syntax built around the concepts of the domain. They implemented the rules in a computer aided manufacturability analysis tool. Additional illustrations of elicited knowledge use can be found in Züst et al. (1990), Cochrane et al. (2008) or Reed et al. (2011).

Once the acquired knowledge is processed and stored, there will be different ways to re-use it (hsien Liao (2003)). Some might need to train new workers about the good practices of the company, others might need to go further in assisting decision-makings. Previously cited literature works are pertinent examples of knowledge leveraging that use expert systems. Ongoing research efforts are also being made on the use of artificial intelligence with learning models that are able find out optimal manufacturing parameters. Also note that the expert systems are included in the artificial intelligence systems (Kumar (2017)).

1.3.1 Limitations of the knowledge leveraging methods, for AM integration

Despite the advances made in the field, the rule based expert systems coupled with CAD feature recognition remain the most used methods today to assist the production preparation. These solutions may exhibit limitations regarding the objectives of the present project. On the one hand, the ways of proceeding of those methods are usually procedural. This means that the application of one rule

depends on the application of another specific one (conditional application). As stated by Bernard et al. (2007), inference engines control the order of activation of the rules. In the example presented in Fig. 1.6 (re-adapted from Kusiak and Chen (1988)), the rule 2 is used only when the rule 1 is satisfied. These relations are precise (*binary*) and do not completely reflect the human reasoning vagueness and imprecision (Werro (2015)). That's why some authors coupled the evaluation of rules with some fuzzy membership functions for supporting decision making. These kinds of mathematical representations will also be used in this thesis.

- (1) (Second order rule)
 IF utilization of the machine is greater than 0.8,
 THEN machine is over loaded.
- (2) (Third order rule)
 IF system is heavily loaded,
 AND machine is over loaded,
 THEN due dates are important. etc.

Figure 1.6: Example of IF/THEN rules

On the other hand, the evaluation is mainly feature-based and thus, passes by the geometrical decomposition of the parts into basic shapes recognized by the system's reasoner. The limitations for its use in additive manufacturing is related to the high complexity of the shapes. In most cases, decomposition are not obvious on the organic shapes (from TO). Moreover, it is complex to represent the link between the geometrical entities. These pitfalls, must be circumvented by first finding a solid framework to quantitatively model expert knowledge. And second, by establishing an alternative way to evaluate that modeled knowledge on geometries, regardless their complexity and without using feature decomposition.

In this context, this thesis will propose approaches to use knowledge for additive manufacturing pre-processing assistance.

1.3.2 Proposal of a novel knowledge leveraging method for assisting AM pre-processing operations

Management of the companies knowledge is a key element for keeping sustainability in production and market lead today. In the CAM context, many attempts have

been made to leverage knowledge as much as possible for enhancing the manufacturing quality and effectiveness. In fact, the available expertise usually helps setting up steady process parameters, proposing process planning with strategic tool path or generating redesign suggestions back to the CAD engineers. COFFA chooses to propose knowledge-based assistance to CAD and CAM engineers by proposing them tools to quantitatively evaluate the proposed scenarios. Owing to the limitations exposed above (for additive manufacturing), new approaches need to be developed.

This thesis proposes then, a novel way to do so. The implemented approach consists of using desirability functions to mathematically represent the rules elaborated from experts knowledge, on the same scale. These mathematical models are evaluated on geometries for various scenarios of parameters settings. Then, scores (desirability) corresponding to the compliance level of each rule for each scenario will be proposed to the CAM engineers or operators. The choice of the scenario will then be performed by achieving comparisons between the resulting scores. A whole methodology for assessing the rules on parts will be explained along this work and detailed and commented algorithms will be provided.

Conclusion

This chapter has presented the CAM operations in additive manufacturing, where most of the processing parameters are set. Owing to their complexity, there is great need to assist those operations by evaluating in some ways the conformity of the chosen parameters. Regarding the latter in AM, a few works have been found in the literature. None of them used formalized knowledge as a basis of analysis. In contrast with AM, in traditional manufacturing methods and many techniques have been proposed and used over decades. They consist of knowledge bases and inference engines to assist the decision making process, and they mainly use feature recognition on geometries. The discussion around knowledge use in CAM stage has shown that the available methods are not fully suitable for AM parts, due to limitations on geometrical decomposition. Moreover, the objective of this thesis was to propose a way to quantitatively represent the experts knowledge and assess their level of compliance for a given product. A new approach will then be proposed, but first, the chapter 2 will present some knowledge typologies and will also explore knowledge resources available for part orientation in additive manufacturing.

Chapter 2

Knowledge Typologies & Knowledge Resources in Additive Manufacturing CAM

Introduction

The routine use of a system with feed-backs naturally generates new skills usually known as the expertise or simply expert knowledge in a defined domain. As stated by Davenport et al. (1998), knowledge is information combined with experience, context, interpretation and reflection. Alavi and Leidner (1999) affirm that knowledge is information processed in the mind of an individual; it can be personalized, or subjective information related to facts, concepts, interpretations, observations, judgments or ideas.

Nowadays, companies are trying more and more to capture, organize, store and transmit the workers knowledge in order to assist usual daily operations like decision-making, problem solving, dynamic learning, or strategic planning, etc. Gupta et al. (2000). The process from knowledge acquisition until its use is usually known as knowledge management (KM). Today, various authors worked on how leading KM would positively influence the competitiveness of manufacturing companies (Gunasekaran and Ngai (2007), de Pablos (2002), Singh et al. (2006), Paiva et al. (2002)), as the volume of available data daily grows (Choudhary et al. (2008)). Globally, KM has been seen as an important element contributing to maintain the sustainability and the competitive advantage of an organization. Basically, the steps for leading KM include the knowledge creation or acquisition

(consisting of elicitation process – collection of knowledge from a human source), the knowledge explication and formalization Cooke (1994), the classification, the storage, the sharing and the reuse.

As mentioned in the objectives (Introduction), target of this work is to use formalized knowledge in the form of rules to assist the CAM operations in PBF. Before proposing models or methodologies to integrate the experts knowledge, some basics have to be explored. Therefore, this chapter presents briefly the different typologies of knowledge focusing on the type that will be used in this study and the knowledge resources available in the additive manufacturing literature and industrial practice and particularly in powder bed fusion.

2.1 Knowledge Typologies

The complexity and variety of knowledge assets make it difficult to put forward models without specifying the typology of knowledge addressed. In general, the captured knowledge can be of different types (Lundvall (2004)), as well as of different levels (deep or superficial as mentioned by de Jong and Ferguson-Hessler (1996)). Knowledge can be classified in different ways, for instance, general and domain specific knowledge, concrete and abstract knowledge, formal and informal knowledge, declarative and procedural knowledge de Jong and Ferguson-Hessler (1996). Each of the categories have to be used according to the context and level of expression. However, even having a variety of natures, knowledge has most often been classified as procedural or declarative (Nonaka (1994)). Further, Alexander and Judy (1988) extensively distinguished three specific types of knowledge, which are declarative, procedural and conditional knowledge. Declarative knowledge is defined as factual information corresponding to “knowing what” (Alexander and Judy (1988)). Procedural knowledge refers to a compilation of declarative knowledge into functional units corresponding to “knowing how” (Gorman (2002)). The procedural knowledge describes the actions to perform in a domain for defined objectives; it is thus a methodological knowledge (Nonaka (1994)). Conditional knowledge indicates “when” and “where” to apply a particular procedure (Alexander and Judy (1988)); it is thus, a procedural knowledge that holds for specified conditions.

Beissner et al. (2008) also pointed another type of knowledge namely the structural knowledge. It characterizes the knowledge of how the concepts within a domain interrelate (Beissner et al. (2008)). This type of knowledge will be used

in this work when dealing with the relational analysis between concepts. Working on the structuring of additive manufacturing knowledge, Grandvallet et al. (2017) identified five sub-categories of declarative knowledge that are definitions, examples, influences, laws, state rules and one sub-category of procedural knowledge namely action rules (Fig. 2.1). State rules describe how concepts are linked in specific conditions without prescribing any action that should take place. Influences designate the possibility of one concept to have effect on the behavior of another one. Laws provide kind of mathematical relations between concepts. Action rules (AR) define actions that should be performed in specific time and place to reach some objectives; this type of “actionable” knowledge are of primary interest in this work. This type of knowledge has the ability to clearly describe an expertise in the form of prescription to fulfill. Procedural action rules (example of AR (1)) are governed by criteria that need to be applied whatever the situation. In contrast, the conditional action rules (example of AR (2)) are applied only when a certain condition is verified.

Examples with knowledge types:

- State rule: If support used, then marks exist on surface and finishing is needed.
- Influence: The use of support has influence on surface quality.
- Law: Surface quality = f (support marks quantity).
- Action rules: (1) Minimize support marks on non-machined surfaces; (2) If machining not allowed, minimize support marks on all surfaces.

This classification of the knowledge acquired from experts is able to clearly guide a re-user to the type of information he exactly needs. As shown in the aforementioned examples, the different sub-categories of knowledge relate in some ways to each other. The influence of support marks on surface quality is described by the law which is a mathematical relation. Cause of this influence, the state rule informs the CAM operator that marks will exist on surfaces and that they need to be finished. The action rule (1) indicates the necessity of minimizing the support marks on very specific entities of the part (here, the non-machined surfaces) before the additive manufacturing. As predictive purpose, the action rule guides the choice of manufacturing parameters such that the support marks will be minimal for non-machined surfaces or for all surfaces in the case of the action rule (2)

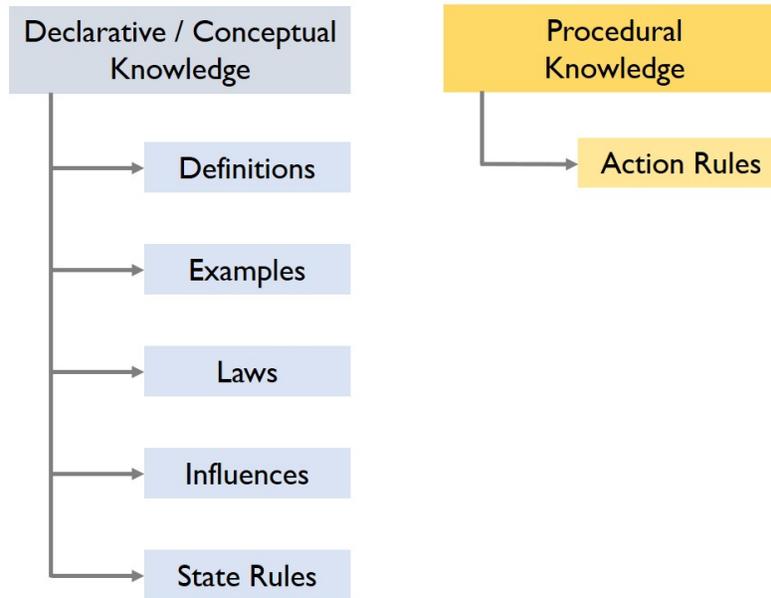


Figure 2.1: Sub-categories of knowledge (built based on results of Grandvallet et al. (2020))

After their classification, each of these types of knowledge can be used for a specified purposes. For instance, the state rules, influences, definitions or examples are very suitable for teams training. In the present context of AM CAM operations, action rules appear to be more practical to assist the decision making on manufacturing parameters. These aforementioned types will be used in next section to extract some knowledge assets from the literature.

2.2 Available Knowledge in Additive Manufacturing

In the current stage of development of AM, knowledge assets are being generated among users either in academics, general public, or industries. For general public users, people often share experience about their own practices to overcome some issues or simply provide recommendations for better production quality through forums. In academics, the know-how is published in the form of research papers

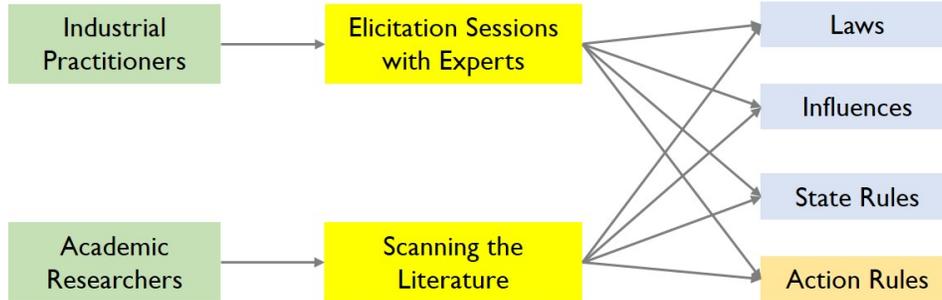


Figure 2.2: Knowledge extraction from academic researchers and industrial practitioners

(the literature). For the industry practitioners, the knowledge is in the form of guidelines or shared via discussion or training sessions, and is not externally shared. This section focuses on the AM CAM knowledge resources that can be extracted from the existing research literature and from industrial experts. The investigation is led on the first operation namely, the definition of part orientation. The goal is to find out the rules researchers and industrial practitioners put forth when they have to select an optimal part orientation (Fig. 2.2). For industrial experts, elicitation process is necessary to acquire their know-how, and in this work the results of Grandvallet et al. (2020) will be used. And, for the academic researchers, a scanning of the literature is achieved. Action rules, state rules, influences and laws are used as reading references (refer to Fig. 2.1).

2.2.1 Part orientation knowledge from literature

The part orientation problem has been investigated by several authors but, globally, the principle of determining the part optimal orientation is based on several criteria mathematically formulated, their calculation evaluates whether a selected orientation comply with them.

Allen and Dutta (1994) proposed an algorithm intended to find the best part orientation by optimizing the volume of support structures and their area of contact. Frank and Fadel (1995) designed an expert tool to assist the decision-making during the orientation selection process. They considered three factors, among which the surface finish was the most important, then the build time and finally the amount of support structures (Fig. 2.3). Cheng et al. (1995) presented a

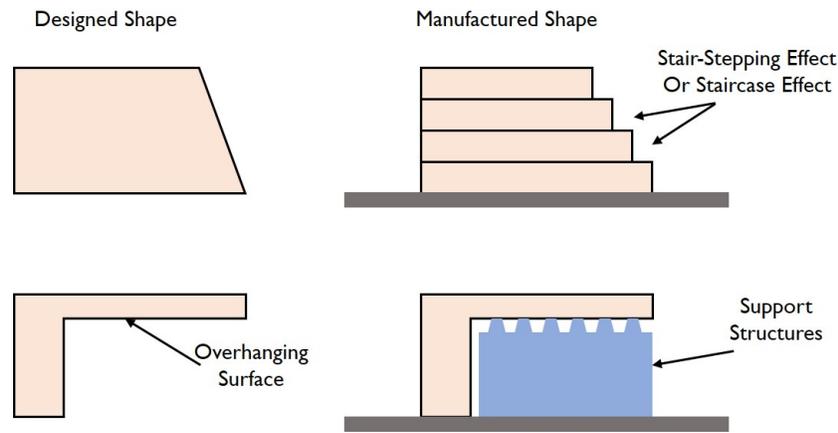


Figure 2.3: Illustration of staircase effect and support structures

progressive multi-objective optimization process to find orientation that optimizes part accuracy and build time. They identified the possible sources of error such as tessellation caused by STL file, missing features, overcure appearing on overhanging area, distortion/shrinkage and stair-stepping effect (Fig. 2.3) to qualify the accuracy, then defined part height and support height as influencing the build time.

Hur and Lee (1998) developed a CAD environment to optimize part build up direction in SLA process, for less stair stepping effect, build time and support volume. Pham et al. (1999) also proposed a CAD feature based tool to recommend optimal orientation for SLA in taking account of part cost and manufacturing time. Another algorithm designed by Lan et al. (1997) also considered surface quality, build time and complexity of support structures for identifying best build direction in SLA. Xu et al. (1999) discussed the selection of build orientation for different rapid prototyping (RP) methods such like SLA, SLS, FDM and LOM (Laminated Object Manufacturing). They examined the differences between the processes with regard to building inaccuracy (distortions), surface finish, manufacturing time and cost. Rattanawong et al. (2001), and Masood and Rattanawong (2002) investigated the determination of part optimal orientation basing on volumetric error caused by the slicing.

Das et al. (2015) suggested a combined optimization for minimizing part tolerance errors and supports. Canellidis et al. (2009) optimized the build time, surface

roughness, and post-processing time by means of genetic-algorithm. Phatak and Pande (2012) designed a genetic algorithm based system to obtain part optimal orientation in the rapid prototyping processes as SLA, FDM and SLS by considering part cost, build time and material used in hollowed model as objectives. They used hollowed models for the minimization of material utilization. The other detailed criteria were the build height, the staircase effect, the contact area of the support with the part and the volume of support. Authors as Byun and Lee (2005) studied the computation of optimal build direction with the use of variable layer thicknesses to minimize the stair stepping effect, the build time and the cost of parts. Thrimurthulu et al. (2004) also used this principle to compute part orientation with respect to minimal surface roughness and minimal build time for FDM. Those studies calculated slice thickness basing on the maximal permitted surface roughness on the part. Zwier and Wits (2016) presented a feature based orientation computation, which allowed selecting orientation with less support structures. The minimization of the amount of support was based on the minimization of overhanging structures.

Zhang et al. (2015) addressed the problem of orientation for multiple parts included in the same build plate. Their methodology consisted of first, finding out a set of orientations that comply with the required quality for each part. Then, a genetic algorithm was used to find the optimal combination of orientation that minimizes the build time and cost. Danjou and Koehler (2009) reported an optimization algorithm considering part quality, build costs and mechanical-technological quality. They defined the build costs as being influenced by the amount of material and the build time. The part quality was characterized by the staircase effect, the marks left by supports and distortions due to uneven thermal distribution.

Other authors also proposed models for predicting the surface quality or roughness (Delfs et al. (2016)) and accuracy in general (Moroni et al. (2014)) with respect of the orientation.

Various methodologies of approaching the orientation problem are available. However, it can be noticed that the different criteria are nearly the same: surface quality, support amount, build time and build cost. As a summary, the Table 2.1 presents a set of information extracted from the literature (note that some of the references are not reported in order to avoid duplication). For each research item, the AM technology, the authors' statement (cited as is), the criteria, the found knowledge type and the inferred knowledge object are emphasized.

Many knowledge objects of influence and law types have been found. A few action rules prescribing the minimization of support amount and stair-stepping

effect are also inferred.

Table 2.1: Knowledge objects inferred from the literature
 part orientation in AM

Authors	AM Tech- nology	Statements	Con- cepts	Knowl- edge Type	Inferred Knowledge
Frank and Fadel (1995)	SLA	<i>Orient the part in a direction that eliminates undesirable stair-stepping feature most often apparent on sloping or curved surfaces.</i>	Surface Finish	Action Rule	<i>Minimize stair-stepping effect</i>
		<i>Build time is related to the amount of time spent in the 'dip and dunk' process. For small parts, the "dip and dunk" (time required to re-coat the part) is the controlling factor.</i>	Build Time	Influ- ence	<i>Re-coating time has influence on the build time</i>
		<i>It is important to minimize supports when possible.</i>	Support Amount	Action Rule	<i>Minimize the amount of supports</i>
Hur and Lee (1998)	SLA	<i>The staircase area is also the factor, which affects the part accuracy.</i>	Part ac- curacy	Influ- ence	<i>Staircase area has influence on the part accuracy</i>
		<i>The build time is directly related to the number of layers, the optimal part orientation corresponding to the minimum number of layers also provides the shortest build time.</i>	Build Time	Influ- ence	<i>The number of layers has influence on the build time</i>

		<i>The need for support structures increases for overhanging surfaces on which material is solidified continuously. In this case, support structures prevent the overhanging surface from toppling.</i>	Support Struc- tures	Influ- ence	<i>Overhanging surfaces have influence on the need of support structures</i>
Pham et al. (1999)	SLA	<i>Time is an important consideration when building a part. The same model in different orientations will take different lengths of time to build, since build time is largely height dependent. It will also depend, to a smaller extent, on the volume and height of the supports.</i>	Build Time	Influ- ence	<i>The recoat time and times for the laser to draw borders, supports and hatches have influence on part building time</i>
		<i>Differing amounts of support will be required, depending on the orientation in which the model is built. Their influence may be split into two factors: overhanging area and volume.</i>	Support Struc- tures	Influ- ence	<i>Overhanging area and volume (height from the plate) have influence on support structures</i>
Thrimurthulu et al. (2004)	FDM	<i>Layer thickness and build orientation, as the two most significant process variables that effect surface finish.</i>	Surface rough- ness	Influ- ence	<i>Layer thickness and build orientation have influence on surface finish</i>
		<i>The build time is influenced by the acceleration and deceleration of nozzle tip during material deposition.</i>	Build Time	Influ- ence	<i>Acceleration and Deceleration of nozzle tip have influence on build time.</i>

Byun and Lee (2005)	FDM, SLS, SLA	<i>Surface quality of rapid prototype parts depends on the staircase effect on inclined planes and curved surfaces.</i>	Surface Quality	Influ- ence	<i>Staircase effect on inclined planes and curved surfaces have influence on surface quality</i>
		<i>The build time is proportional to the sum of the processing time between layers (except curing/sintering/deposition operation) (T_l), the time it takes to fabricate a part (T_s), and the time regardless of part geometry (T_e).</i>	Build Time	Law	$=f(T_l, T_s, T_e)$
		<i>Part cost will have terms proportional to labor time, build time, the volume of the part, and the volume of the supports.</i>	Part Cost	Law	$= f(\text{labor time, buildtime, partvolume, supportvolume})$
Das et al. (2015)	DMLS	<i>It is essential to minimize the use of these supports as reduced contact area between the part and these structures will result in better part quality and also reduce the post processing efforts.</i>	Support Struc- tures	Action Rule	<i>Minimize the use of support</i>
Canel- lidis et al. (2009)	SLA	<i>Two critical orientation-dependent cost factors are identified, namely, the build time and the support removal time.</i>	Build Cost	Law	$= f(\text{build time,support removal time})$
		<i>Excessive surface roughness is mostly due to the stair stepping effect that is observed in all inclined surfaces of a part as a result of the layer nature of the building process.</i>	Surface Rough- ness	Influ- ence	<i>Stair stepping effect on inclined surfaces has influence on surface roughness</i>

Danjou and Koehler (2009)	AM (generic sys- tem)	<i>Functional surfaces should be considered in such a manner that the contact area of attaching supports is preferable minimized in the selected orientation.</i>	Area of contact of support	Action Rule	<i>Minimize support contact area on functional surface</i>
		<i>The orientation-dependent building costs are primarily defined by the amount of material and the required build time.</i>	Build cost	Influ- ence	<i>The amount of material and build time have influence on build cost</i>

2.2.2 Part orientation knowledge from industry practice

To date, industry practitioners knowledge elicitation works about AM in general are still rare. However, recent works led by Grandvallet et al. (2017) and Grandvallet et al. (2020) allowed the identification of a couple of elicitation data for PBF. In fact, they used an elicitation technique called “iterative limited information task” to acquire experts knowledge about the selection of part orientation and the support structures construction. The iLIT consisted of asking experts “if you had only 3 elements to tell us, which one would you give for orienting a part?” The additional question “and why?”, fosters experts to formulate procedural knowledge in the form of action rules. Below are listed a set of action rules (from Grandvallet et al. (2020)) for orienting parts in PBF and particularly in electron beam melting.

2.2.2.1 AR1. Minimize part shadow on start plate

The projected area of the part on the build platform (start plate) must be minimal to allow the maximum nesting. The extent of the shadow varies with the orientation of the geometry. Thus, the orientation is here again a significant factor upon the production efficiency. Indeed, the productivity in PBF is driven by the quantity of products treated simultaneously. In electron beam melting, for instance, it takes time to prepare a build due to operations like setting the plate to the right elevation, filling the powder or preheating and making vacuum in the chamber; and these operations need to be repeated at any production. It is thus more profitable to put as many parts as possible on the

same batch to save time. The activity of organizing the position of parts so that they fit in the build space is called nesting (refer to section 1.1.4).

For some other technologies (such as FDM and SLA), parts are better when their greatest flat area is oriented horizontally to ensure the production stability (Hur and Lee (1998)) and minimize the build time (Pham et al. (1999); Thrimurthulu et al. (2004); Byun and Lee (2005)). However, in PBF the part is stabilized thanks to the surrounding powder of the build chamber. In addition, the build time in the industrial context is more governed by the ability of producing several parts at a time than the build height as exposed by Vayre (2014). During the elicitation process led by Granvallet et al. Marin (2020), the experts stated that this AR is the first thing they look at. For these reasons minimizing the part shadow is an important action rule which would allow getting maximum nesting density on the build plate and then, reduce the products delivery time.

2.2.2.2 AR2. Minimize total of overhanging non-machined surfaces

According to its topology and its orientation a component might exhibit different overhanging zones. In AM in general, built overhanging surfaces have deformations resulting from shrinkage and warping due to residual stresses (Körner (2016)). To alter or eliminate those harmful effects, support structures are added during the manufacturing process to get the surface anchored and prevented from the eventual distortions (Hussein et al. (2013)). However, after their removal, those support structures will in turn leave undesired marks impacting the surface quality.

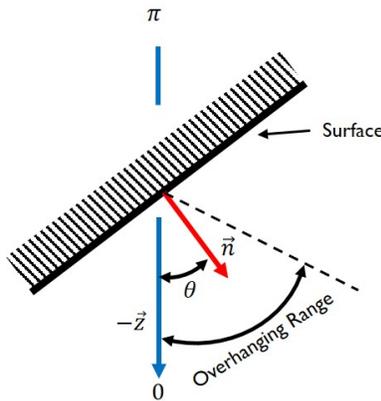


Figure 2.4: Overhanging surface definition

That is why, most of times post processing operations such as machining, grinding are carried out to improve the finishing. This rule intends then, to minimize the marks on

surfaces for which machining will not be performed (not planned). Note that machining is also achieved on the functional surfaces of the part. Hence, it is assumed that one should put support structures on those surfaces for the profit of the non-machined surfaces. Indeed, the post machining dedicated to the functional surfaces will subsequently remove the marks left by the support structures without additional costs as it was planned by the engineers.

An overhanging surface is characterized by its normal vector angle with the negative vertical as shown in Fig. 2.4. Usually, support structures are only required for surface angles less than a specified value, or simply if they are comprised in the overhanging range shown in Fig. 2.4. This value depends on the technology, the material and the machine.

2.2.2.3 AR3. Orient part priority surfaces (PPS) close to vertical

Priority surfaces constitute the most important surfaces of a given part. According to the experts, a surface is called priority when it has to be of good quality from the additive manufacturing step (here PBF); that is to say that no post-processing operation will be performed on it. Shortly speaking, a priority surface must be acceptable or good “AS IS”.

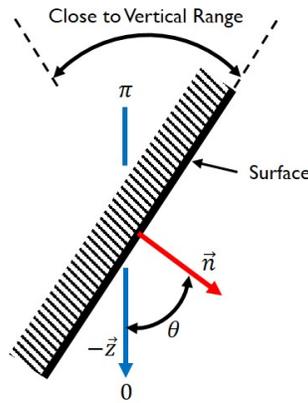


Figure 2.5: Priority surface definition

In order to reach a certain quality, these types of surfaces must be oriented vertically or near to the vertical (a *close to vertical range* can be defined as shown in Fig.). It is obvious that this can be impossible, since the given set of priority surfaces can be mutually perpendicular. In the literature, experimental works led by Kranz et al. (2015) also show that the surface roughness decreases as the surface gets near to the

vertical. The roughness Ra was approximately $10\mu m$ for 90° and $30\mu m$ for 0° ; the angle is measured between the surface normal \vec{n} and the negative \vec{z} axis (see Fig.).

This AR has different utilities. For instance, as geometries are generally complex with organic shapes or lattices, it is not obvious to perform finishing or polishing on some surfaces. First, because finding systems able to maintain or clamp the components in position is costly. Second, because the tool trajectories might be complex and require massive efforts to establish a process planning. Moreover, it may happen that the tool cannot access the surface. For these reasons, one must identify them when defining the build orientation. Finally, it should be noted that defining a surface as priority would also exclude the possibility of building support structures on it. Thus, the close to vertical range must be conveniently specified.

2.2.2.4 *AR4. Orient machining datum surfaces (MDS) out of horizontal*

As post-processing is usually required for PBF parts (especially the machining of functional surfaces), it is necessary for CAD engineers as well as for CAM engineers to think of the isostatic positioning. For this reason, in the part orientation activity, those surfaces must clearly be indicated; they are called *machining datum surfaces*. Inaccuracies linked with parallelism, perpendicularity, flatness (mainly) and so on, need to be avoided. Experts indicated that the machining datum surfaces should be oriented out of horizontal in order to avoid such inaccuracies.

Let's refer to the cantilever part in Fig. 2.6. The surfaces **M1** and **M2** are post machined using milling process and will be held in position by the surfaces **R1**, **R2** and **R3** (Fig. 2.6a). The tolerance values are taken from the works of Das et al. (2015). The output component is manufactured using EBM (Ti-6Al-4V) in the indicated orientation (Fig. 2.6b).

After manufacturing, the surface **R1** is subjected to a deformation making it curl upwards despite the added support structures (the same results can be found in Körner (2016) and Mugwagwa et al. (2018)). Therefore, the required perpendicularity and flatness conditions are no longer respected. In addition, the reference surface **A** is a little bit bent towards the left side (Fig. 2.6c). Machining the part basing on the datum surfaces **R1**, **R2** and **R3** would obviously result in many errors and could damage the tools used. Owing to these different issues, it is vital to consider the MDS during the orientation selection. In the present example, the support structures are put on the functional surfaces (**M1** and **M2** cause of the orientation), but even without support structures the functional surfaces usually need to be post-finished.

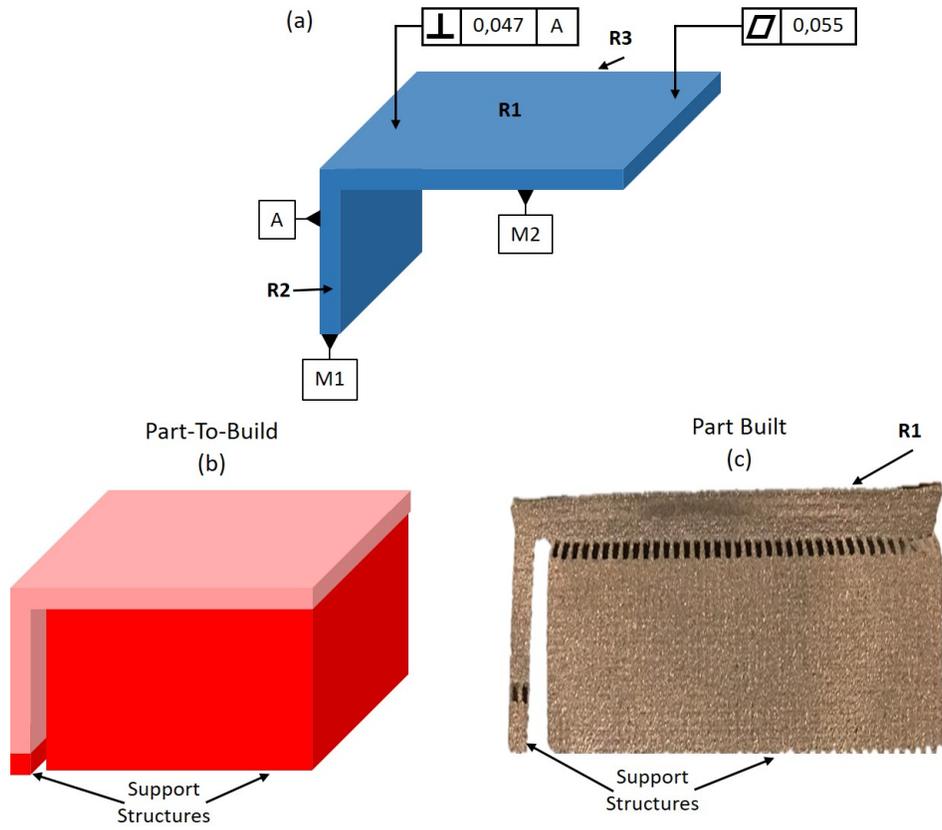


Figure 2.6: Example of part having machining datum surfaces: (a) product manufacturing information; (b) part to build with support structures; (c) manufactured component

2.2.2.5 AR5. Minimize shape deformation risks

Parts made with PBF technologies are usually subjected to deformations linked with the solidification process of the fused metal layers. By experience, if a certain number of long layers are stacked, there may be risks of progressive shrinking deformation (Vo et al. (2018)). Therefore, the final shape completely deviates from the targeted one.

Phenomenology – In EBM, the shrinkage usually causes loss of the lower edges of parts as illustrated in Fig. 2.7 (the left side of the part is fixed). From several experiments led by Vo et al. (2018) and Ghaoui et al. (2020) it has been inferred that the shrinkage of a layer is highly dependent on the number of layers above it. In fact, every deposited layer i shrinks when solidifying and cooling. The following melted layer $i + 1$ also does the same, but this time it influences the layer $i - 1$ making it shrink again. This continues until the number of layers stacked below the layer i is massive enough to stop the induced shrinkage. Therefore, for the layer i , the influence of the layer $i + 1$ is greater than that of $i + 2$ which is greater than that of $i + 3$ and so on.

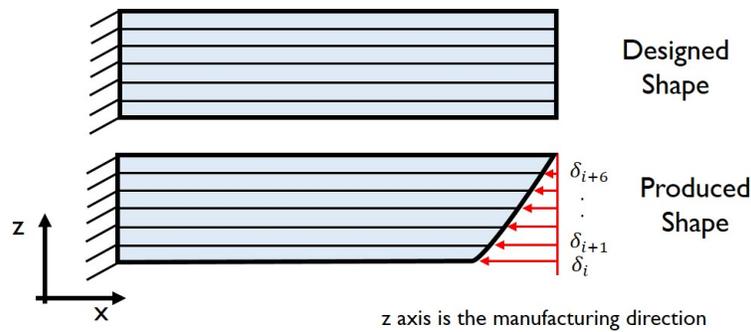


Figure 2.7: Loss of edge (adapted from Vo et al. (2018))

The chart in Fig. 2.8 shows a trend of layer influence; it is built based on the simulation and experimental results of Ghaoui et al. (2020). Reported values have been obtained by finite elements analysis for Ti6Al4V for a layer thickness of $50\mu m$. Different parts of various thicknesses have been analyzed, the first has 20 layers, the second 40, the third 60, the fourth 80 and the last 100 layers. For each one, the deformation of the first layer is measured. The values on the X-axis represent the number of layers above a certain layer i , and the Y-axis is the displacement in mm . For instance, if the bottom layer (which has a length of $35mm$ in this example) has 20 others above then, it shrinks of $0.34mm$. Beyond a 100 layers, the displacement tends to a horizontal asymptotic; as aforementioned, the impact on a given layer is less and less important

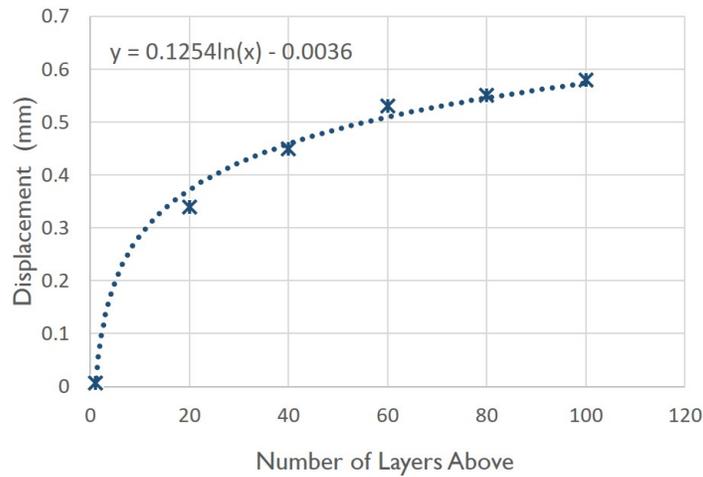


Figure 2.8: Simulated influence function for Ti6Al4V (adapted from Ghaoui et al. (2020))

with the increasing manufactured height. From these statements, it can be inferred that the deformation depends on the way the layers are stacked, thus, on the geometry and the orientation.

It has to be noted that, the final deformation is also highly dependent on the length of the layers. The greater the length, the greater the displacement.

Distributing support structures highly helps preventing some surface from this issue. Used practitioners usually prefer finding orientations for which long stacked layers are avoided. In fact, changing the orientation of a part modifies the configuration of the layers through a different slicing. For this reason, to date this shape deviation is mainly solved by finding the right manufacturing orientation that avoids long stacked layers.

2.2.2.6 AR6. Avoid support structures and support removal difficulty on surfaces with potential support difficult to remove (SSDR)

The formulation of this AR might seem intricate, but shortly, it means “don’t put support structures on a surface if you cannot or have difficulty to remove them after manufacturing”. This kind of requirement is not usually treated in the literature. In fact, not much effort has been concentrated on it, regardless the fact that it constitutes one of the most important criteria for defining a good orientation and building support structures. A badly located support removal can necessitate great efforts or consume

much time and can even be irremovable. For these non-profitable reasons, practitioners usually do this analysis, but manually.

Here, the removability of support on a surface is corollary to its degree of accessibility. Fig. 2.9a shows examples of support removal by using screwdrivers; if their size is greater than the available space, the removal is impossible. Fig.2.9b shows different scenarios of removal operated with cutting tools. If the tool size (diameter, width, height) is bigger than the slot in which the support is built, the removal becomes impossible (scenario 1) unless the dimension l is violated. In scenario 2, the tool size perfectly fits, but the base of the hole will be modified. Moreover, the machining chips evacuation might cause issues. Other types of tools (manual or motorized) such as pliers or grinders are also used for support removal.

This work suggests that the accessibility of a surface of interest depends on the available space in front of it. Therefore, the distances separating it from the surrounding surfaces. To comply with this action rule, one these conditions need to be satisfied: (1) the surface in question must not be overhanging *or* (2) there must be enough space to access this surface.

2.3 A Comparison between Research Literature and Industry Practice

The first main difference between the scientific literature and the industry practice is that the latter usually reason while having in mind the necessity of building a group of parts (called a build). In contrast, most of the works in the literature are centered on the orientation of a single part except a few works (Zhang et al. (2015)). For instance, most of the studies in the literature consider that the build time criterion is highly influenced by the build height. Then, to minimize the build time, one must orient the part such that its maximum distance is horizontal instead of being vertical (Fig. 2.10). This no longer holds for industry experts for two reasons. First, for productivity purposes, it is better putting horizontal the minimum distance to enable a high nesting density on the build plate. Indeed, in PBF the time for preparing the machine is long and the unmolten powder usually needs to be treated before reuse; thus, producing by single part would result in extra costs. Second, long horizontal distances result in long layers that are likely to deform during their solidification.

Another important point is that the industrial practitioners do not handle all of the surfaces of a given part as equal in contrast with the literature. In their philosophy, the part is made of different categories of surfaces for which a specific quality is expected. They can be priority surfaces, datum surfaces, post machined surfaces, non-machined

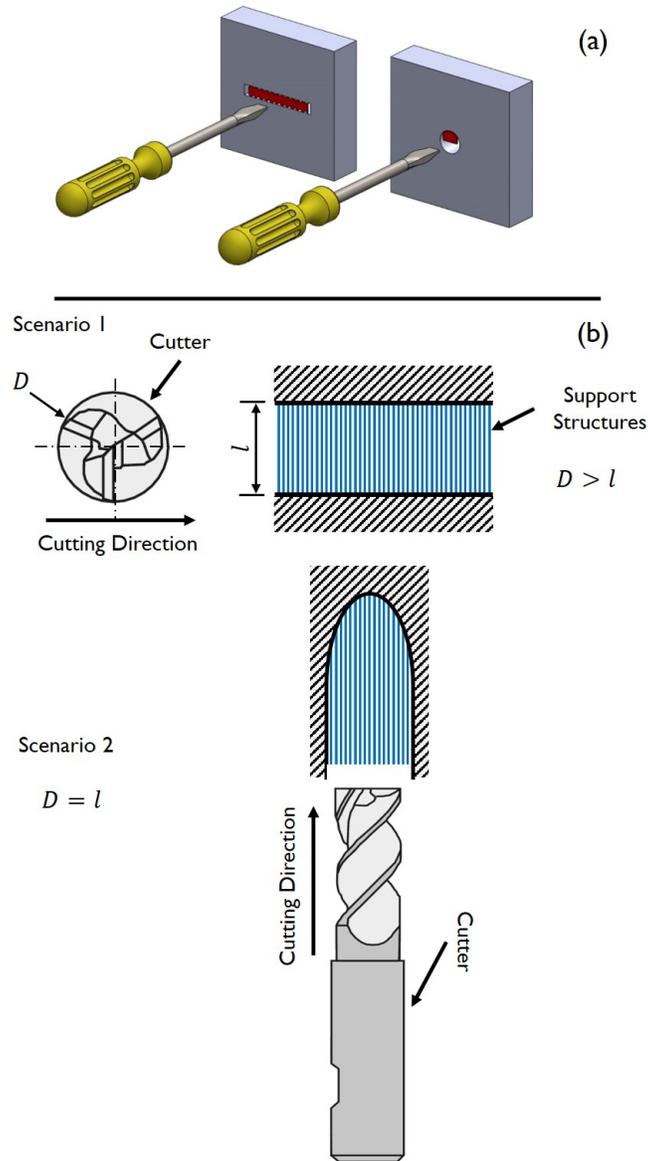


Figure 2.9: (a) Illustration of support removal with screwdrivers; (b) Scenarios of removal with cutting tools

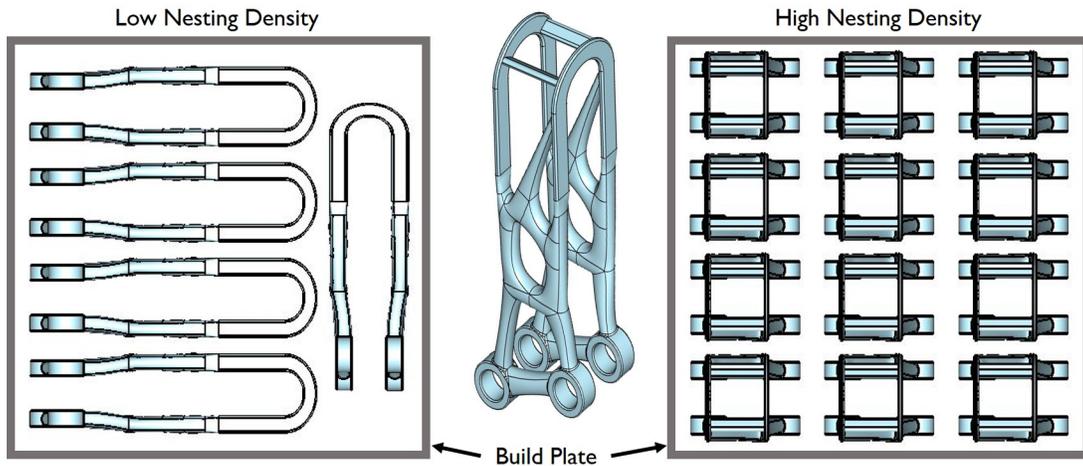


Figure 2.10: Top view of two different nesting strategies

surfaces etc. At this present time, there is no tool that allows taking into account this important property.

In addition, in industry, they do not point out directly the three main criteria namely the build time, cost and quality. In fact, the action rules refer to those criteria. For the experts, selecting an orientation complying with the action rules conducts to the expected quality, cost and processing time. For instance, minimizing the overhanging non-machined surfaces allows minimizing the marks left by the support removal, thus, improving the surface quality. Another illustration is the support removal difficulty which may lead to expensive removal operations and may also lengthen the processing time.

Conclusion

In this chapter reviews on knowledge typologies and available knowledge resources in additive manufacturing have been presented. First, the review of knowledge typologies allowed to find out a set of knowledge types which are influences, laws, examples, definitions, state rules and action rules. For this work, *action rules* have been identified as describing well the expertise for decision making assistance about the manufacturing parameters.

The review of the part orientation literature has revealed a set of knowledge resources that mostly are influences and laws. In contrast, for the industry practice, only the recent works led by Grandvallet et al. (2020) provided elicitation data dealing with the

part orientation problem and particularly the six action rules presented in section 2.2.2. These will be used along this document. Their associated explanation showed differences of practices between the research literature and the industry use. It has also been noticed that most of the results proposed by the literature are based on other AM techniques that are completely different from PBF techniques which are the target here.

As this work supports the knowledge-based assistance of the CAM operations, the next chapter proposes an approach to transform action rules into quantitative values and how to evaluate them on geometries.

Chapter 3

A Knowledge Mathematical Representation Approach

Introduction

The profitable use of knowledge can be achieved by various ways. For instance, a consulting company specially makes use of formalized knowledge when providing services. From another point of view, a CAM operator may also need expertise to for example, adjust the parameters of a machine. As exposed in the previous chapters, diverse CAM systems rely on formalized knowledge bases made of rules to assist the choices or decisions. In that context, the methods found (to use knowledge) are mostly procedural and use inference engines (IF/THEN rules, see section 1.3). However, operators having to consider a list of action rules, would naturally check up the compliance level of each of the action rules simultaneously in order to make comparisons between scenarios of manufacturing parameters. In addition, to make decisions, the operators make balances or trade-offs between the action rules as they might be conflicting. Evaluating the actions rules compliance level might be completely impossible to achieve manually, if several rules are considered or if the involved geometries and manufacturing systems are complex. Another issue is that the assessment algorithms used are mostly based on feature decomposition (see Chapter 1), that is no longer consistent for AM because of the complex shapes that usually are of organic types.

For these reasons, the COFFA project proposes another principle allowing to process the elicited knowledge by simultaneously considering the ARs and evaluating whether they are satisfied on the part or not. This chapter proposes to use desirability functions (coming from decision making approaches) in order to mathematize the informal knowledge of experts. The mathematization approach aims at transforming the action rules

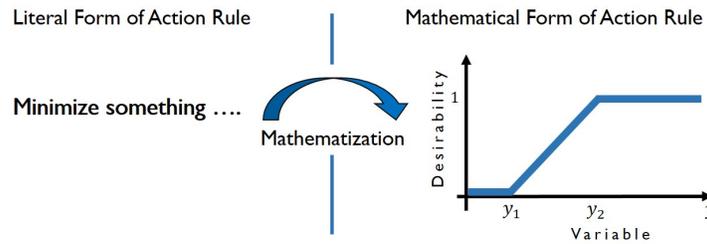


Figure 3.1: From literal to mathematical representation of action rule

(literal form) into unitary fuzzy-like functions (mathematical form) as illustrated by the Fig. 3.1. This way, every AR's compliance level on the part is obtained through the calculation of its desirability value.

Before presenting the main approach, the next subsection discusses some basics of desirability functions.

About Desirability Functions

Desirability functions (DF) allow the conversion of different scales of quality measures into 0 to 1 functions (Trautmann and Weihs (2005)). These functions were first introduced by Harrington and then Derringer and Suich (1980) proposed a modification to show their ability to transform multiple responses into only one single aggregated output. DF approach is one of the most used methods in industries for optimizing processes in which different parameters must be conveniently adjusted. They have notably been combined with the response surface methodology or fuzzy logic to solve manufacturing parameter optimization problems (Datta et al. (2006); Aggarwal et al. (2008); Kim and Lin (2000); Singh et al. (2011)). There are various types of DFs available in the literature (from the less sophisticated to the most sophisticated) (Costa et al. (2011)). The Fig. 3.2 shows examples one sided and two sided desirability functions.

Another advantage with this approach, is the possibility to make a weighted combination of the involved n functions. For instance, the equation 3.1 shows a weighted geometric mean, where the d_i are the desirability values of each function and the w_i represent the weights given to each function. In other words this type of relation allows the assignation of priorities between the objectives. This property is usually necessary in decision-making problems, as objectives might result in conflicting responses.

$$D = d_1^{w_1} . d_2^{w_2} . d_3^{w_3} \dots . d_i^{w_i} \quad (3.1)$$

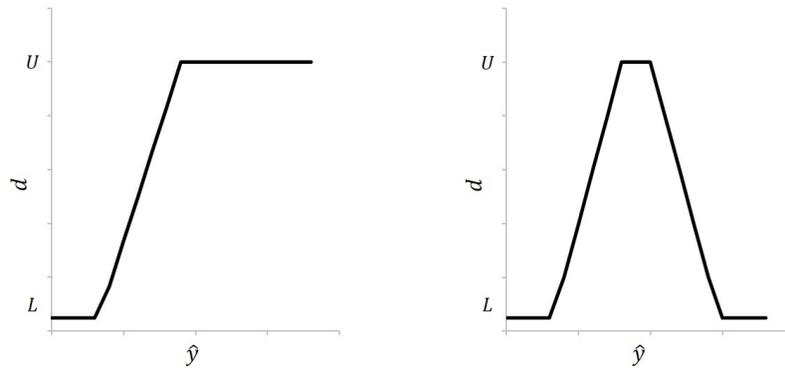


Figure 3.2: One sided and two sided desirability functions

$$\sum w_i = 1 \tag{3.2}$$

Through the years, the formulation of desirability functions has evolved with a variety of proposals. However, for the sake of simplicity, this study will consider the formulation proposed by Derringer and Suich (1980).

The use of desirability functions for modeling systems is usually based on experimental studies from which a given variable \hat{y} and its threshold values are identified (Fig. 3.2). Variables \hat{y}_i represent the factors influencing the output response of a system of interest. In fact, they are adjustable values on which one can act to modify the output compliance level. For example, in the machining context, modifying the cutting speed would have an impact on the final quality of the part. In the DF approach, the different \hat{y}_i are transcribed into desirability indices (d_i) by experimental means or by using any expertise.

In the present work, these variables are directly referred in the action rules arising from experts. From a given AR the variable is inferred from the fundamental relationship between its different constitutive concepts. For this purpose, a relational analysis of the rules content must be led in order to extract \hat{y} and its threshold values. These operations are made along with the opinion of the experts. Next, is detailed the approach overview.

Proposed Approach Overview

A translation of the action rules expressed in natural language with the use of desirability functions is proposed. The main aim is to provide a mathematical image as close as

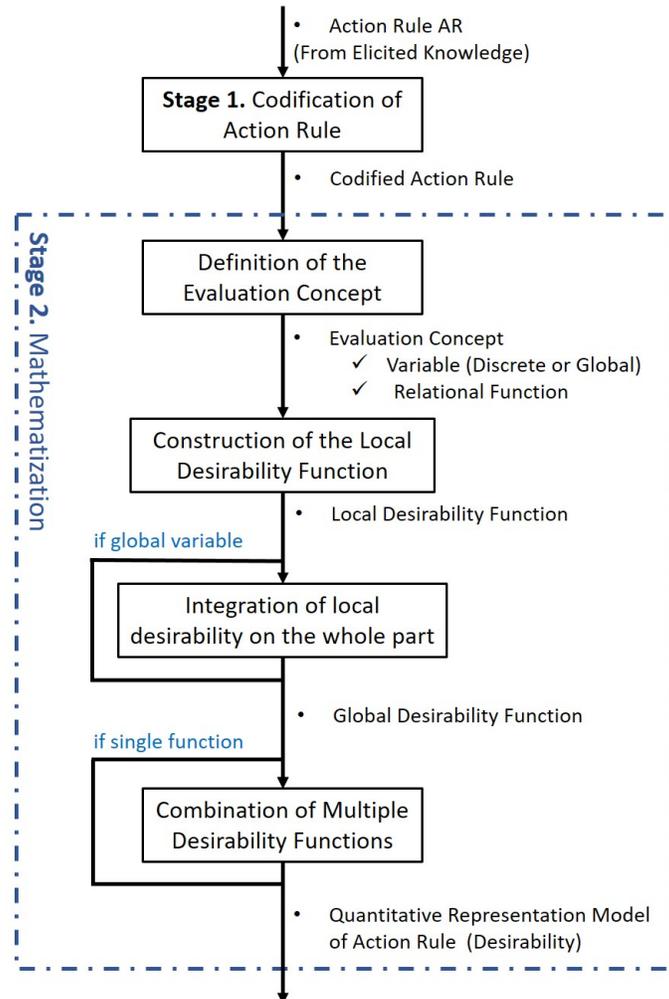


Figure 3.3: Modeling approach for knowledge quantitative representation

possible to the intent of a given AR. This modeling approach has the advantage of normalizing variables of diverse natures into dimensionless values between zero and one.

The Fig. 3.3 summarizes the general stages of the methodology. For a given AR:

- The first phase codifies its content in order to put it in the form of objective (if necessary) using a common grammar.
- The second stage proceeds to a mathematization of the action rule by achieving a

certain number of steps that will be described.

In the whole mathematization stage of the action rules, knowledge is generated with the collaboration of the experts. Therefore, this process is part of the elicitation process and it involves the experts as well as the research team.

3.1 Action Rule Codification

Action rules acquired from experts are expressed in different forms with different grammatical structures. This diversity makes it difficult to define and handle a general modeling process. Therefore, this work proposes to codify the action rules in the form of objectives using a common grammar made of words classified in different categories of concepts related with the domain of interest.

Each action rule implicitly includes an objective to complete. The codification intends to explicitly show that objective by replacing its action verb. For instance, the rule “Orient machining datum surfaces out of horizontal” seeks to get the maximum machining datum surfaces possible out of horizontal position. Therefore, the codified version of this example could be either “Maximize machining datum surfaces out of horizontal” or “Require machining datum surfaces out of horizontal” depending on the severity wanted. It should be noted that the codification step is not always necessary because, in some cases, the ARs are by default expressed in the form of objectives. For instance, in the list aforementioned, the rules (AR1), (AR2), (AR5) and (AR6) are already codified.

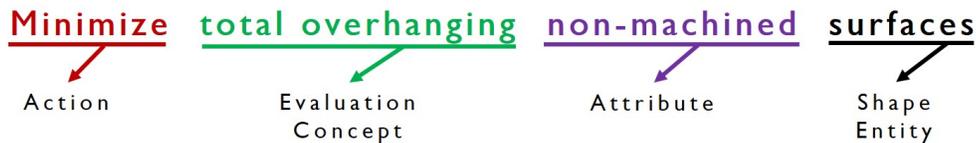


Figure 3.4: Action rule concepts codification

The codification proposed in this work classifies the different concepts of the action rules in categories related to the domain of interest which is additive manufacturing in the present context. Fig. 3.4 shows the classification of the concepts of an action rule used in this work. However, note that some authors have recently proposed concept categories to represent additive manufacturing knowledge, but these are not appropriate for the current need. That is the case of Kim et al. (2018). The concepts of the example in Fig. 3.4 are classified in three categories namely, *Part*, *Evaluation Concept* and *Action*. Each of the categories is discussed in the following sub-sections.

The structure of an action rule is such that the action applies to one or more evaluation concepts and each of the evaluation concepts is associated to the part (geometry of interest).

3.1.1 Part:

This concept gathers the different information related to the geometry in question. The class Shape provides the distinct entities constituting the part's topology. Shape is defined by a volume which, breaks down like a BREP (boundary representation Stroud (2006)) in surfaces, edges and vertices. As a complement, the class Specifications (corresponding to the global product specifications) indicates the extrinsic and intrinsic characteristics of the Shape entities. For instance, this class provides information about the roughness or the tolerances on the dimensions of a surface or between surfaces. The class Attributes is used to classify the Shape entities according to their expected quality or post processing need (e.g. machined surfaces). Fig. 3.5a shows a summary of a part composition, the solid lines refer to "is defined by" relation and the double lines stand for "is limited by". A non-exhaustive list of Attributes including hole, non-machined, machining datum and priority are defined based on the action rules formulated by experts. It has to be noted that the Attributes may or not exist in the action rule. They point on the involved Shape entities as illustrated in Fig. 3.5a by the dashed lines.

3.1.2 Evaluation Concept:

Evaluation concepts (EC) are the pivotal base of the decision-making through an action rule since they allow evaluating and understanding the consequences of an action onto the final requirements namely, part quality, cost and processing time. In ARs, evaluation concepts are related to shape entities. The relationship between the evaluation concept and shape entities is governed by a quantifiable variable (discussed in section 3.3.1). The identified evaluation concepts for the list of rules given in the section 3 are reported in the Fig. 3.5b.

3.1.3 Action:

The Actions are introduced to normalize the ARs in order to explicitly express them as objectives by using the following words: minimize, maximize, avoid or require. They make it possible to transform an action rule into an objective to reach. *Minimize* and *maximize* are used when intermediary cases are accepted; that is to say that these terms allow to AR compliance level be compensated. In contrast *avoid* and *require* are used when the non-acceptable cases (zero desirability) cannot be compensated (i.e. orientation

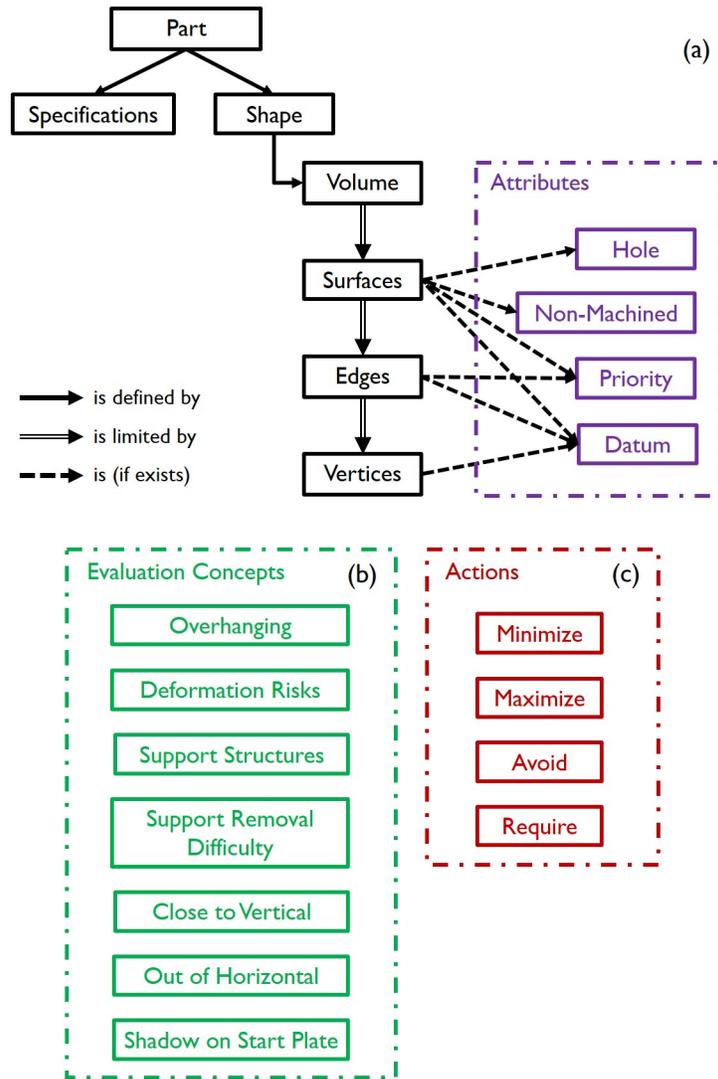


Figure 3.5: Categories of concepts: (a) Part classification; (b) Evaluation Concepts; (c) Actions

with non-acceptable local situation has to be avoided). The impact of these actions will be seen in the section 3.5.

3.2 Mathematization Process

As previously described in Fig. 3.3 after the action rule codification, the mathematization process follows. To do so, different information related to the different elements of the codified action rule, to the CAM parameters and the manufacturing environment are used. In the graph of Fig. 3.6, the boxes *part definition* and *actions* have fixed content and the boxes *evaluation concepts*, *attributes*, *CAM parameters* and *environment* are domain specific. The environment allows getting information related to for example, the global reference or the start plate of the machine (case of additive manufacturing). CAM parameters are handles that one can vary to check the desirability of the action rules. If that desirability is high enough, the decision-maker might choose that set of CAM parameters to manufacture his parts. The central box contains the main modeling steps that will be detailed from sections 3.3 to 3.5. Step 0 corresponds to the application of the CAM parameters on the part and will not be described.

The following steps will be performed to to get the quantitative representation model (desirability function) of a given action rule:

- Define the evaluation concept. In this step an analysis of the evaluation concept with respect of the part is carried out to find out the quantifiable variables \hat{y}_i and their related laws of evolution. Fuzzification step can be required when the evaluation concepts are quantified notions. The results of the evaluation concepts will be used for the construction of the desirability functions.
- Construct the desirability functions locally.
- Define an integration or summation operator to calculate the overall desirability on the part when necessary.

3.3 Step 1 of Mathematization - Definition of the Evaluation Concept

In the literal expression of action rules, there are implicit interrelations linking the concepts defined as structural knowledge by Beissner et al. (2008). Building structural

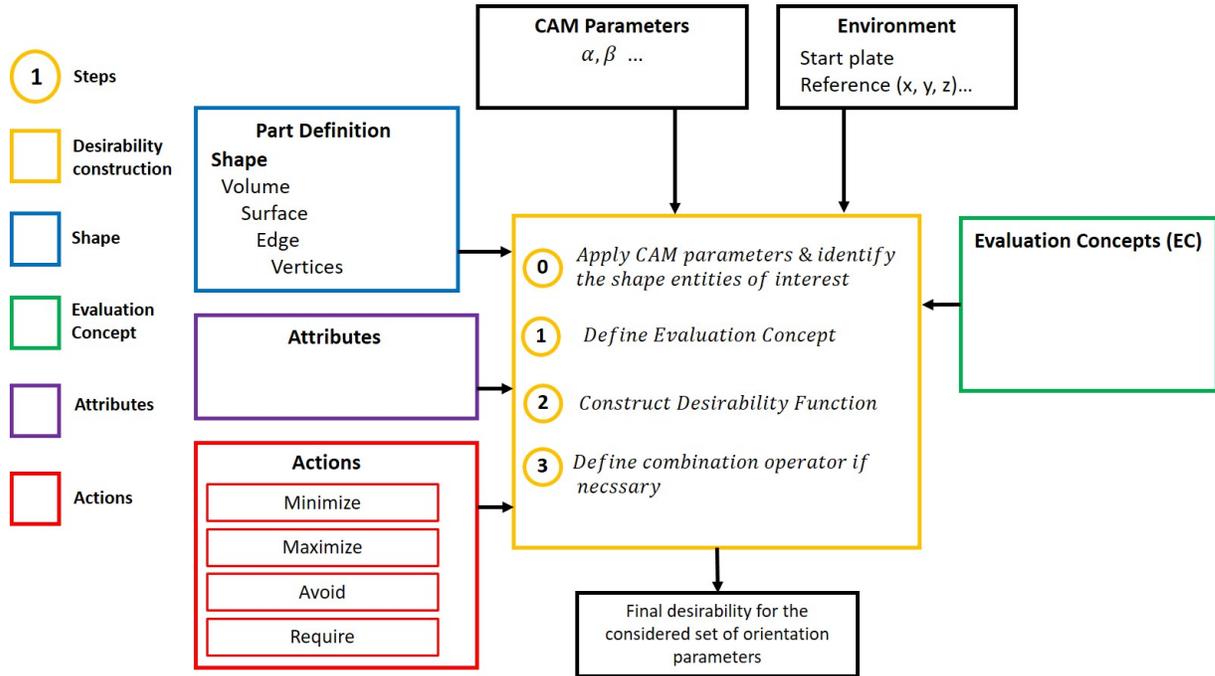


Figure 3.6: Global methodology used to build desirability functions

knowledge might require the preliminary scientific comprehension of interactions between the involved parameters and the intervention of the experts. The idea in this step is to perform a mathematization of the action rules to reflect the relationship between the concepts by following three main steps. The assumption that an evaluation concept is influenced by a specific quantifiable variable \hat{y} of the shape entity, is made. Then, the first mathematization step is to identify that \hat{y} ; second, the way to measure the value of \hat{y} on the shape entity is determined. Finally, the evolution of the evaluation concept according to \hat{y} is established. The expected outputs are the variable itself, the way to measure it and the function linking it with the evaluation concept.

3.3.1 Identification of the variable

By analyzing the fundamental law between the involved shape entity and the evaluation concept, the identification allows getting one or more quantifiable variables \hat{y}_i . This process involves the experts opinion about which quantifiable variable of the shape entity has the greatest impact (or have a significant impact) on the EC. A CAD expert might also be needed to facilitate the identification of the variable. In fact, each shape entity

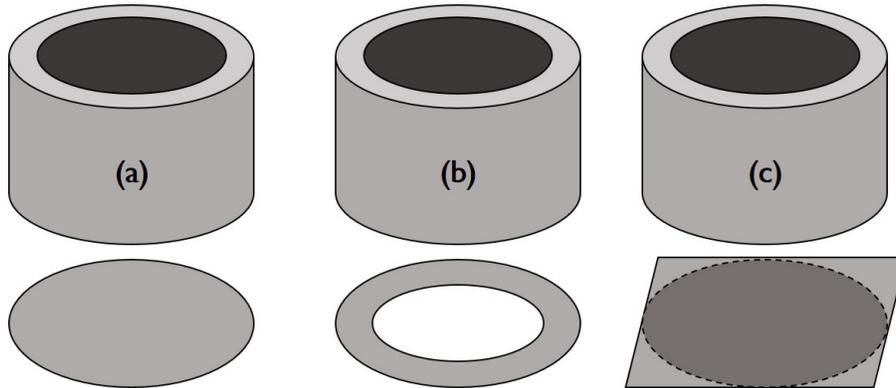


Figure 3.7: Choice of variable: part shadow example

has its characteristic parameters; for instance, for a surface, the angle, the area or the projected area etc, can be identified. The parameter among those that fits more with the evaluation concept will be indicated as the variable \hat{y} . Different opinions might arise from this process. The rule about the minimization of part shadow on start plate, for which different types of measures have been identified, is an illustration. The measurement of part shadow can be the area of the projection, the maximum dimension of the projection etc, and the projection itself can be the silhouette (Fig. 3.7a), the contour (Fig. 3.7b) or the contour bounding box (Fig. 3.7c). In the case of the Grandvallet et al. (2020) elicitation, the discussion finally converged on the solution (b). The justification was that in PBF, it can be foreseen to put other parts inside the hole of the shadow in order to save place. Somehow, the final number of retained variables depends on the number of ECs mentioned in the action rule. One EC equals to one variable chosen among the possible \hat{y}_i .

3.3.2 Measurement of the variable on the shape entity

According to the involved shape entity, the way to measure the variable might differ. However, as mentioned in the previous point, the set of measurable variables is limited and also depend on the used CAD tool capabilities.

For some cases, a specific discretization method for local evaluation is required. For instance, to find the local angle \hat{y} of a complex surface by its normal, it is good practice to tessellate the latter to transform it into triangular flat elemental surfaces. When this discretization occurs, a combination operator allowing to aggregate the individual local values may be required in some cases (see section 3.5). Indeed, the decision maker needs to have the overall desirability over the entire part instead of having it for each patch of

Shape Entity	Request	Geometrical Operation	Discretization
Volume	Shadow Area or Length	Projection	–
	Size (Length, Width, Height)	Bound-Box	–
	Layer Area	Contour Filling (Triangles, Pixels)	Slicing
	Layer Max./Min Length	Multi-Directional Hatching	Slicing
Surface	Shadow Area or Length	Projection	–
	Surface Angle	Normal Vector Mapping	Tessellation

Table 3.1: Geometrical operation and discretization of shape entities

surface. Helpful geometrical operations on shape entities for the evaluation of desirability are reported in Table 3.1.

3.3.3 Establishment of the relational function

This step is intended to establish the relationship between \hat{y} and the evaluation concept. This analysis is one of the most important steps that allow going from a conceptual view to a mathematical view of the ARs. The expected output for each identified variable is a relational function showing the evolution of the evaluation concept according to the variable \hat{y} as given in Eq. 3.3.

$$EC = f(\hat{y}) \tag{3.3}$$

To understand the method, an example is detailed in the following lines.

3.3.3.1 Example

Given the action rule depicted in the Fig. 3.8, a codification, according to the discussed

categories, firstly allows identifying the concepts on which the analysis is carried out. As a reminder, the attribute non-machined indicates that the action rule only applies to a subset of the surfaces of the part.



Figure 3.8: Action rule concepts codification

Based on its definition, the fact that a surface is overhanging depends on its orientation (explanation in section 2.2.2). Thus, the surface angle θ can be identified as the shape variable that more varies the evaluation concept. The measurement of θ is not global on the part, so a tessellation is necessary in order to calculate it on each elemental triangular surface. Then, the evolution of the overhang according to θ is given by the equations below (equation 3.4) and shown in Fig. 3.9. In fact, the relational function is a kind of existence function dictating how overhanging is a surface when its θ varies. If the later is less than θ_1 , the surface is considered as overhanging. The interval between θ_1 and θ_2 in an uncertainty zone for the experts in which, the surface becomes less and less overhanging. θ_1 and θ_2 could be equal, and in that case the transition between overhanging and not overhanging is not gradual. Above θ_2 , the surface is no longer overhanging.

$$\begin{cases} EC = 1 & \text{if } \theta \leq \theta_1 \\ EC = \frac{\theta_2 - \theta}{\theta_2 - \theta_1} & \text{if } \theta_1 < \theta < \theta_2 \\ EC = 0 & \text{if } \theta \geq \theta_2 \end{cases} \quad (3.4)$$

The threshold values θ_1 and θ_2 must be indicated by the experts. Also, note that one can use more complex functions or simply smooth the one used in the example.

Thereafter, the desirability functions are built based on the established structural knowledge. As shown in Fig. 3.9, the relational functions are mapped between 0 and 1 in the form of fuzzy functions, but for some evaluation concepts a fuzzification is necessary (refer to section 3.3.3.2). In case of more than one evaluation concept, the mathematical considerations in the section 3.3.3.3 are used to carry out logical combinations.

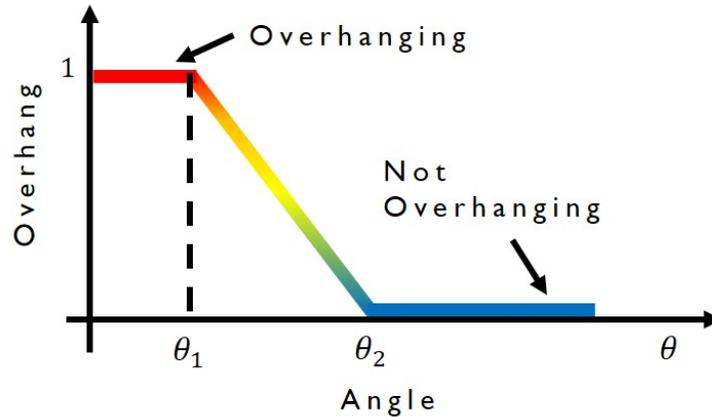


Figure 3.9: Example of relational function

3.3.3.2 Fuzzification

The evaluation concepts can be of different types; they can be abstract when they are non-quantifiable notions (e.g. deformation risks, overhanging), and they can be quantifiable notions (e.g. part shadow). In the first case, the relational diagram is built on the basis of the existence and magnitude of the evaluation concept according to the variable. While in the second case, the relation is dictated by the maximum and minimum values of the quantifiable evaluation concept. For these reasons, a fuzzification is led to scale this kind of EC between 0 and 1. This consists of mapping their maximum and minimum possible values with values defined in the interval $[0, 1]$. For a variable \hat{y} , there is a function associating to each of its values a real $m \in [0, 1]$ defined by:

$$m = f(\hat{y}) \tag{3.5}$$

This definition describes the relation between the evaluation concept (through its quantification parameter m) and the variable linking it to the involved shape entity of the part. For instance, if the shadow on the start plate is considered, the maximum and minimum values are not limited between zero and one. Therefore, the fuzzification is done such that the maximum is assigned the value 1 and the minimum the value 0 Fig. 3.10.

3.3.3.3 Operations on evaluation concepts

The previous illustration (in Fig. 3.9) shows a simple case for which, there is a single variable, but in some cases, more than one variable can exist depending on the number

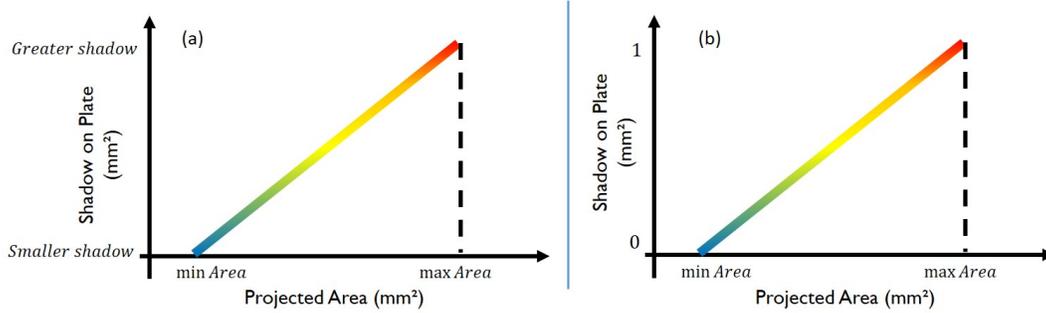


Figure 3.10: Evaluation concept fuzzification: (a) quantified shadow; (b) fuzzified shadow

of evaluation concepts. Logical operations such as “and” and “or” combine the latter in the AR; for instance, the AR6 in section 2.2.2, for which, there is an “and” operator. Hence, some mathematical notions are introduced to make possible the combination of multiple desirability functions. The properties used here are the generalization of the properties used in fuzzy logic theory introduced by Zadeh (1965). A few definitions such as the negation of a relational function, the intersection or union of multiple relational functions and useful De Morgan laws are given as follows.

Definition 1: Negation

Given a relational function A, this operation corresponds to the complementary of $f_A(\hat{y})$ defined as:

$$\overline{f_A(\hat{y})} = 1 - f_A(\hat{y}) \tag{3.6}$$

Definition 2: Intersection

The intersection C of two relational functions A and B (equation 3.7) defined by $f_A(\hat{y}_A)$ and $f_B(\hat{y}_B)$ respectively, for a given scenario, corresponds to the logical “and” operation (Zadeh (1965)). The resulting value is the minimum between m_A and m_B

$$C = A \cap B \tag{3.7}$$

$$m_c = \min(m_A, m_B) \tag{3.8}$$

Definition 3: Union

The union C of A and B (equation 3.9) defined by the relational functions $f_A(\hat{y}_A)$ and $f_B(\hat{y}_B)$ respectively, is the logical “or” operation (Zadeh (1965)). Different formulas for the union are available in Zimmermann (2010), but here the maximum value is retained.

$$C = A \cup B \quad (3.9)$$

$$m_c = \max(m_A, m_B) \quad (3.10)$$

Definition 4: De Morgan Laws

$$\overline{A \cup B} = \bar{A} \cap \bar{B} \quad (3.11)$$

$$\overline{A \cap B} = \bar{A} \cup \bar{B} \quad (3.12)$$

3.4 Step 2 of Mathematization - Construction of the Desirability Function

As described in the introduction of this chapter, the desirability functions make it possible to translate any variable into normalized positive values in the interval $[0,1]$. For the CAM operations, the purpose of using expert knowledge is to compare different scenarios of parameter combination for the sake of quality, cost or time optimization (main drivers for experts to define evaluation concepts). Thus, here, the desirability approach makes it possible to see all of the experts’ rules in the same map of comparable dimensionless values. The desirability function DF of each action rule is constructed based on the relational function from the mathematization and its relative action. For minimize and avoid, the corresponding desirability function is the opposite of the relational function (Eq. 3.13). Then, for maximize and require actions, the desirability function will be equivalent to the relational function (Eq. 3.14).

$$DF = \overline{EC} = 1 - f(\hat{y}) \quad (3.13)$$

$$DF = EC = f(\hat{y}) \quad (3.14)$$

In the example of Fig. 3.9, the variable linking the part involved shape entity (surface) and the evaluation concept (overhanging) is the angle (θ) of the surface, it characterizes the support structure requirements. The unit relational function describes when a surface

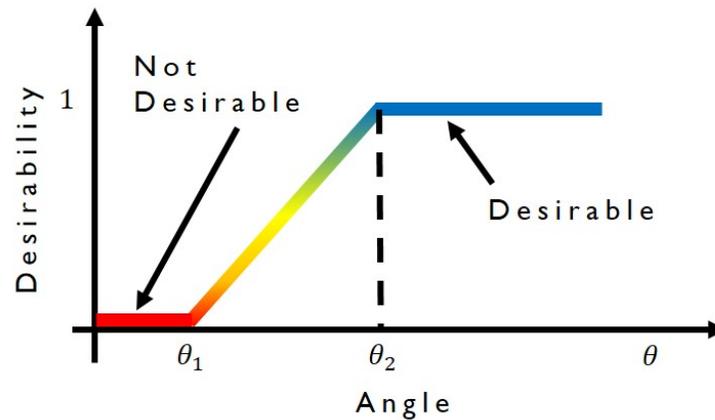


Figure 3.11: Desirability function built for the example

is overhanging and needs support i.e. the angle θ is less than θ_1 and when the surface is progressively not overhanging i.e. θ tending to be greater than θ_2 . To get the desirability function representing the action rule, the related action “minimize” is used. Owing to the fact that this action rule prescribes to minimize the overhanging non-machined surfaces, the situation in which those are overhanging is not desirable and the opposite situation is desirable. Therefore, the desirability function in Fig. 3.11 is obtained by inverting the relational function in Fig. 3.9.

This function associates to each value of the variable θ of the considered surface a compliance value ranging from 0 to 1 (the best values being those near 1). As an example, let’s consider the simple cubic geometry shown in Fig. 3.12, for which the orientation desirability (basing on the Fig.3.11) of the indicated scenarios is searched. Threshold angles of the desirability function θ_1 and θ_2 are 15° and 55° respectively. The desirability values are locally assessed for each of the its surfaces (all of them considered as non-machined). A summary of the local desirability values is provided in the Table 3.2.

As illustrated, it can be seen that for different orientations of the part, the desirability of each surface is sensitive to its inclination. When a couple of surfaces have good desirability, others have poor ones. In fact for this geometry, the typology of the applied desirability function (and its threshold values) does not allow getting a scenario for which all of the surfaces have the maximum desirability ($d = 1$). For this example, the number of surfaces can easily be managed when choosing an orientation. For instance, it is easy to see that the Scenario 3 seems to be the best one according to the local values. However, if the number of surfaces is high, one could not see in which extent a scenario

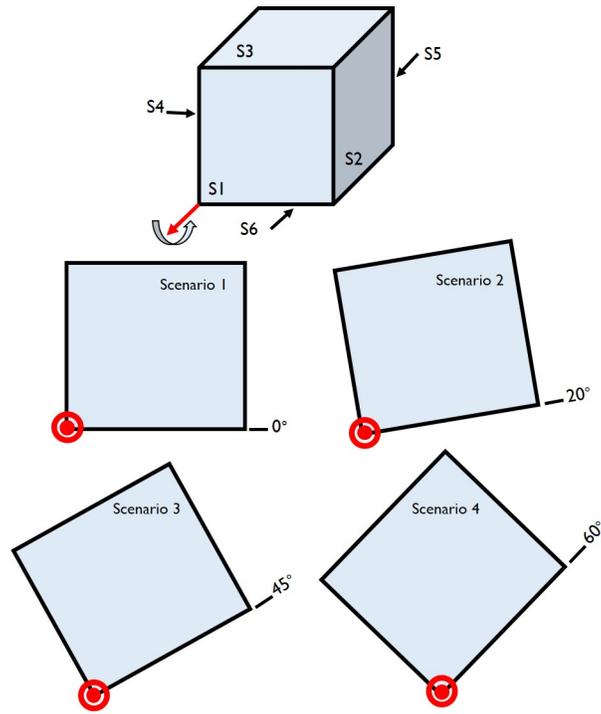


Figure 3.12: Example of cubic part orientation scenarios

	S1	S2	S3	S4	S5	S6
Scenario 1	1	1	1	1	1	0
Scenario 2	1	1	1	1	1	0.125
Scenario 3	1	1	1	0.75	1	0.75
Scenario 4	1	1	1	0.375	1	1

Table 3.2: Local orientation desirability values for the cubic part example

satisfies the action rule. For this reason, in order to ease the analysis of the results, the local desirability values have to be combined using averaging operators to get a global desirability value for the scenario. Different averaging operators are presented in the next section.

3.5 Step 3 of Mathematization - Definition of the Summation Operator

Globalization is the way chosen to reduce the number of decision metrics from thousands per action rule to only one per action rule. To globalize averaging operators are usually used in the literature. Different averaging operators are proposed, arithmetic in Eq. 3.15 and geometric Eq. 3.16, where D_{part} is the overall desirability of the part, S the domain and s the elementary surface. These operators have their counter part in the discrete world (tessellated surfaces). The two operators are discussed in section 3.5.1 and the choice of the operator based on the AR in section 3.5.2.

$$D_{part} = \frac{1}{S} \int_S DF(s) ds \quad (3.15)$$

$$D_{part} = \prod_S DF(s)^{ds/S} \quad (3.16)$$

3.5.1 Some discrete averaging operators

There are various discrete averaging operators, but, the chosen one must reflect as much as possible the knowledge in question by compensating or preventing from compensation when necessary. Given the geometry in Fig. 3.13, associated with a desirability function (according to AR2), let's analyze the global desirability values of the two scenarios. Using simple arithmetic means would result in equivalence of both scenarios 1 and 2 (desirability = 0.5625) and 3 and 4 (desirability = 0.8125), what might not be relevant. In fact, the AR2 is about overhanging surfaces, thus, the larger surface requires more support structures and is more subjected to deformation than the smaller one. Hence, it is better considering the surface as a weight in this case, in order to help the decision-maker get a consistent relative comparison.

This study puts forward the utilization of the generalized Hölder power mean (Bullen (2003)) (Eq. 3.17).

$$D(d_1, \dots, d_j, \dots, d_m) = \left(\frac{1}{m} \sum_{j=1}^m d_j^p \right)^{1/p} \quad (3.17)$$

where, $d_1, \dots, d_j, \dots, d_m \in [0, 1]$ are m positive real numbers representing the local desirability values of the m facets of the part, p is a real exponent. For a set of m

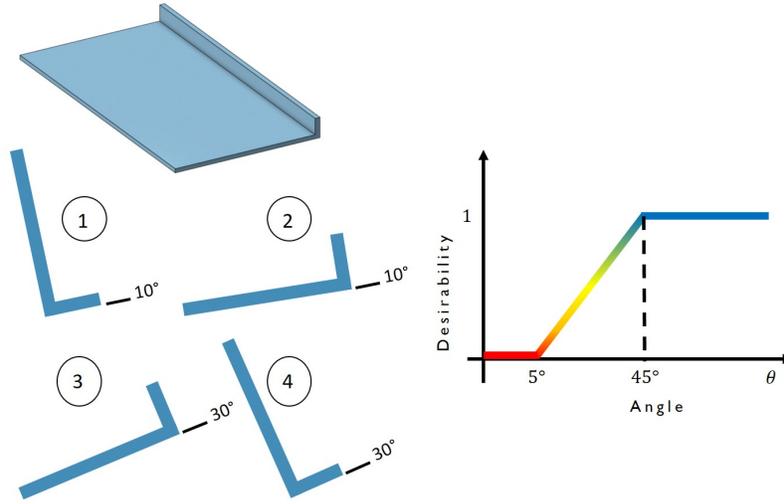


Figure 3.13: 2D L geometry with desirability function illustrating global desirability equivalence

positive weights (r_1, r_j, \dots, r_m) satisfying the condition $\sum r_j = 1$, the weighted mean D is defined as follows.

$$D(d_1, \dots, d_j, \dots, d_m) = \left(\sum_{j=1}^m r_j d_j^p \right)^{1/p} \quad (3.18)$$

The following cases for the limit of p are considered:

$$\lim_{p \rightarrow -\infty} D(d_1, \dots, d_j, \dots, d_m) = \min(d_1, \dots, d_j, \dots, d_m) \quad (3.19)$$

$$\lim_{p \rightarrow -1} D(d_1, \dots, d_j, \dots, d_m) = \left(\sum_{j=1}^m \frac{r_j}{d_j} \right)^{-1} \quad (3.20)$$

$$\lim_{p \rightarrow 0} D(d_1, \dots, d_j, \dots, d_m) = \prod_{j=1}^m d_j^{r_j} \quad (3.21)$$

$$\lim_{p \rightarrow 1} D(d_1, \dots, d_j, \dots, d_m) = \sum_{j=1}^m r_j d_j \quad (3.22)$$

$$\lim_{p \rightarrow +\infty} D(d_1, \dots, d_j, \dots, d_m) = \max(d_1, \dots, d_j, \dots, d_m) \quad (3.23)$$

Other results such as the quadratic and cubic means can be obtained by performing respectively $p = 2$ and $p = 3$. The minimum (Eq. 3.19) and the maximum (Eq. 3.23) solutions are discarded because the weighting is not possible, but they could be useful in the cases where the minimum or maximum desirability is representative enough. Equations 3.20, 3.21 and 3.22 are by definition harmonic, geometric and arithmetic weighted means respectively. Relations of inequalities have been demonstrated for these solutions (Qi et al. (2000), Bullen (2003)). In fact, for given reals $d_1, \dots, d_j, \dots, d_m$, the arithmetic mean returns a result greater or equal to that returned by the geometric mean. Similarly the geometric mean will be greater or equal to the harmonic mean.

When the weights r_j are equal, the Eq. 3.20, 3.21 and 3.22 become equivalent to classic means (harmonic, geometric and arithmetic without weights). Here, the r_j are linked with a characteristic parameter of the involved shape element. They can for example be relative surface area as discussed in the illustration of Fig. 3.13. The choice of this weighting variable depends on the practitioners. It has been noticed that experts commonly define weights with facet area. Exploring different possibilities is part of future works.

$$r_j = A_j / A_{total} \quad (3.24)$$

Considering that one of the surfaces of the example in Fig. 3.13 is 6 times bigger, the three means weighted by r_j in Eq. 3.24 would return for each scenario the values in Table 3.3. Globally, the results are quite compliant. However, with the harmonic mean, it is noticed that the scenario 3 has better desirability than the scenario 1; this is not the case for the other means. In the practice, the scenario 1 would be privileged compared to scenario 3. And the scenario 4 would be finally chosen for the manufacturing. In this work, the geometric (non-compensatory: local low desirability weakens the result) and arithmetic (compensatory: local good desirability highly compensates a low one) means are used, and the way to choose between is explained in the next section.

3.5.2 Choice of the operator according to the action rule

The choice of the averaging operation depends on the *Action* prescribed in the AR. On the one hand, the concepts minimize and maximize show that intermediary values are allowed. In fact, for these actions, the local desirability values are combined on the whole part such that low values are balanced with the high values. Thus, they will use

Means	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Arithmetic	0.874	0.25	0.678	0.946
Geometric	0.742	0.168	0.668	0.935
Harmonic	0.499	0.142	0.66	0.92

Table 3.3: Comparing mean desirability values

a compensatory operation i.e. the weighted arithmetic mean as it refers to a sum (Eq. 3.22).

On the other hand, avoid and require actions do not accept the low desirability cases. This means that even if only one of the elemental entities j has a low desirability, the whole geometry of n entities will have an aggregated weak desirability regardless the other values. These actions will use the geometric weighted average in Eq. 3.21. Thanks to the product, the compensation effects are relatively low, and can even be nil when some local desirability values are equal to zero.

Note that the discretization parameters affect the combined values very slightly. For the triangulation case, different parameters (linear and angular deflections) have been tested and reported in tables 3.4 and 3.5 for the weighted arithmetic and geometrical means respectively. Two action rules have been applied to the same geometry.

For the weighted arithmetic mean, the combined desirability remained constant except for the finest tessellation which has 3609146 triangles. The desirability values decreased of 0.01 for all sample points. For the geometric mean nothing changed in terms of desirability for all points (even for the finest triangulation). Globally, in both cases, the computation time is expected to increase when using fine tessellations but the values remain constant.

Tessellation Parameters	Nb Tri-angles	Time for 700 orientations (s)	Desirability of random sample points				
			0°-0°	90°-0°	140°-120°	110°-280°	10°-130°
lin. deflection: 1.0 ang. deflection: 0.5	6650	3	0.91	0.89	0.76	0.83	0.86
lin. deflection: 0.01 ang. deflection: 0.5	143030	19	0.91	0.89	0.76	0.83	0.86
lin. deflection: 0.01 ang. deflection: 0.1	233622	32	0.91	0.89	0.76	0.83	0.86
lin. deflection: 0.0001 ang. deflection: 0.1	3609146	380	0.90	0.88	0.75	0.82	0.85

Table 3.4: Comparison of different tessellation parameters for arithmetic mean

Tessellation Parameters	Nb Tri-angles	Time for 700 orientations (s)	Desirability of random sample points				
			0°-0°	90°-0°	140°-120°	110°-280°	10°-130°
lin. deflection: 1.0 ang. deflection: 0.5	433	1	1	0.94	0.29	0	0.55
lin. deflection: 0.01 ang. deflection: 0.5	11731	3	1	0.94	0.29	0	0.55
lin. deflection: 0.01 ang. deflection: 0.1	22545	5	1	0.94	0.29	0	0.55
lin. deflection: 0.0001 ang. deflection: 0.1	1135574	185	1	0.94	0.29	0	0.55

Table 3.5: Comparison of different tessellation parameters for geometric mean

3.6 Summary and Conclusion

In order to assess the action rules compliance level, this chapter presented a novel knowledge quantitative representation model aiming at transforming the knowledge of experts into desirability functions. In the codification step, the objective behind

an AR is clearly indicated by using specific actions. This output codified AR is the entry of the global mathematization which was given in the graph of Fig.3.6. This diagram was generic; now let's apply it to the part orientation case. The data filled in the boxes of Fig. 3.14 are from previously discussed definitions and literature. First, the CAM parameters box is replaced by the orientation parameters α and β angles that define the rotations around two chosen axes. As a reminder, this work mostly interests in part orientation which is the first CAM activity in additive manufacturing. The manufacturing environment box is set up to additive manufacturing. Attributes and evaluation concepts are those from section 3.1. For each action rule, only the necessary concepts are picked.

In step 0, the parameters are applied to the whole shape from part definition. It is about orientation, thus the AM machine's start plate is used as rotating reference. The corresponding output is an oriented shape from which the entities of interest are extracted. By default, if no attribute is defined, it is considered that the action rule applies to the whole shape. Following that, the evaluation concept of interest from the right box, is defined ($EC = f(\hat{y})$) in step 1, and in step 2 the desirability function ($DF = EC$ or $DF = \overline{EC}$) is inferred from the definition of that evaluation concept and the action. When necessary, a combination operator is defined with respect of the action. Finally, the desirability value corresponding to that set of parameter can be calculated. In practice, the steps 1 to 3 are only carried out once, and for analysis purposes, the handles (α and β) are incrementally varied. This way, the decision-maker will get set of alternative solutions.

This graph proposes a synthetic representation of the modeled knowledge by explicitly showing the manufacturing environment of interest, the parameters to handle, and all of the information related to the action rules given by the experts. It can be noticed that the rules can be independently applied to the product to make. Hence, the decision-maker can balance between them by comparing their desirability values which are considered as the compliance levels of the rules. To ease the modeling process, an assistant has also been designed (please, refer to Appendix A).

The chapter 4 will apply this modeling approach to the part orientation action rules discussed in chapter 2. And to support computation of orientation desirability and assist decision making the chapter 5 proposes a tool.

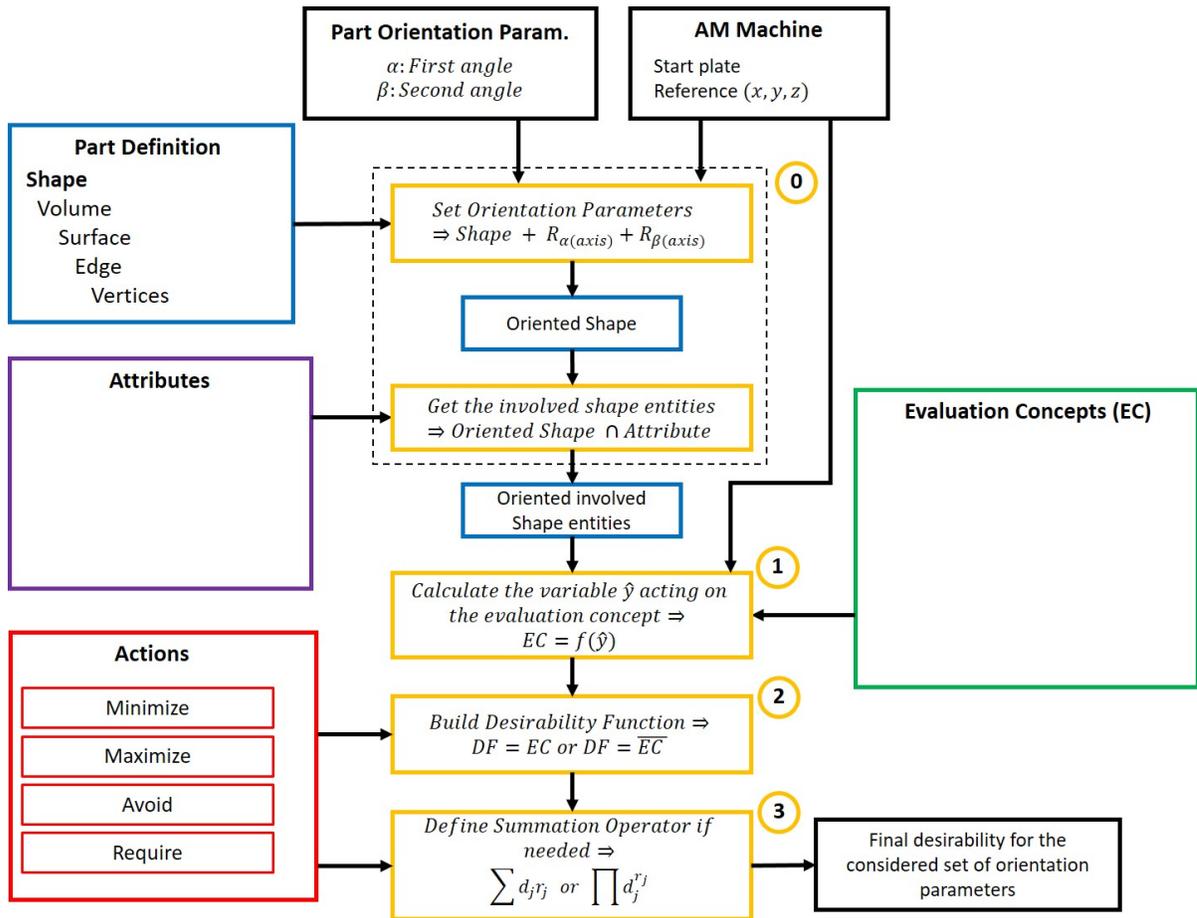


Figure 3.14: Relational diagram applied to part orientation

Chapter 4

A Knowledge-Based Computation of Part Orientation Desirability

Introduction

In the chapter 2, a set of action rules used by industry practitioners for the part orientation problem have been discussed. The Chapter 3 proposed a modeling approach to quantitatively represent action rules. Now in this chapter, the modeling approach will be applied to the part orientation action rules. Disposing of a set of action rules to optimally orient his parts, an operator would logically seek of evaluating whether each rule is respected by the part when a set of parameters are applied. Therefore, the aim is to be able to evaluate the compliance level of the action rules by using the desirability functions. A compliance level refers then to the desirability value calculated for a given part in a given configuration, here the orientation in the build space. It has to be reminded that for the experts when the action rules are globally compliant, the required quality and the optimal build time and cost are considered as reached.

Each section proposes the codification, mathematization and computation algorithms for action rules in providing explanations and details.

4.1 AR1 – Minimize part shadow on start plate

4.1.1 Codification

In its expression, this action rule includes the concept “Minimize” which is classified in the category *Action* in section 3.1. The concept “part” refers to the whole geometry of interest. Thus, based on the classification given in section 3.1, the corresponding shape entity is the *volume*. The composition of the codified action rule is given by Fig. 4.1.



Figure 4.1: AR1 codified and concept classification

4.1.2 Mathematization

Experts stated that this action rule aims at increasing the nesting density (Grandvallet et al. (2020)). By definition, minimizing object’s shadow on the start plate consists of minimizing its occupancy extent. Thus, the variable that is likely to change the occupancy is the object’s orthogonal projected area. Three projection possibilities can be used as previously discussed in Fig. 3.7. In the context of PBF, the value from Fig. 3.7b is chosen since other parts could occupy the void parcels. Details on the modeling of this action rule are given by the graph in Fig. 4.2.

As no attribute has been specified, the second box of the step 0 returns the whole part; this is referred to as “whole” in Fig. 4.2.

The evaluation concept “shadow on start plate” is measured with respect to the variable A_s that corresponds to the projected area of the part, the corresponding relation is given in Eq. 4.1. By varying the orientation handles, the value of the projected area A_s will vary between A_{smin} (the minimum projected area) and A_{smax} (the maximum projected area) found when sweeping the domain.

$$EC = \frac{A_s - A_{smin}}{A_{smax} - A_{smin}} \quad (4.1)$$

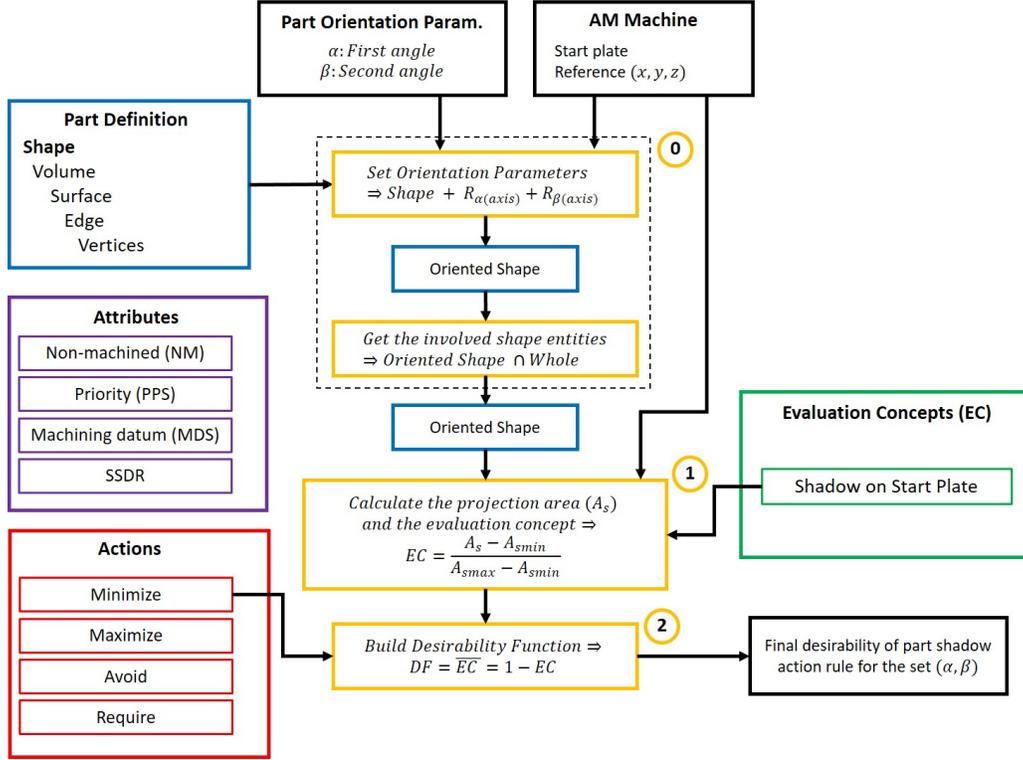


Figure 4.2: Desirability evaluation process for AR1

The relational function is then a simple growing function bounded by A_{smin} and A_{smax} as shown by Fig. 4.3a. Owing to the prescribed action “Minimize”, the resulting desirability function is the negation of the relational function; it is given by Eq. 4.2 and depicted in Fig. 4.3b. In other words, great shadow area is not desirable, while a small one is desirable. No averaging operator is needed, because this applies to whole volume. In this specific action rule, the threshold values of projected area are not predefined by experts. They entirely depend on the geometry.

$$DF(A_s) = 1 - EC(A_s)$$

$$DF(A_s) = 1 - \frac{A_s - A_{smin}}{A_{smax} - A_{smin}} \quad (4.2)$$

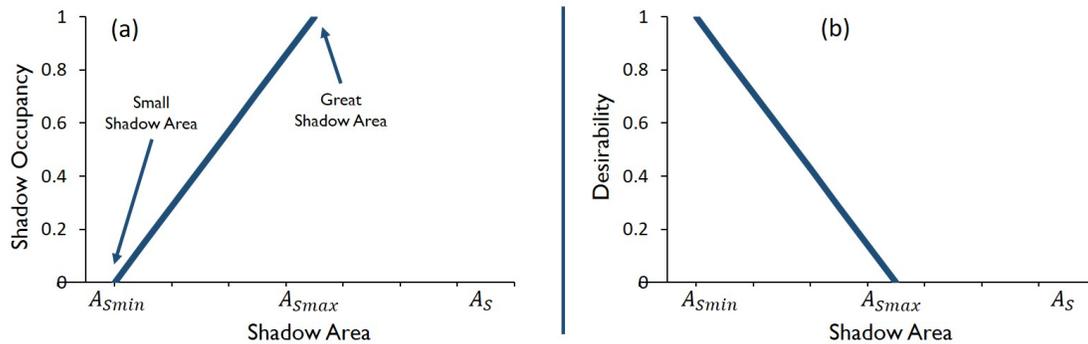


Figure 4.3: AR1 - Quantitative representation model: (a) Relational function; (b) Desirability function

4.1.3 Computation Algorithm

To compute the shadow area, the whole volume is projected on a plane that has the normal direction $\vec{z}_0(0, 0, 1)$. The CAD library (Opencascade) used does not allow getting the area of the projection since all of the lines of the part's top skin are projected. For this reason, another method is used. First, the bounding box of the part is determined, then, a pixel grid is created on the top rectangle of the box. A function checks whether a line traced from the center of each pixel intersects the part or not. If this is case, the pixel's area is added to the area of the shadow, otherwise it is eliminated. Fig. 4.4 shows an illustration of shadow print on the start plate by using the pixel-ray tracing method. It gives the occupancy as required. In fact, other parts can be inserted in the void spaces, even inside the holes of the part to enhance the productivity.

4.2 AR2 – Minimize total overhanging non-machined surfaces

4.2.1 Codification

The action “minimize” is used to indicate the purpose; the codification does not change the concepts in this action rule. In accordance with the categories given in section 3.7, the concepts are classified as shown in Fig 4.5. The attribute “non-machined” indicates the surfaces of the part to which the rule applies. Regarding the action, one could also change it to “avoid” but in this case, desirability compensation effects would not exist.

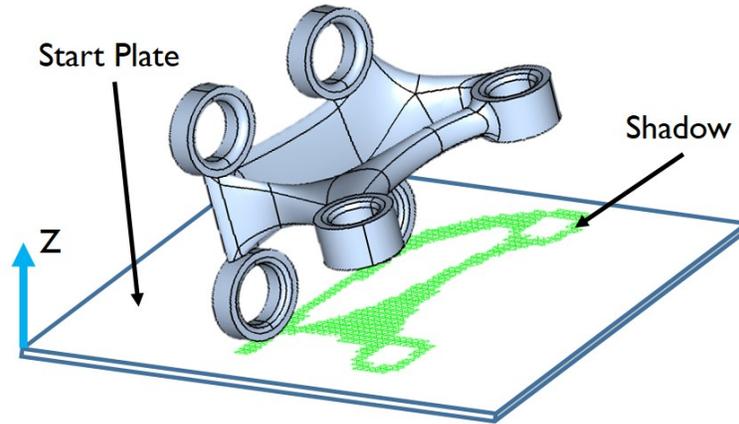


Figure 4.4: Illustration of part shadow on start plate

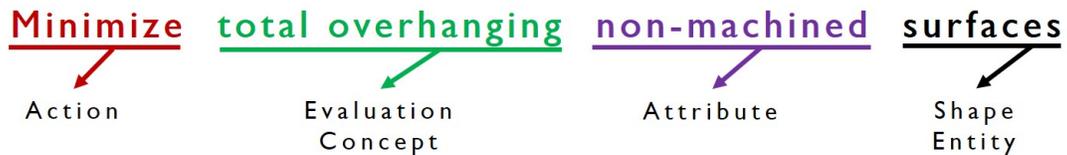


Figure 4.5: AR2 codified and concept classification

4.2.2 Mathematization

A surface is qualified as overhanging when the angle between its normal and the negative vertical (i.e. its tangent angle from the horizontal) is in a certain range of value (see Fig. 2.4). Based on this definition, the fact that a surface is overhanging can be controlled through this angle. Thus, here, the variable of the surfaces of interest is the angle θ . The latter is obtained for each surface as no global measure of θ can be provided for the whole part. This measurement is only done for non-machined surfaces.

Function of the values of θ of the surface ($\theta \in [0, \pi]$), the evaluation concept varies between 0 and 1 which are two states that respectively correspond to “not overhanging” and “overhanging”. Eq. 4.3 provides a description of the influence of the variable on the evaluation concept. The desirability function is the opposite of the relational function due to the action “minimize” ($DF = \overline{EC} = 1 - EC$). Fig. 4.6a and Fig. 4.6b show respectively the corresponding relational function and

desirability function.

$$\begin{cases} EC = 1 & \text{if } 0 \leq \theta \leq \theta_1 \\ EC = \frac{\theta_2 - \theta}{\theta_2 - \theta_1} & \text{if } \theta_1 < \theta < \theta_2 \\ EC = 0 & \text{if } \theta_2 \leq \theta \leq \pi \end{cases} \quad (4.3)$$

Below the value of θ_1 , the surface is overhanging, between θ_1 and θ_2 the surface gradually goes out of the overhanging range. As aforementioned, within the interval $[\theta_1, \theta_2]$ the value is not certain but if $\theta_1 = \theta_2$ the relational function simply becomes a binary one. Then, when θ is greater than θ_2 , the surface is no longer considered as overhanging until it reaches π . The values of the thresholds θ_1 and θ_2 highly depend on the material and the machine used. Usually, the value of θ_2 is known as support structures threshold or limit. Values from 30° to 50° can be found Calignano (2014). In the context of this work, the involved experts indicated the following values for the angles: $\theta_1 = 30^\circ$ and $\theta_2 = 50^\circ$.

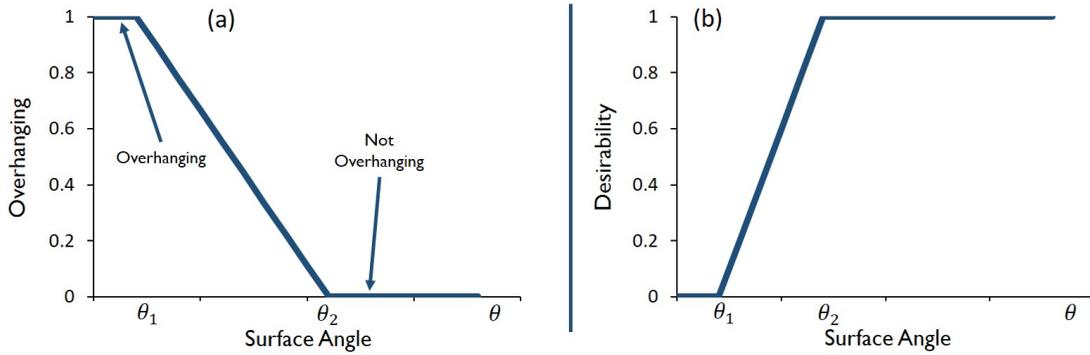


Figure 4.6: AR2 - Quantitative representation model: (a) Relational function; (b) Desirability function

The "overhanging level" is a local characteristic of a surface, which should be evaluated on each single point of a complex shape. Thus overhanging evaluation is performed on each single elemental surface through a tessellation process. Therefore, the total desirability of the part is calculated by using an averaging operator; here, an arithmetic mean weighted by the relative area (Eq. 4.4) as the action is "minimize" that allows compensations.

$$D_{part} = \sum_{j=1}^m r_j d_j \quad (4.4)$$

$$r_j = A_j/A_{total} \quad (4.5)$$

$$A_{total} = \sum A_j \quad (4.6)$$

Fig. 4.7 summarizes all of the modeling of this action rule about the minimization of overhanging non-machined surfaces. For a given part, the sequence is to set the orientation (α, β) , get the oriented non-machined surfaces, tessellate them and calculate the normal of each triangle. Then based on the graph in Fig. 4.6b, their desirability values (d_j) are calculated. The Eq. 4.4 is finally used to evaluate the overall part's desirability.

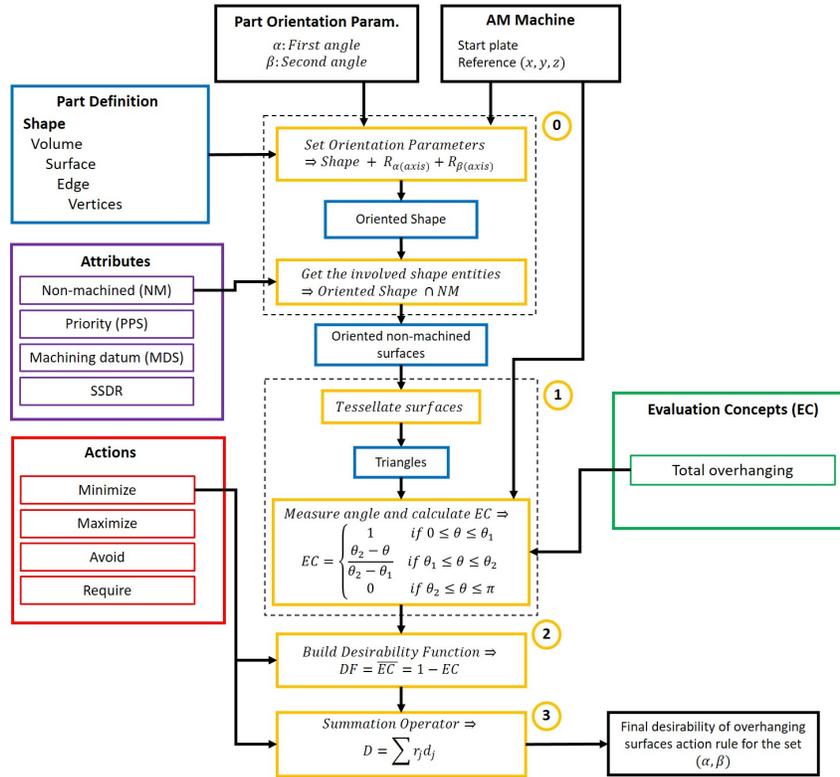


Figure 4.7: Desirability evaluation process for AR2

4.2.3 Computation Algorithm

As said in previous section, the local overhanging characteristic of a free-form surface is evaluated through a tessellation process, meaning discretization of the continuous geometry into a set of flat triangles. Calculating the normal for those geometrical entities is quite simpler. For triangle ABC (A, B and C are vertices in counter clockwise order as seen from outside of the part), the normal \vec{n} consists of the cross product between \vec{AB} and \vec{AC} . To get the orientation of the triangle, the angle θ between its normal and the reference $-\vec{z}$ is calculated (this is equivalent to the angle between the tangent vector and the start plate). That is measured by applying the dot product between $-\vec{z}$ and the normal \vec{n} . The result will be in the interval $[0, \pi]$, a vertical surface corresponds to when $\theta = \pi/2$ as well. Some CAD tools or libraries are also able to directly give the normal vector from complex surfaces (Rhinoceros), but still, it will be calculated at several different points.

4.3 AR3 – Orient Priority Surfaces Close to Vertical

4.3.1 Codification

Based on the explanations given in section 2.2.2.3, it can be inferred that the main objective is to have as many priority surfaces as possible oriented near vertical. Then, the possible actions are “Maximize” and “Require”. As it is most the of times impossible to get all priority surfaces “close to vertical”, it is necessary to enable desirability compensation i.e. if one of those surfaces has a weak desirability, the others will compensate it. Therefore, the action rule becomes that in Fig. 4.8. Otherwise, choosing “Require” would result in zero desirability for several orientations or possibly for all of the analyzed orientations.

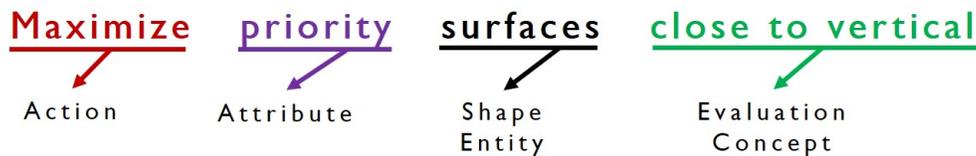


Figure 4.8: AR3 codified and concept classification

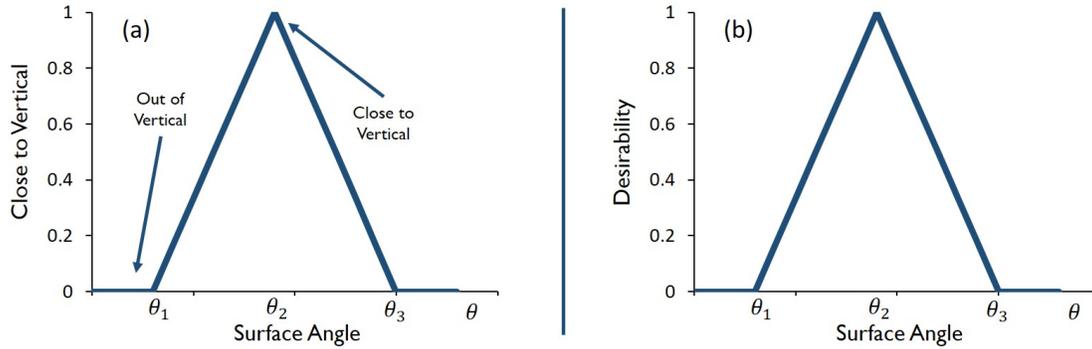


Figure 4.9: AR3 - Quantitative Representation Model: (a) Relational function; (b) Desirability function

4.3.2 Mathematization

In AM, surfaces oriented vertically or close to have better quality, that is why the industry practitioners aim at orienting the priority surfaces (very important surfaces of the part) close to vertical through this rule. The fact that a surface is close to vertical is governed by its angle θ . As said for AR2, the angle cannot be evaluated globally on the part, thus it is measured locally on each of the involved surfaces. Given that the vertical position corresponds to when $\theta = \theta_2 = \pi/2$, the equation 4.7 summarizes the evaluation concept “close to vertical”. From 0 to θ_1 , and θ_2 to π the surface is considered totally out of vertical. Between θ_1 and θ_2 the surface gets closer and closer to the vertical then from θ_2 to θ_3 , it is less and close to vertical.

$$\begin{cases} EC = 0 & \text{if } 0 \leq \theta \leq \theta_1 \\ EC = \frac{\theta - \theta_1}{\theta_2 - \theta_1} & \text{if } \theta_1 < \theta < \theta_2 \\ EC = \frac{\theta_3 - \theta}{\theta_3 - \theta_2} & \text{if } \theta_2 \leq \theta < \theta_3 \\ EC = 0 & \text{if } \theta_3 \leq \theta \leq \pi \end{cases} \quad (4.7)$$

From the definition of the evaluation concept, the relational and desirability functions are drawn in Fig. 4.9. Due to the action used, the desirability function is equivalent to the relational function, $DF = EC$.

The values of threshold given by the experts are $\theta_1 = 45^\circ$, $\theta_2 = 90^\circ$ and $\theta_3 = 135^\circ$. For this function, one could also put a plateau at the place of the peak point θ_2 by adding a point, but this depends on the acceptable range of verticality. The whole model of this action rule is represented in Fig. 4.10. A combination operator is also used to get a

global desirability of the part for each set of parameters. Since the action is “maximize”, this operator is compensatory and weighted by the relative area $r_j = A_j/A_{total}$ (Eq. 4.8).

$$D_{part} = \sum_{j=1}^m r_j d_j \quad (4.8)$$

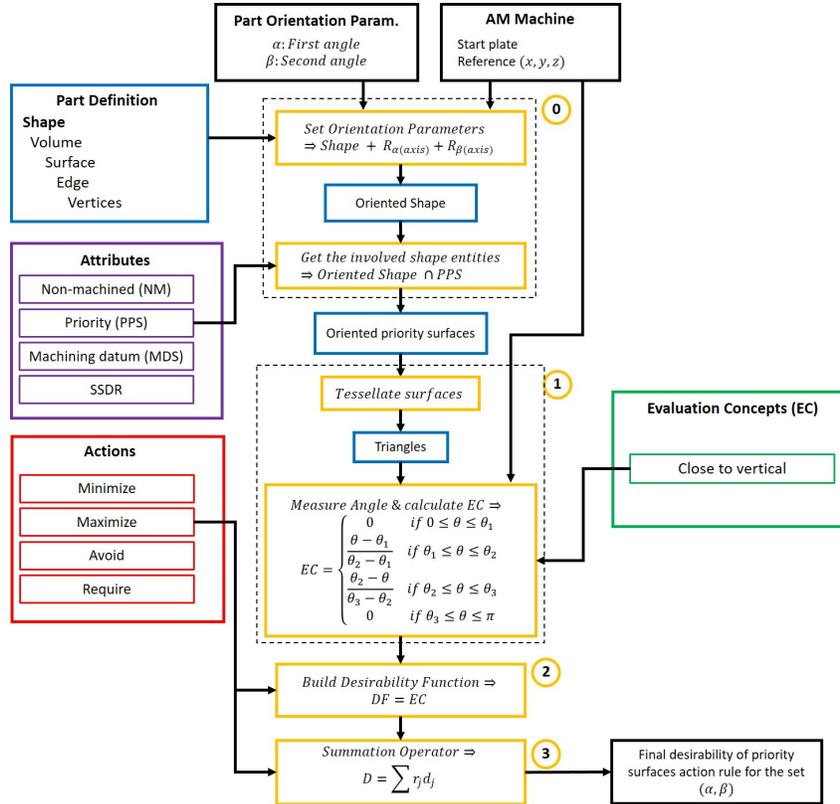


Figure 4.10: Desirability evaluation process for AR3

4.3.3 Computation Algorithms

As the variable of interest is the angle, please refer to the section 4.2.3. The same algorithm is used.

4.4 AR4 – Orient machining datum surfaces out of horizontal

4.4.1 Codification

Machining datum surfaces allow the positioning of the part for post machining. If they are positioned horizontally (close to 0° or close to 180°), they might exhibit geometrical distortions that would clearly compromise the precision of the machining. During the discussion with experts, this rule has been stated as: “Orient the machining datum surfaces out of horizontal” (Grandvallet et al. (2020)). Hence, a codification is required to bring out the objective of the rule. Here, the verb “Orient” is replaced with the action “Require” because the involved surfaces are of a great importance since they govern the quality of all the machined surfaces. Using this action means that, whenever one of those surfaces orientation is undesired (desirability equal to zero), the whole part orientation is undesired for the given set of CAM parameters. The classification of the concepts is shown in Fig. 4.11.



Figure 4.11: AR4 codified and concept classification

4.4.2 Mathematization

Similarly to the priority surfaces case, here, the evaluation concept “out of horizontal” is directly influenced by the inclination of the surface in question. Thus, the identified variable is the surface angle θ ($\theta \in [0, \pi]$) as in AR2 and AR3. Eq. 4.9 provides the definition of the evaluation concept with respect of the variable measured for each triangle as the datum surfaces are tessellated. Instead of having a peak for the vertical point, a plateau is defined since the rule only aims at avoiding the horizontal positions i.e. when $0 \leq \theta \leq \theta_1$ and $\theta_4 \leq \theta \leq \pi$.

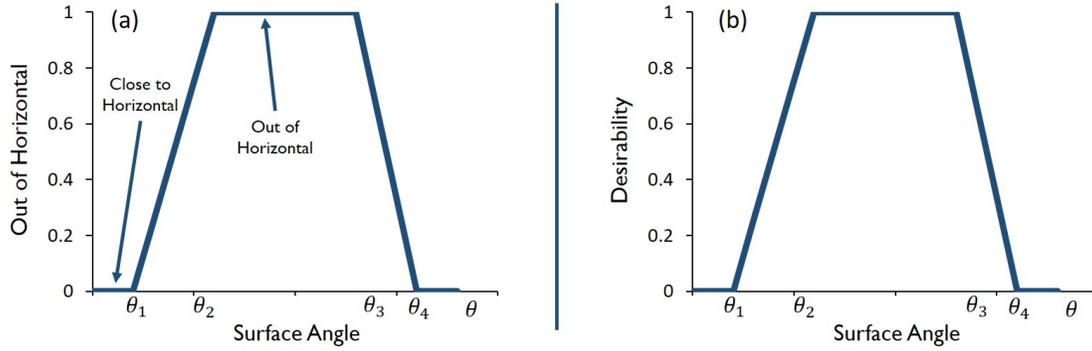


Figure 4.12: AR4 - Quantitative Representation Model: (a) Relational function; (b) Desirability function

$$\begin{cases} EC = 0 & \text{if } 0 \leq \theta \leq \theta_1 \\ EC = \frac{\theta - \theta_1}{\theta_2 - \theta_1} & \text{if } \theta_1 < \theta < \theta_2 \\ EC = 1 & \text{if } \theta_2 \leq \theta < \theta_3 \\ EC = \frac{\theta_4 - \theta}{\theta_4 - \theta_3} & \text{if } \theta_3 \leq \theta < \theta_4 \\ EC = 0 & \text{if } \theta_4 \leq \theta \leq \pi \end{cases} \quad (4.9)$$

Resulting functions in Fig. 4.12a and Fig. 4.12b are respectively the relational and desirability which are equal cause of the action “Require” ($DF = EC$). For this rule, the experts provided the following values for the points: $\theta_1 = 20^\circ$, $\theta_2 = 60^\circ$, $\theta_3 = 130^\circ$ and $\theta_4 = 160^\circ$. It can be noticed that this function is not symmetrical with respect of the vertical point. Indeed, on the left side between $[0, \theta_2]$ the considered datum surface might be overhanging and thus might need support structures to be manufactured. As a consequence, this datum surface will have support marks that also need to be machined. To avoid this, the value of θ_2 needs to be greater than the overhanging limit which was defined at 50° in AR2.

Here, the operator combining the m local desirability values on the whole part is the geometric mean (Eq. 4.10) weighted by the relative area $r_j = A_j/A_{total}$. The graph corresponding to the modeling of this rule is given by Fig. 4.13.

$$D_{part} = \prod_{j=1}^m d_j^{r_j} \quad (4.10)$$

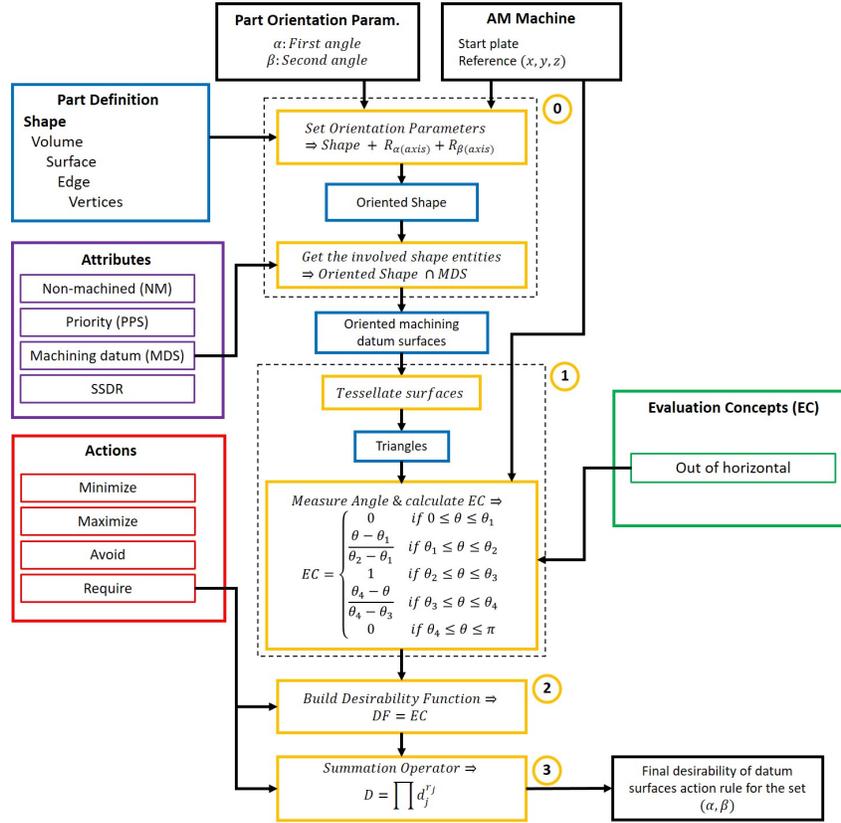


Figure 4.13: Desirability evaluation process for AR4

4.4.3 Computation Algorithms

As the variable of interest is the angle measured between the normal \vec{n} and the negative vertical axis $(-\vec{z})$, please refer to the section 4.2.3. The same algorithm is used.

4.5 AR5 – Minimize Shape Deformation Risks

This action rule is about very complex phenomena taking place during the manufacturing process that lead to shape deviations from the theoretical design. The main shape

deviations are usually linked with two problems namely, the shrinkage and the warping effects. However, this action rule only treats the shrinkage effect.

4.5.1 Codification

Due to the presence of the action “minimize”, this action rule is considered as already codified. The concept of shape represents the whole part. Here, the evaluation concept is “Deformation Risks”.

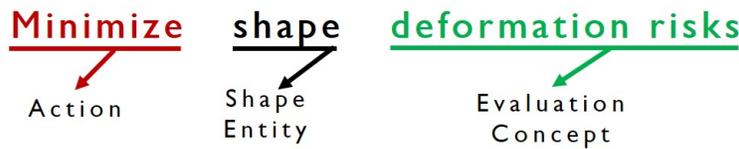


Figure 4.14: AR5 codified and concept classification

4.5.2 Mathematization

Identification & Measurement of the Variable.

The kind of shape distortion of interest is due to the stacking of long layers which progressively shrink each other as the part is built up. Referring to the definition in section 2.2.2.5, every deposited layer has an impact on the layers below it. By definition, one would choose to check the area of contact between the layers, but in reality, for experts and scientific collaboration team, the variable that reflects better the shrinkage is the layers intersection length (as reported by Vo et al. (2018); Ghaoui et al. (2020)). Actually, different reasons lead to prefer the length rather than the surface area. The cross sectional area of the thin wall in Fig. 4.15a is quite small, but its lower part is however likely to deform. If only large melt pool area is considered to be exposed, this example proves different. In Fig. 4.15b, the layers i and $i + 1$ have a great contact surface through the sum of the different island areas of $i + 1$. Nevertheless, the shrinkage of the latter will only locally affect the layer i , and the shrinkage deformation can barely be seen (negligible over the contour). Hence, it can be concluded that the length gives more information about the progressive shrinkage resulting from layers interaction. It has to be reminded that the aim is not to quantify the deformation, but to predict the risks of deformation through the desirability.

Through various observations, the contact length between two layers has been retained as more reflective of the deformation risks. Let’s consider the successive layers

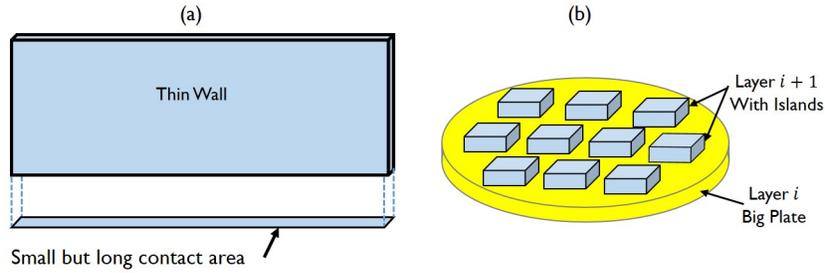


Figure 4.15: Variable pertinence

($i, i + 1, i + 2, i + 3, i + 4, i + 5$) belonging to a part of p layers; i being the layer of interest. The influence on the latter during the additive manufacturing (EBM) is broken down into steps below (illustrated by Fig. 4.16). Let's denote \cap_i^{i+u} the result of the intersections between the layers i and the layers $i + u$.

- Step 1: the first layer i is deposited and its only existing interaction occurs with the powder around. This layer shrinks freely.
- Step 2: the layer $i + 1$ is built over i . This layer shrinks and induces additional shrinkage to i . Their interaction zone ($\cap_i^{i+1} = i \cap (i + 1)$) has a maximum length of L_{max1} .
- Step 3: the layer $i + 2$ is built over i and $i + 1$. This layer shrinks and influences i and $i + 1$ through the interaction zone ($\cap_i^{i+2} = \cap_i^{i+1} \cap (i + 2)$). The max intersection length is L_{max2} .
- Step 4: the same phenomena as in step 3 occurs when the layer $i + 3$ is deposited ($\cap_i^{i+3} = \cap_i^{i+2} \cap (i + 3)$).
- Step 5 & 6: no intersection zone exist between them ($i + 4$ and $i + 5$) and the intersection result remains \cap_i^{i+3} .

Note: the maximum length in a contour is the magnitude of the vector connecting the two furthest points of the contour. However, the vector must be inside the closed contour, i.e. if the vector crosses a hole, the length is no longer valid.

Whenever, a void intersection exists, the influence is no longer transmitted to the layer considered, and the analysis can be stopped there. As aforementioned in the definition, the impact of each above layer onto i is not the same, thus, this work proposes to weight them basing on the influence function depicted in Fig. 2.8 (chapter 2). Note that the

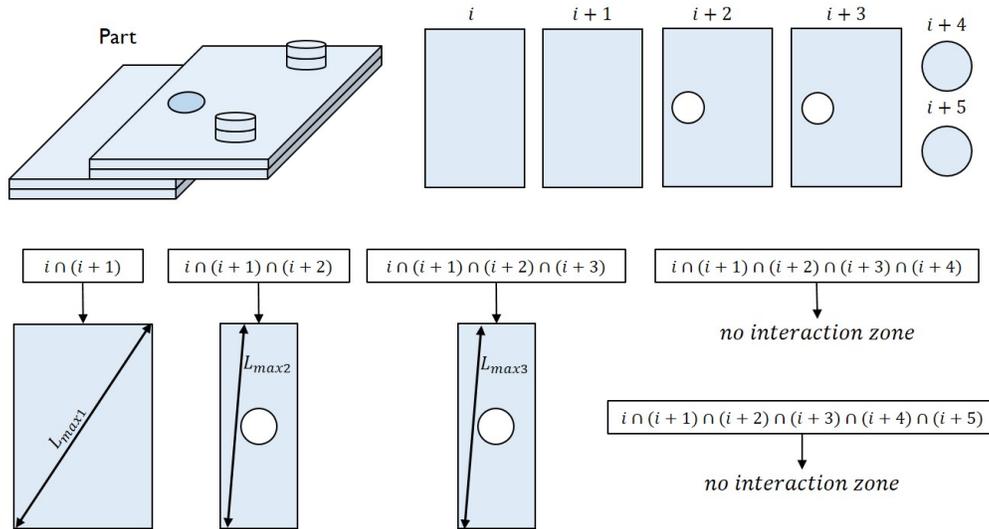


Figure 4.16: Layers intersections and maximum length

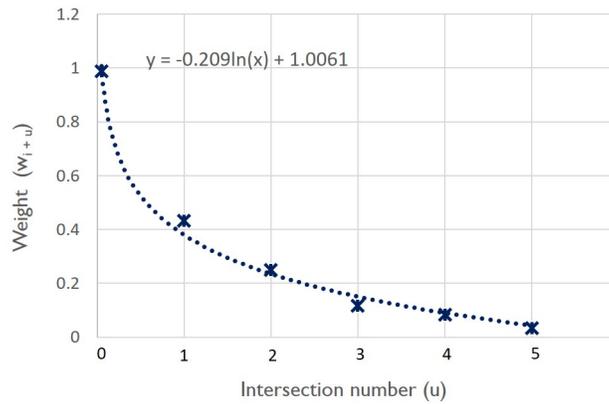


Figure 4.17: Shrinkage weighting function calculated from displacement function (chapter 2) for Ti6Al4V processed in EBM

data used for that chart are for Ti6Al4V (Ghaoui et al. (2020)); for other materials, extensive simulations are required. The weights are obtained by mapping the minimum and maximum values of displacement with 0 to 1 values (Fig. 4.17). The points in the chart are traced for super layers of 1mm thick.

Hence, weighted length are obtained by multiplying the maximum intersection length

with a value w between 0 and 1 (Eq. 4.11, where u is the intersection number). The total *weighted deformation length* for the layer of interest is given by the sum in Eq. 4.12. For each layer of the part, this value is then evaluated by considering the same number of layers above (h). The number h can be chosen around 100 layers (or 5 super layers of 1mm thick), because beyond this value, the layers above have very weak or null effect on the layer i .

$$l_{w_{i+u}} = w_{i+u} * L_{max_u} \quad u = 1, \dots, h \quad (4.11)$$

$$L_{w_i} = \sum_{u=1}^h l_{w_{i+u}} \quad (4.12)$$

For a given orientation of the part, the greatest weighted length is retained and will be used as value of the variable for calculating the desirability of that orientation. Measuring this layer intersection length on the part is quite complicated. First, a slicing is achieved to construct the different layers contour. Then, repeated contour intersections are performed between layers. After each intersection, hatching (Kurz et al. (1987)) with parallel lines is done inside the contour to find out the maximum layer length (details are provided in section 4.5.3).

Relational & Desirability Functions.

Based on the explanations provided above, the evaluation concept “deformation risks” can be calculated with respect to the weighed intersection length as shown by Eq. 4.13. Relational and desirability functions associated to this are depicted in Fig. 4.18a and Fig. 4.18b respectively. For this case $DF = 1 - EC$. The threshold indices a and b are used to avoid confusions with indices of Eq. 4.12.

$$\begin{cases} EC = 1 & \text{if } 0 \leq L_w \leq L_{wa} \\ EC = \frac{L_w - L_{wa}}{L_{wb} - L_{wa}} & \text{if } L_{wa} < L_w < L_{wb} \\ EC = 0 & \text{if } L_w \geq L_{wb} \end{cases} \quad (4.13)$$

When the total weighted length is less than L_{wa} , the deformation risks are very weak. Above this value the risk progressively increases until it is considered as great from L_{wb} . As a reminder, for a given orientation, the value of the variable retained is the maximum value among the calculated L_{w_i} . So, according to the resulting function, the good orientation is that one having a small intersection weighted length. The threshold values provided are $L_{wa} = 15mm$ and $L_{wb} = 100mm$.

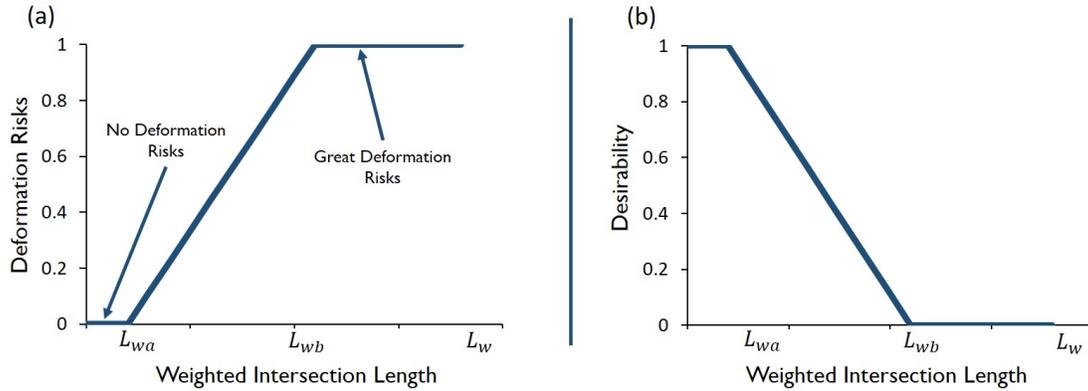


Figure 4.18: AR5 - Quantitative Representation Model: (a) Relational function; (b) Desirability function

4.5.3 Computation Algorithm

The variable of interest here is not a direct CAD variable that can be found in classical tools. Therefore, various operations are led to find it out (see below sections).

Slicing – When dealing with layers of a given geometry, one must necessarily perform slicing on that geometry. Slicing operations consist of the intersection between a geometry and a plane with the specified direction \vec{n}_p (Fig. 4.19). The result is an approximate contour of points ordered or not. It can be repeated from bottom to top of the part with a given interval called slice thickness. This operation is well known in additive manufacturing as it enables the so-called layer by layer manufacturing and today multiple tools are available for it (CURA). However, in the case of massive computation, the efficiency of those tools can be called into question.

In fact, in this work, the method is to compute hundreds of orientation desirability in order to give a set of solutions to analyze. Hence, the slicing is performed hundreds of times, i.e. for each orientation. This might require hours and hours depending on the geometry and the computer capabilities. For this reason, in this work, CPU and GPU parallel processing techniques (Park et al. (2013) and Navarro et al. (2014)) are used to shorten long processing times. For the libraries used, the slicing of only one orientation takes long duration. For instance, the turbine shown in Fig. 4.19 is processed in 35 seconds using Opencascade intersection classes. Then, by simply doing parallel processing in the CPU with the same classes, the time reduces to 9.5 seconds (for the same computer).

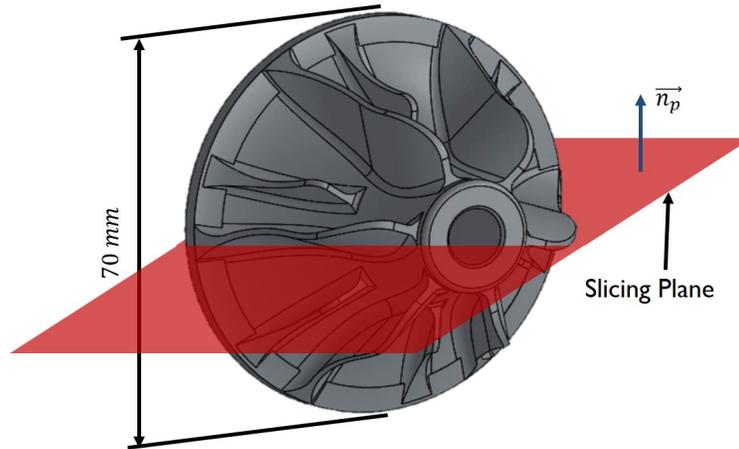


Figure 4.19: Example of part & plane intersection

To get better performances, GPU processing with the help of CUDA toolkit from NVIDIA has also been used. The slicing algorithm has completely been re-written because of the fact that CUDA can not consider objects (such as points, contours, surfaces etc.) from other libraries. So, only numbers, tables and characters have been used. Moreover, a faster way to do the slicing has been developed. In fact, the intersections are achieved on the tessellated geometry, making it possible to slice triangle by triangle on their whole height. Instead of searching the intersections of a plane with a triangle Fig. 4.20a, the routine simultaneously searches for the different slices of each triangle Fig. 4.20b. This has allowed to attain shorter processing times around 1 second for the turbine again.

The output of the slicing is a list of contour points that will be used in the continuous intersections.

Layer Iterative Intersection – This step allows getting the zone of interaction (represented by a contour) between two stacked layers. Especially, only the considered layer and the layer above are intersected, the following intersections are performed between the result of the previous intersection and the following layer above.

(see section 4.5.2 for more details).

Let's consider the two superposed contours in Fig. 4.21. The method used consists of searching which points of first contour are in the second one, and which points of the second contour are in the first one. The intersection points I_A and I_B are then calculated to close the contour of the interaction zone.

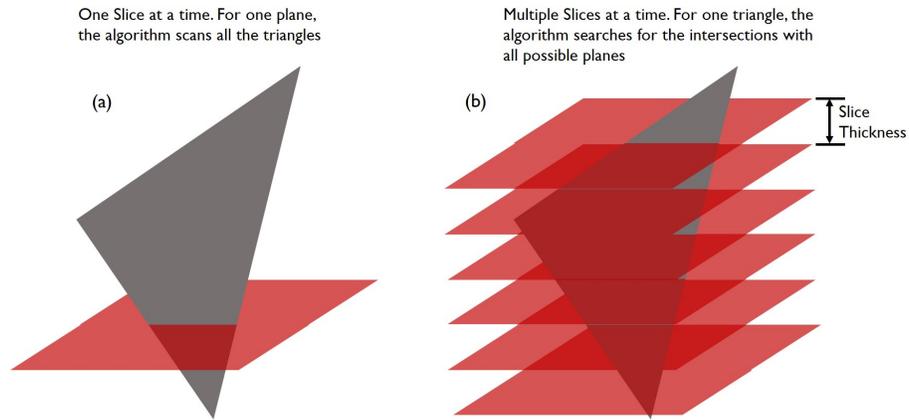


Figure 4.20: Two slicing sequences: (a) Scanning triangles with one plane; (b) Scanning planes simultaneously with one triangle

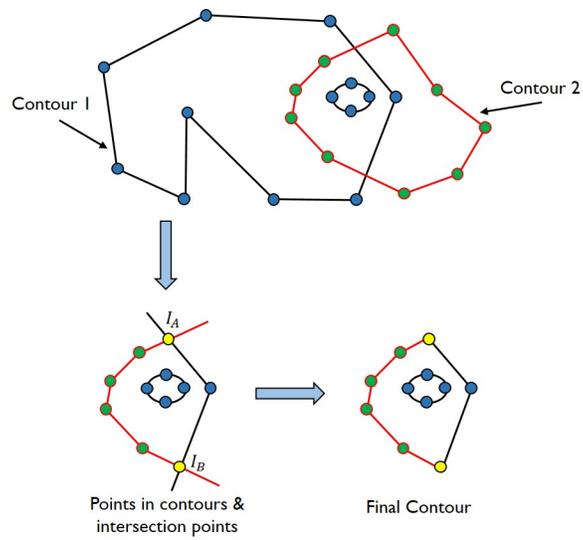


Figure 4.21: Illustration of contour intersection

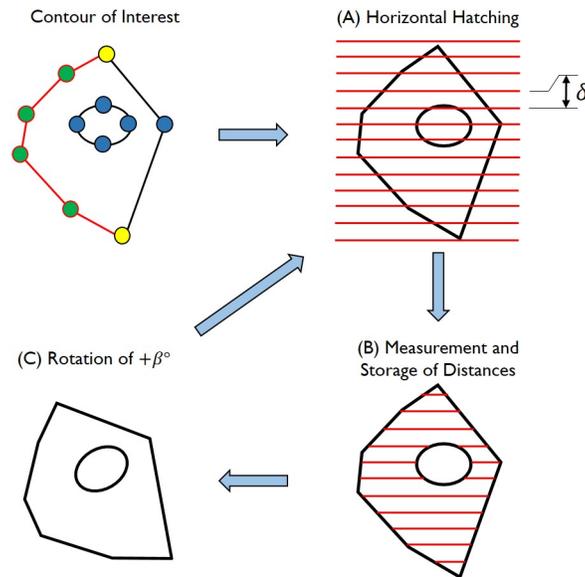


Figure 4.22: Illustration of multi-directional hatching for contour maximum length measurement

Measurement of Maximum Length – At each intersection, the maximum length inside the contour is searched and saved. The maximum length is the magnitude of the vector made of the two furthest points of the contour. A condition for this measurement is that the vector’s line must not cut any other edge of the contour in question. It is not trivial to find algorithms dedicated to this type of measure. In the view of that, multi-directional hatching is proposed here. It consists of drawing horizontal parallel lines with constant spacing δ , over the contour Fig. 4.22. For each line, the intersection points with the contour are calculated; then, distances between points are calculated and stored. After doing that for all the lines, the contour is rotated of β degrees around the axis centered in O . The smaller the values of β and δ , the more accurate the measurement is. Steps (A) then (B) are repeated at each increment of β from 0° to 180° . The final maximum length is the maximum of list of all of the calculated distances.

Finally the whole algorithm for the measurement of the variable “*Layer Intersection Maximum Length*” is shown in Fig. 4.23. Note that the denotation \cap_i^{i+u} designate the results of the iterative intersections.

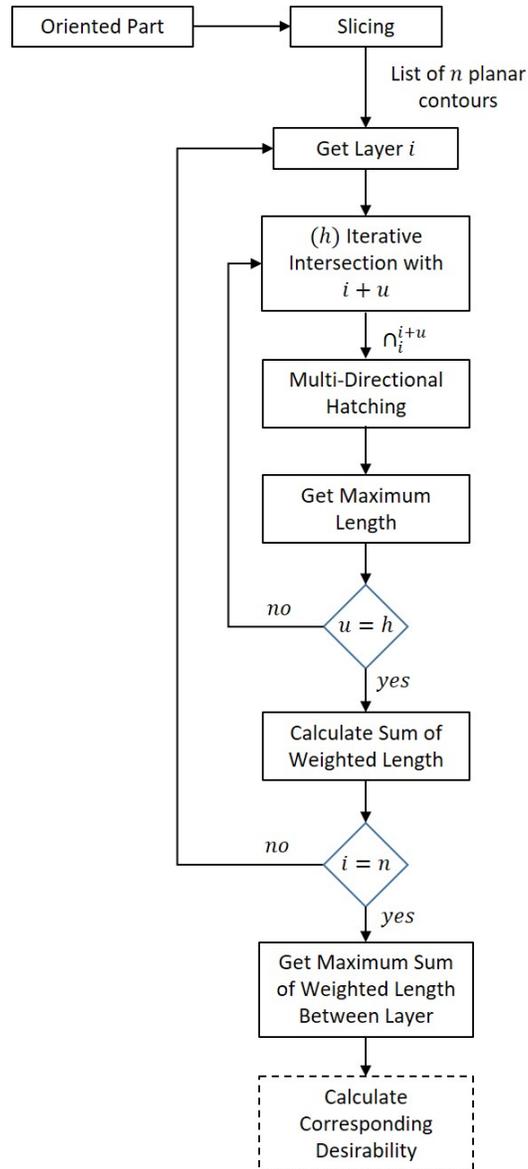


Figure 4.23: Continuous layer intersection full algorithm

4.6 AR6 – Avoid Support Structures & Support Removal Difficulty on Surfaces with Potential Support Difficult to Remove (SSDR)

This rule suggests taking account of the support removal difficulty. In PBF, a tool is used to remove the support structures after manufacturing. For this reason, the accessibility needs to be considered. Here, by making the assumption that the support is difficult to remove when the surface in question has another one in front of it, the removability depends on the distance between the two opposite surfaces. Then, a surface is qualified as a SSDR, when its accessibility is limited by the other surrounding surfaces.

4.6.1 Codification

No codification is required for this rule. The concepts are classified in Fig. 4.24. This action rule is a special case as it has two evaluation concepts that are support structures and support removal difficulty. Therefore, two influence variables will be involved.



Figure 4.24: AR6 codified and concept classification

4.6.2 Mathematization

Identification & Measurement of Variables for Evaluation concepts A & B.

The evaluation concept *A* is nearly the same as that of AR2 (overhanging), which was influenced by the surface angle θ . Usually, the overhanging threshold angle is the same as that of support structures requirement. The surface angle is measured the same way; tessellate the surface, get facet normal and perform dot product with negative \vec{z} .

As exposed in the definition of this action rule (see section 2.2.2.6), the evaluation concept *B* is governed by the minimal gap distance (l) between the considered surface

and the other surfaces around. Ray tracing methodology is used to measure the distances from the considered elemental surface to the others. In fact, from different points of a given elemental surface, different lines from normal of points are traced (Fig. 4.25). Some conditions must be fulfilled to check whether a surrounding surface bothers.

- First, as only the faces in the front are searched, the dot product between the normal (\vec{n}) and the directional vectors (\vec{d}_i) of the traced lines must be positive (Eq. 4.14).

$$\vec{n} \cdot \vec{d}_i > 0 \quad (4.14)$$

- The intersected surfaces must be opposite to the considered one, i.e. the dot product between the normal (\vec{n}) and the surrounding surface normal (\vec{n}_j) must be negative (Eq. 4.15).

$$\vec{n} \cdot \vec{n}_j < 0 \quad (4.15)$$

- Finally, the distance between the incircle center G and the intersection point I with the surface j must be less or equal to a predefined threshold distance l_0 (Eq. 4.16). The latter can for example, be the diameter of the available cutting tool.

$$\| \vec{GI} \| \leq l_0 \quad (4.16)$$

Relational & Desirability Functions.

The fact that a surface is a SSDR is given by the intersection of the support structures requirement (A) and support removal difficulty existence (B). Relational functions corresponding to A and B are depicted in Fig. 4.26a and Fig. 4.26b respectively. To obtain the desirability function, let's refer to the following reformulation of the action rule:

$$AR6 = \text{Avoid } A \text{ and } B \text{ on SSDR} \quad (4.17)$$

Due to the action "Avoid" the desirability is the negation of the evaluation concepts, then, the desirability is:

$$DF = \overline{A \text{ and } B} \quad (4.18)$$

By applying the De Morgan's laws, this becomes:

$$DF = \overline{A} \text{ or } \overline{B} \quad (4.19)$$

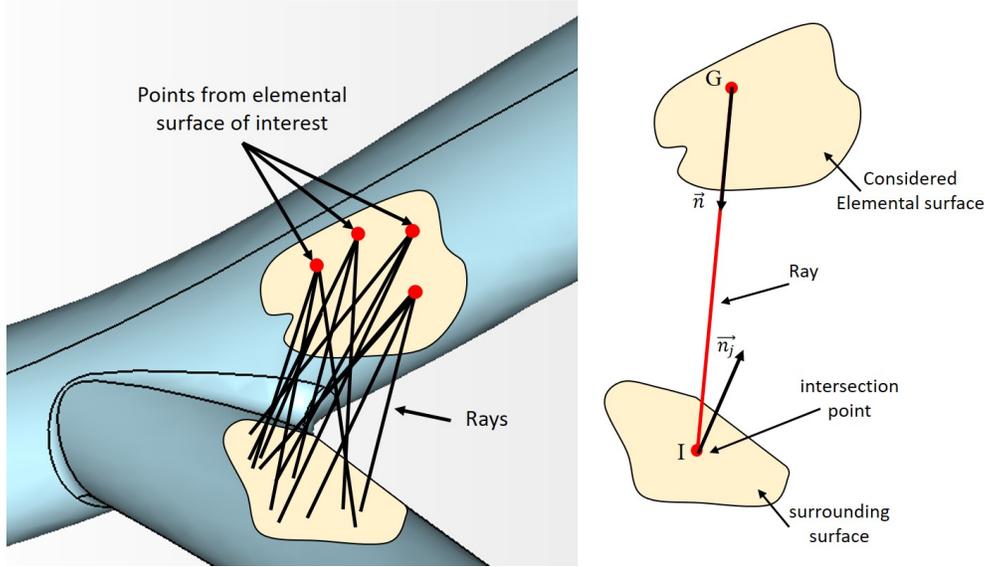


Figure 4.25: Ray tracing for detecting surface accessibility

For a given surface j of a part, its desirability (d_j) is calculated based on each of the two evaluation concepts. However, two values of desirability are obtained, and the global one is calculated according to the operator in the action rule (*AND/OR*). Here, with the transformation performed, the operator is *OR*; the corresponding value is the maximum between the desirability \bar{A} (d_{jA}) and that of \bar{B} (d_{jB}) (refer to section 3.3.3.3, *Definition 3*). Thus, the Eq. 4.20 is used. Following this, the global desirability of the part is calculated by using the geometric mean (Eq. 4.21) weighted by the relative area $r_j = A_j/A$.

$$d_j = \max(d_{jA}, d_{jB}) \quad (4.20)$$

$$D_{part} = \prod_{j=1}^m d_j^{r_j} \quad (4.21)$$

The satisfaction of one of those conditions \bar{A} or \bar{B} is enough to say that the action rule is fully compliant for the considered surface. The *AND* operator has been changed into an *OR* operator. Logically, if there is no removal difficulty, one can put support. In the same logic, if no support is required, no matter the removal difficulty. This transformation has simplified the handling of the AR6.

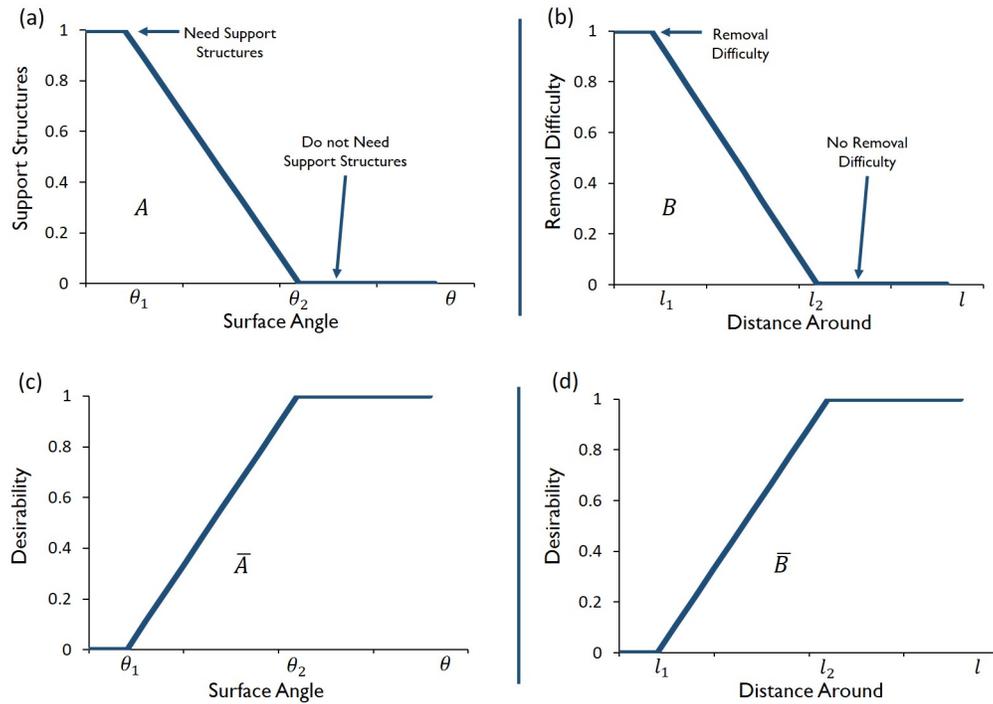


Figure 4.26: AR6 - Relational functions: (a) Support structures requirement with respect of the angle; (b) Removal difficulty with respect of distance; (c) Negation of A – Desirability function; (d) Negation of B – Desirability function

The threshold values are for A $\theta_1 = 30^\circ$ and $\theta_2 = 50^\circ$ and for B l_1 and l_2 entirely depend on the support removal tools that the post-processing team have access to. As an example, if the tool has a diameter of $30mm$, the thresholds values can be $l_1 = 10mm$ and $l_2 = 30mm$.

4.6.3 Computation Algorithm

Many details about the measurement of this variable have been provided in the definition and description of surfaces with potential support difficult to remove (see section 4.6.2 about SDR). As exposed, the surface accessibility is driven by the distance of the surfaces around the considered one. In fact, the cutting tools used to remove supports must be able to freely touch the surface of interest. Therefore, the distance or space between the latter and the surfaces around is defined as the variable influencing the accessibility.

To measure the relative distance between one surface and another, ray tracing is used. First, the surface is discretized into small triangles. From the center of each triangle, outgoing rays with different directions are traced. Then, the intersections of those rays with the surrounding surfaces are searched (please refer to Fig. 4.25). The distance between the intersection point and the center of the considered triangle is calculated, and will represent the accessibility according to a minimal accepted distance such as the diameter of a cutting tool.

4.7 Summary & Conclusion

In this chapter, the modeling of the industrial action rules about the part orientation has been carried out. All action rules have then been transformed into quantitative entities (summarized in Table 4.1), and the process showed a variety of variables that are not trivial to calculate manually.

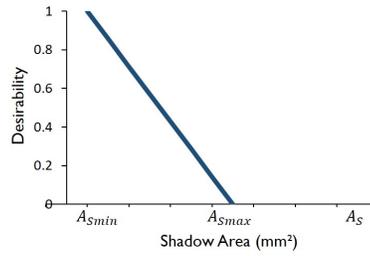
- For the evaluation concepts overhang (AR2), close to vertical (AR3), out of horizontal (AR4) and support structures (AR6), the identified variable is the angle of the surface of interest. This is relatively simple to measure.
- For deformation risks, the identified variable was the layers intersection length for which the measurement requires a set of complex CAD operations and experimental results.
- The AR6 illustrated the case of an action rule with two evaluation concepts to combine. One was measured with respect to the angle (support structures), the other one with respect to the accessibility of the surfaces (removal difficulty). A transformation with respect to the De Morgan laws has simplified the construction of the desirability functions.

Also, for each built desirability function the threshold values are provided. For a given company and a given process, this work of mathematical representation is only achieved once, then the models can be used anytime some optimal CAM parameters need to be computed. The action rules presented here can be adapted and used by other companies or research teams.

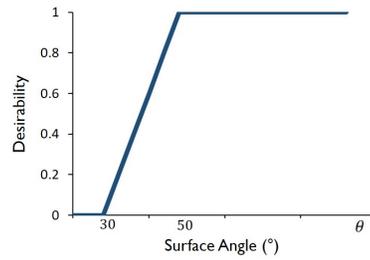
Table 4.1: Summary of modeled action rules

Codified Action Rules	Desirability Functions
-----------------------	------------------------

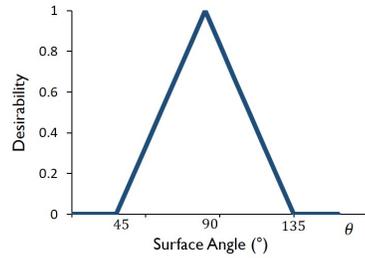
AR1. Minimize
Volume Shadow on
Start Plate



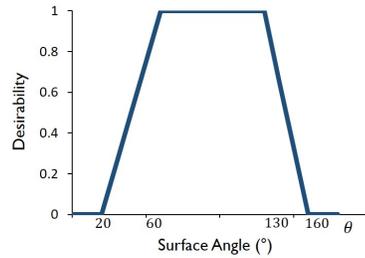
AR2. Minimize
Total of
Overhanging
Non-Machined
Surfaces



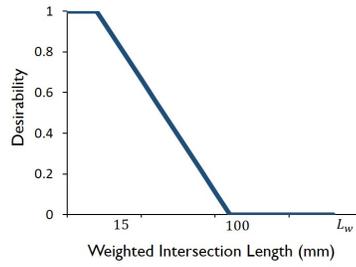
AR3. Maximize
Priority Surfaces
Close to Vertical



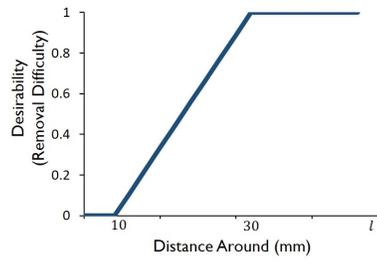
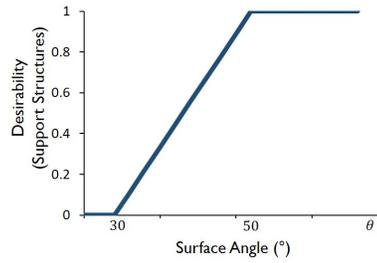
AR4. Require
Machining Datum
Surfaces out of
Horizontal



AR5. Minimize
Shape Deformation
Risks



AR6. Avoid
Support Structures
and Support
Removal Difficulty
on SSDR



Chapter 5

COFFA: Knowledge-based Assistance of Part Orientation Definition in AM

Introduction

Knowledge based systems for manufacturing need a well designed tool assisting the decision making process. As presented in the previous chapters, a whole framework has been designed to include as efficiently as possible the knowledge of experts in the CAM procedure and particularly for the definition of the part orientation. This chapter presents the COFFA tool and which is designed for computing part orientation desirability and assisting the decision making. It has to be reminded that the purpose of this work is not to provide optimal solutions, but to assist the decision making among various solutions.

The present chapter firstly presents the composition and design of the tool for computing part orientation desirability, then, some tools to help the decision makers. In the third part, case studies of orienting industry parts are presented. Finally, results from tests carried out with engineering students are presented. The action rules discussed in chapter 4 are used for all of the examples and applications that will be presented.

5.1 Tool for Computing Part Orientation Desirability

The modeling of the action rules has shown that various types of variables might be

evaluated on parts (see chapter 4). It would be delicate to manually evaluate the different ARs, and it is even impossible for some of them. That is why, an interactive tool named COFFA is proposed and described in this section. Its purpose is not to automatically select an orientation (α, β) , but to compute the desirability of different scenarios, so that the CAM engineer or operator can analyze and choose among them. To ease the use, some minimal functionalities are required as listed from 1 to 7. All of the developments and algorithms are coded in C++ language.

1. **Expertise resource description framework (XRDF) file reader** – An XRDF file contains the action rules and their quantitative representation models or desirability functions. Its structure and the data stored are detailed in Appendix A. In the COFFA tool, a parsing algorithm is made to classify important elements required to the computation of orientation desirability.
2. **Geometry importation and interactive viewing** – Standard exchange file formats STL and STEP are used to import information relative to the part's geometry. Opencascade technology provides classes for reading such files. When opened, all the necessary data are automatically parsed and saved in structured containers as BRep entities. To enable a good sight of the processed part, a viewer is also developed based on some classes from by Opencascade libraries. This is encapsulated in a QT window and includes classical interaction tools: rotating, panning, zooming and selecting specific view point (front, back, left, right, top and bottom views).
3. **Selection of shape entities with attributes** (for details about attributes, see section 3.1) – One of the most needed features in this work is the ability for a CAM engineer to interactively add attributes to specific surfaces of a part, and consider them specifically in the solving algorithms. A selection manager is developed to this end. A container is created for each attribute (e.g. container of priority surfaces), so that the selection manager can classify the selected surfaces. When a surface is clicked from the viewer, a virtual function queries its id and creates a copy of it in the dedicated container. Later on, they will be used in computation algorithms.
4. **Definition of orientation range to explore** – see section 5.1.1
5. **Computation algorithms for each type of evaluation concept** – The computation algorithms are written for evaluating the desirability of an action rule on a part. For the evaluation concepts shadow on start plate, overhang, support structures, support removal difficulty, close to vertical, close to horizontal and deformation risks, algorithms are detailed in chapter 4.

- 6. **Presentation of the computation results in a comprehensive way** – see section 5.1.2
- 7. **User friendly design** – see section 5.1.3

5.1.1 Definition of Orientation Range to Explore

For comparison purposes, different orientation scenarios desirability need to be computed. Rotation matrices of type Tait-Bryan (Dawson (2012)) are used to achieve this. The labels α , β and γ in the matrices represent the first, second and third rotation angles respectively and the letters c and s are the angles cosine and sine respectively. Six sequences of rotations are possible $X_\alpha Y_\beta Z_\gamma$, $X_\alpha Z_\beta Y_\gamma$, $Y_\alpha X_\beta Z_\gamma$, $Y_\alpha Z_\beta X_\gamma$, $Z_\alpha X_\beta Y_\gamma$ and $Z_\alpha Y_\beta X_\gamma$. For each sequence there is a dedicated rotation matrix as in the example of Eq. 5.1. In the latter, the rotations are successively performed around the axes OX , OY then OZ ; this matrix will be used in all the examples presented in this document. According to the definition of part orientation in AM, only two angles are enough to define a position. Thus, the third member of the Eq. 5.1 can be set up to zero ($\gamma = 0$).

$$X_\alpha Y_\beta Z_\gamma = \begin{pmatrix} c_\beta c_\gamma & -s_\beta & c_\beta s_\gamma \\ s_\alpha s_\gamma + c_\alpha c_\gamma s_\beta & c_\alpha c_\beta & c_\alpha s_\beta s_\gamma - c_\gamma s_\alpha \\ c_\gamma s_\alpha s_\beta - c_\alpha s_\gamma & c_\beta s_\alpha & c_\alpha c_\gamma + s_\alpha s_\beta s_\gamma \end{pmatrix} \quad (5.1)$$

5.1.2 Presentation of Results

One of the most important things is to know how to present the quantitative evaluations of the action rules to the decision maker. The part orientation in AM is defined by two angles in the global reference (x, y, z) . So, with the desirability D of each couple of angle, three variables can then be used to define an orientation and its goodness. This makes it possible to build 3D response surfaces (RS) which have the ability to give a holistic view about the desirability variations like heat maps (Fig. 5.1). This supposes that many orientations desirability have been computed (thanks to the rotation matrices). The libraries used to build these RSs allow the user to visualize the parameters of a scenario by simply clicking on the points. For each action rule, an RS is expected. Using this type of representation opens up to different methodologies simplifying the future analysis for decision making process.

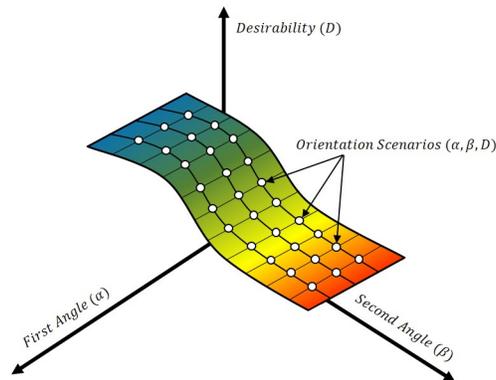


Figure 5.1: Response surface representing orientation scenarios

5.1.3 Design

The tool built in this work is one of the main outputs of the COFFA project. The purpose is to get an interactive assistant. As depicted in Fig. 5.2, tools as loading part (STEP or STL), importing expertise file (.xrdf), exporting oriented part, rotating, moving and so on are proposed. On the left side, there are four tabs; in the Project one can be found the loaded part and the attributes parsed from the imported expertise file. The Settings tab allows defining the orientation range to explore and selecting the α and β axes (OX, OY, OZ). The tab Responses shows the computed desirability values on response surfaces and the Analysis tab will be discussed in 5.2.

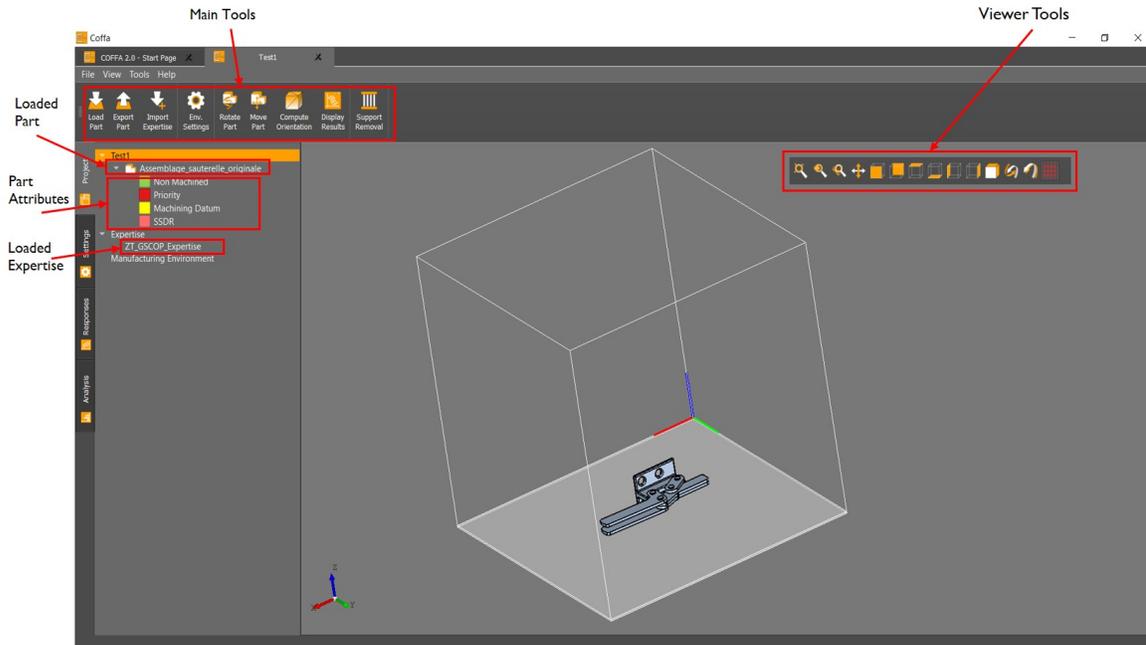


Figure 5.2: General interface design

5.2 Tools for Decision Making Assistance

In this section, ways to visualize the results in order to ease the decision making process are shown for the case of part orientation desirability. For this CAM activity, the decision making of orientation is highly important because, on the one hand, it has a significant influence on the downstream steps such as the definition of regions to support or the nesting. On the other hand, it partly governs the build time, the production cost and the geometrical quality (the mechanical quality is not treated here). Thus, the decision making consisting of choosing the best couple (α, β) has consequences on the product competitiveness and effectiveness for the company. The desirability function approach offers a set of comparable quantitative values resulting from various orientation alternatives. Even if, it is not usually the case, for a limited set of scenarios, it might be easy to decide. Following, are some tools to assist the analysis of the results. The turbine in Fig. 5.3 will be used along the discussions; the responses resulting from the application of action rules of Table 4.1 are displayed in Table 5.1. The color code indicates the surface attributes.

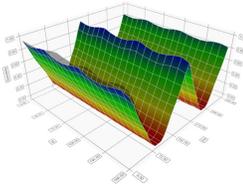
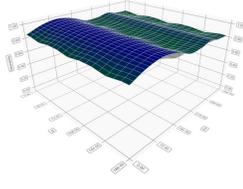
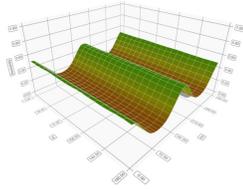
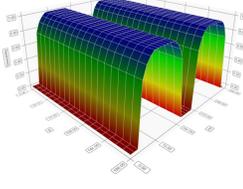
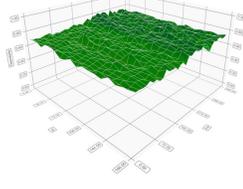
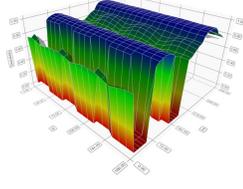
Action Rules	Responses
AR1: Minimize Part Shadow on Start Plate	
AR2: Minimize Total of Overhanging Non-Machined Surfaces	
AR3: Maximize Priority Surfaces Close to Vertical	
AR4: Require Machining Datum Surfaces out of Horizontal	
AR5: Minimize Part Deformation Risks	
AR6: Avoid Support Structures and Support Removal Difficulty SDR	

Table 5.1: Turbine orientation problem responses

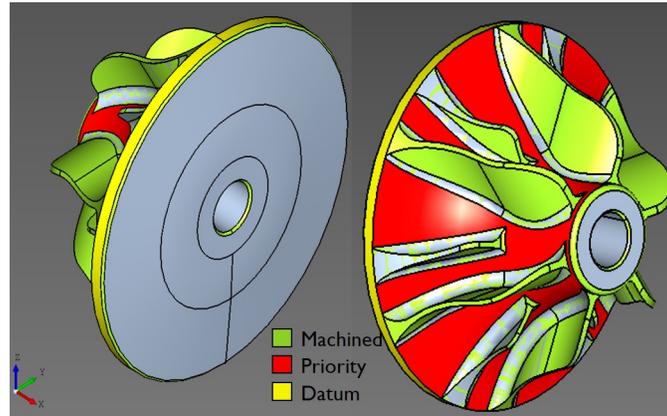


Figure 5.3: Turbine with specifications

5.2.1 Dashboard of Multiple Responses

This visualization mode simultaneously proposes every single response surface in the same dashboard. That is to say that the calculated level of compliance for each AR is displayed and for hundreds of scenarios (Fig. 5.4). The user can, in this way, appreciate all the ARs at the same time. Note that the RSs are built to be interactive, i.e. their points can be pressed to display the corresponding orientation and its desirability. Moreover, a point pressed in one response surface is also highlighted in the other response surfaces, so that the analysis can be lead with ease. This kind of visualization is also used by a commercial tool namely Amphyon (by Additive Works); where they display in 2D surface graphs orientation results with respect of color scales from mathematical models.

The decision maker can start analyzing by pressing on one of the RSs, probably that, corresponding to the most worrisome action rule. Relative points on the other ARs will show-up, then, with the color code, the comparison can be visually done. The first instinct will be to avoid the near-red zones. In exploring the different scenarios, the user can, with his skills complete the judgments given by the desirability.

The definition of thresholds can also be coupled with this analysis tool to limit the field of choice. It consists of assigning a range of acceptable desirability values $[D_{min}, D_{max}]$ to each action rule. Then, the responses less than D_{min} and those above D_{max} are automatically eliminated and not shown to the CAM operator. The elimination of the undesired points for each RS, the results are then simplified. Thresholds are actually cutting different zones of the response surfaces not necessarily the same way. This way, it is easier to see if a point complying with an AR also complies with the others.

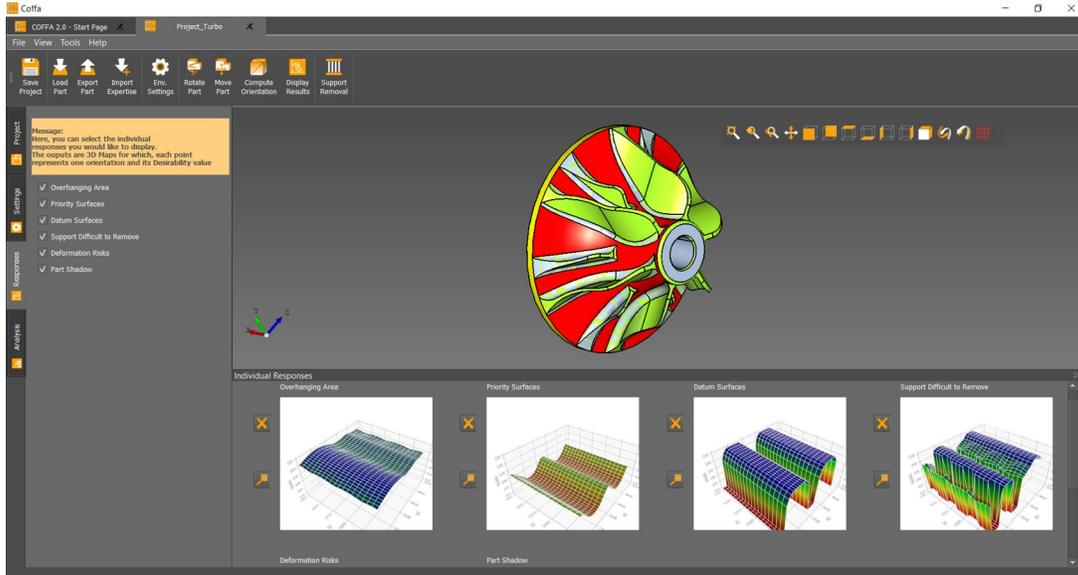


Figure 5.4: Dashboard of multiple individual responses

Nevertheless, here, the user must be careful about the values he chooses because for some cases, he might not find solutions. For instance, for a given geometry and AR, if the final desirability vary from 0.15 to 0.45, it would not be relevant to define $D_{min} = 0.5$ and $D_{max} = 1.0$ as acceptable range. The response surface would be empty.

Having a dashboard of responses can be helpful, however, the user can in some ways be lost when there are several responses to analyze. And that is usually the case. To allow reducing the response surfaces into one aggregated response surface, the following section presents a method of aggregation.

5.2.2 Aggregation into a Single Composite Response

It is usually easier to analyze one global response output in order to make decision quickly and efficiently. For this reason, in this section, we propose a tool that allows the combination of the different responses into one single output. In the literature on desirability functions, various works have used some analytical methods to get single response. For instance, weighting is one of the most used methods. It has already been used for different problems in manufacturing scenarios analysis (Sharma et al. (2014), Datta et al. (2006)) and even not using desirability functions in some cases (Bramall et al. (2003)). Here also, the composite desirability given by the Eq. 5.2 is used to combine

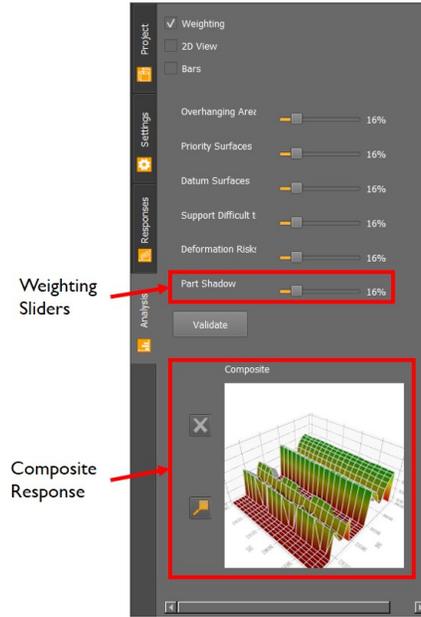


Figure 5.5: User interface for weighting responses

the single responses with specified weights depending on their level of importance. The d_i are the individual desirability computed for each AR and the w_i are the weights.

$$D = \prod_{i=1}^m d_i^{w_i} \quad \text{with} \quad \sum w_i = 1 \quad (5.2)$$

For its implementation, the developed tool interactively shows the orientation corresponding to a selected point on the CAD viewer. Optionally, the user can simultaneously display the dashboard of multiple responses in order to highlight the points corresponding to that clicked on the aggregated output. Mutual comparisons can be led that way. As shown in Fig. 5.5, sliders make it possible to set up the weights which are expressed in percentage to simplify the usage. If one rule is assigned 100%, the result is purely the response of that rule.

Let's define the weighting cases in Table 5.2. For the first case all of the action rules have equal significance. Two random orientations (Or.1 and Or.2) desirability are reported in Table 5.3. Fig. 5.6 shows that whatever the weights, the aggregated response is pulled by the action rules that are not compensated (those are AR4 and AR6) except for the case 4, where the non-compensated action rules have 0 weight. Remember, the non-compensated ARs have the actions *Avoid* or *Require* and the compensated ones have

Cases	AR1	AR2	AR3	AR4	AR5	AR6
1	1/6	1/6	1/6	1/6	1/6	1/6
2	0.1	0.1	0.1	0.3	0.1	0.3
3	0.1	0.3	0.1	0.1	0.3	0.1
4	0.25	0.25	0.25	0	0.25	0

Table 5.2: Action rules weighting cases

actions *Minimize* or *Maximize* (refer to section 3.5 in Chapter 3). What is revealed by the results for the Or.1 means that, when an orientation is not desirable for the surfaces with potential support difficult to remove (AR6) or for datum surfaces (AR4), the composite output will not be desirable regardless the values of the others

This shows that, the effect of the action (avoid, require, minimize, maximize) chosen for the action rules in the modeling process always remains. Therefore, the decision maker can start by discarding all of those scenarios that do not comply with the non-compensated ARs. For example, he could select an orientation such as Or.2 for which, the aggregation returns good values. In the case 1, the rules mutually compensate each other in a balanced way. However, when the weights are no longer the same, the compensation is pulled in one direction. That can be verified in case 2 and 3, where the compensation is higher because the greater importance is given to rules having high desirability. The compromise given by the Eq. 5.2 matches well with the requirement that when a rule is not satisfied, it negates to global output.

The weights play an important role on the output. However, their definition might be a complicated task; the experts may support it. One could also use analytical hierarchy process to represent the problem as a hierarchy that includes a decision goal, alternative solutions for reaching the goal and criteria for evaluating the alternatives (here the criteria would be the action rules). A weighting process is included as well to propose a final global ranking of each alternative (orientation).

5.2.3 2D Superposition of Responses

This mode of visualization simultaneously shows all the responses on the same graph. A sort of plane section is performed on the 3D response surfaces for each step of the 1st angle α . For a value of α , the different desirability with respect of β are reported. This analysis tool makes it possible to see on the same scale all action rules compliance level in a simplified way.

Orientations	Cases	Aggregate	Desirability Values					
			AR1	AR2	AR3	AR4	AR5	AR6
Or.1 (90°, 40°)	1	0.0						
	2	0.0	0.43	0.93	0.32	0.88	0.69	0.0
	3	0.0						
	4	0.55						
Or.2 (90°, 230°)	1	0.60						
	2	0.72	0.32	0.85	0.26	0.97	0.79	0.90
	3	0.68						
	4	0.49						

Table 5.3: Maximum and minimum desirability values of aggregated responses

Fig. 5.7a shows the interface designed for it, the first knob corresponds to α and allows moving the section plane. The second knob controls β and moves the blue vertical line in the chart, which, simplifies the reading of the desirability for one point (α, β) . The tool also allows activating and deactivating the responses the user wants to see or not.

Additionally, a bar graph visualization mode is also proposed. For the selected couple of angles, the desirability with respect to all of the action rules is reported on the graph. Therefore, the result will be some kind of equalizer, making it simple to relatively compare the action rules compliance. Similarly, two knobs are available to vary the angles α, β (Fig. 5.7b) and interactively get the corresponding orientation and desirability levels.

Regarding these two visualizations, it can be concluded that the main difference is that, the bars allow comparing action rules level for one scenario, while the charts extensively give a big sight of several scenarios.

5.3 Case Studies of Industry Parts

This part presents illustrative cases of part orientation problems with specific requirements. The action rules modeled in the chapter 4 are used here. For all the cases, the manufacturing was planned on an Arcam A1 EBM machine using Ti6Al4V. The rotations α (around OX) and β (around OY) vary in the ranges $[0^\circ, 180^\circ]$ and $[0^\circ, 360^\circ]$

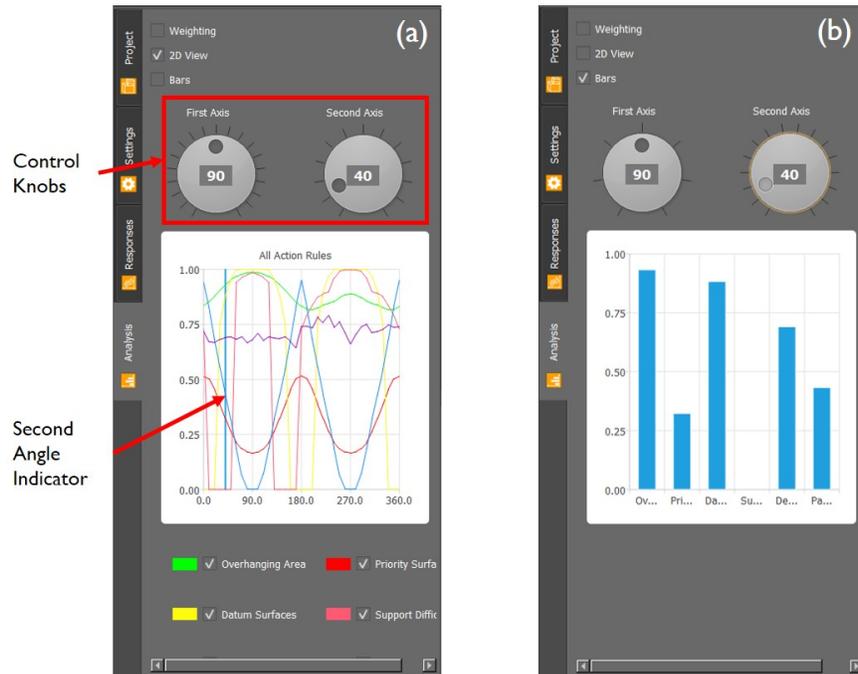


Figure 5.7: Result graphs: (a) 2D superposed charts; (b) Bar representation

5.3.1 Case of a Topology Optimized Bracket

5.3.1.1 Problem Definition

Let's consider the bracket depicted in Fig. 5.8; the aim is to determine an optimal orientation around the X and Y axes with respect of the action rules AR1 to AR6 (see chapter 4 for details). The green surfaces are post machined, thus, no matter if they have support structures (the machining cost and time is already intended). All of the other surfaces are non-machined. Priority and datum surfaces are highlighted in red and yellow respectively. Datum surfaces will be part of the references in the post-machining of green surfaces. The surfaces with potential support difficult to remove are computed by a dedicated algorithm, since their manual selection would be difficult to achieve. Deformation risks and part shadow on start plate are assessed over the whole shape.

5.3.1.2 Results & Discussion

Fig. 5.9 shows for every assigned action rule, around 700 different desirability values of the bracket's orientations. The effect of the type of action (e.g. minimize) can be

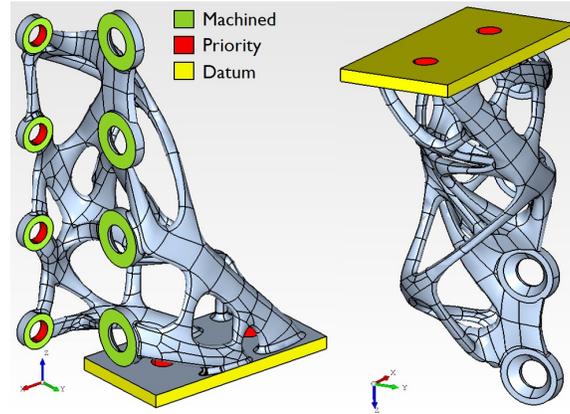


Figure 5.8: Topology optimized bracket with different surface attributes

noticed on some of the results for which summation on the whole part has been carried out (refer to section 3.5). That is the case for AR2 and AR3, that include “minimize” and “maximize” respectively. For this specific geometry, the overhanging non-machined surfaces return high desirability values. In fact, for this action rule the downfacing surfaces (overhanging) are completely compensated by the upfacing surfaces. Replacing the use of “minimize” by “avoid” would change the result as no compensation is allowed. This can be illustrated by AR4 and AR6 for which a zero local desirability automatically causes a weak global desirability. For these two action rules (Fig. 5.9c and Fig. 5.9f), most of the orientations have weak desirability.

Regarding the computation times, Table 5.4 shows that for action rules AR2, AR3, AR4 and AR6 the time for processing 700 orientations remains less than one minute. It even takes 1 *second* for AR3 and AR4. However, the action rules AR1 and AR5 take a little long to compute this great number of orientations. For AR1, the total time is 1600 *seconds*; this is equivalent to a rate of approximately 2.3 *seconds per orientation*. AR5 take much more time (5460 *seconds*) because of the different steps in the back-end to measure its variable (see section 4.5). Each orientation takes around 8 *seconds* to compute. When all action rules are grouped and computed simultaneously the total time is 6720 *seconds* (9.6 *seconds per orientation* for six action rules).

Each response is bounded by the maximum and minimum values reported in the Table 5.4. A set of rotations may produce conflicts between the action rules. For instance, at $\alpha = 0^\circ$ and $\beta = 60^\circ$ the overhanging non-machined surfaces and the datum surfaces return good desirability values (0.87 and 0.91 respectively) whereas all the other action rules have a poor desirability less than 0.3 (Fig. 5.10S1). Another scenario at $\alpha = 40^\circ$ and $\beta = 120^\circ$ would result in AR2, AR4, AR5 and AR6 greater than 0.5 and AR1 and

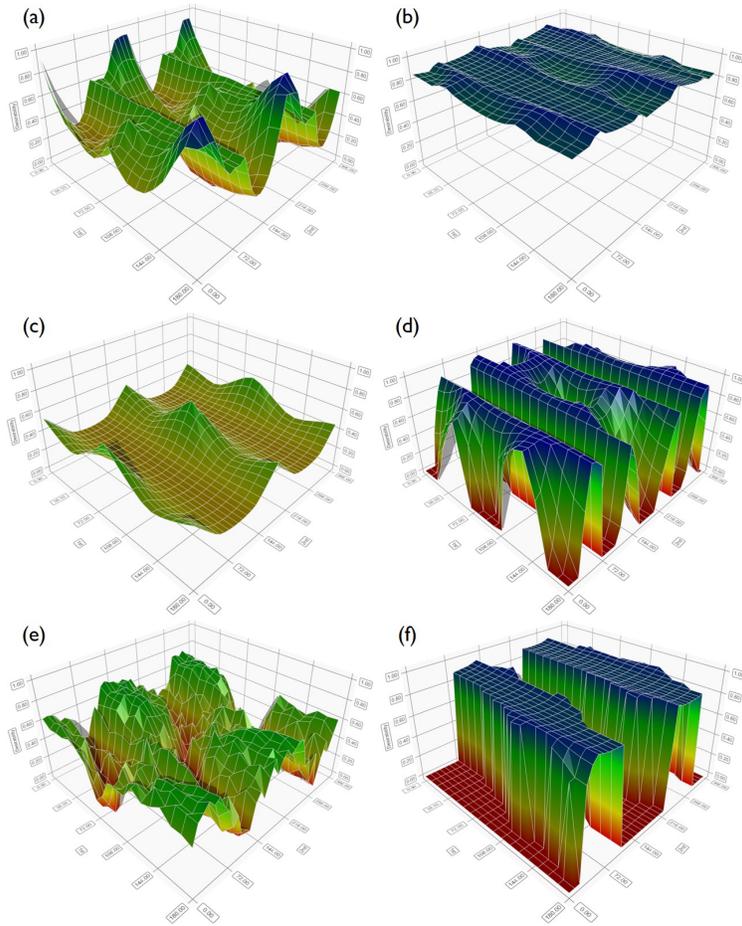


Figure 5.9: Response surfaces for each action rule: (a) AR1; (b) AR2; (c) AR3; (d) AR4; (e) AR5; (f) AR6

Action Rules	Minimum	Maximum	Individual Processing Time (s)	Simultaneous Processing Time (s)
AR1	0.0	1.0	1600	
AR2	0.83	0.96	33	
AR3	0.25	0.71	1	6720
AR4	0.0	0.98	1	
AR5	0.0	0.77	5460	
AR6	0.0	0.95	32	

Table 5.4: Minimum and maximum desirability values

AR3 are lower than average (Fig. 5.10S2).

For most of the scenarios, the rule AR3 about the priority surfaces does not return a good desirability while the others are sufficiently high. In fact, the surfaces involved in this rule can not be simultaneously vertical because of their perpendicularity. The maximum desirability of AR3 is reached for $\alpha = 90^\circ / \beta = 0^\circ$ and $\alpha = 90^\circ / \beta = 180^\circ$, but for those scenarios, the rules on datum surfaces and support difficult to remove would be minimal (Fig. 5.10S3). The solution in Fig. 5.10S4 can also be foreseen; it differs from the scenario S2 by the slight growth of AR1 and AR3 and the decrease of AR5. Manufacturing can then be operated using one those parametric points.

Obviously, owing to this variety of solutions, it is not trivial to choose a point complying all of the AR simultaneously. However, one can make trade-offs by selecting a pair of angles for which the individual desirability reach an acceptable value.

5.3.1.3 Benchmark with Commercial Tools

The optimum desirability proposed by Magics is reported on the 3D responses to find the associated desirability. Only supported surfaces (equivalent to AR2) and projection on start plate (equivalent to AR1) are considered. By assigning a weight of 50% to each criterion, the orientation found by Magics is the pair $\alpha = 170^\circ - \beta = 220^\circ$ for which the desirability values are 0.83 and 0.92 for respectively the projection on the start plate (AR1) and the overhang surfaces (AR2). This orientation is a trade-off (the results of both tools are coherent), but the desirability approach shows that other orientations would be even better on these criteria.

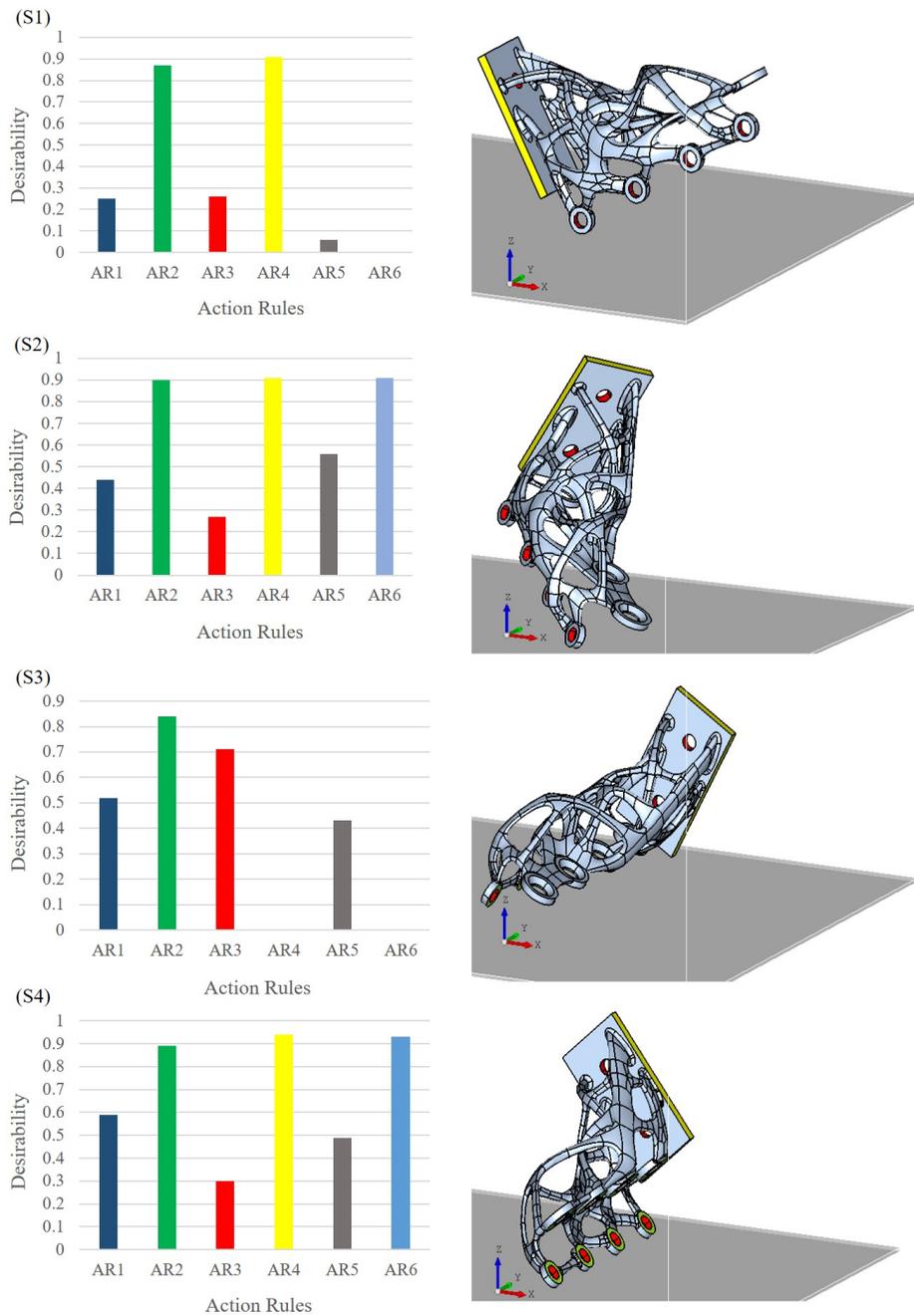


Figure 5.10: Comparison of scenarios: (S1) $\alpha = 0^\circ - \beta = 60^\circ$; (S2) $\alpha = 40^\circ - \beta = 120^\circ$; (S3) $\alpha = 90^\circ - \beta = 180^\circ$; (S4) $\alpha = 90^\circ - \beta = 50^\circ$

In contrast with Magics, analysis with the Additive Prep tool can be performed on different points as it returns orientation heatmaps. Due to the fact that Additive Prep cannot take attributes into account, the surfaces to be machined are ignored in order to be on the same basis. To make comparisons with the COFFA approach, the minimum and maximum desirability values are scaled with the color map returned by Additive Prep as shown in Fig. 5.11a. The results of Additive Prep for this part is given in Fig. 5.11b. Note that Additive Prep uses OX and OZ for rotations, while COFFA used OX and OY , thus only some equivalent orientations are compared.

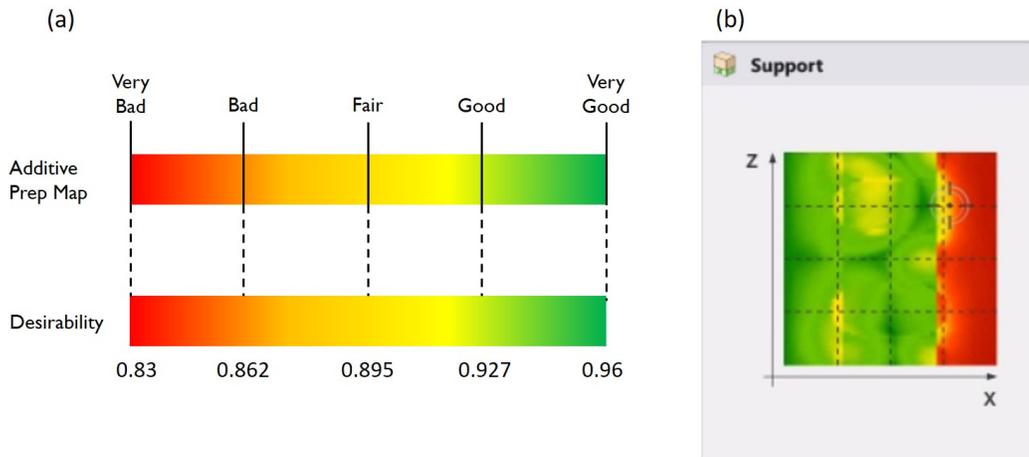


Figure 5.11: (a) Approximate correspondance between results in Additive Prep and COFFA; (b) Heatmap provided by Additive Prep

Table 5.5 proposes ratings according to the minimization of supported or overhanging surfaces (for some points, the angles are given with respect of COFFA axes). Fig. 5.12 shows the orientations from Additive Prep and COFFA for each point in Table 5.5. Unexpectedly, Additive Prep indicates that the $0^\circ - 0^\circ$ orientation is very good while in terms of desirability it is rather bad. And yet, several surfaces are overhanging, especially the large base of the part. When the part is set at $180^\circ - 360^\circ$, Additive Prep judges the scenario as very bad even if in terms of overhang this orientation is almost equivalent to the previous one. For both of them the desirability is weak. The origin of this problem is not mastered in this work since the tool in question is not open source. And the user does not know on which criteria basis the orientations are evaluated in this tool. Different other points can be compared, those in Table 5.5 are only chosen for illustrative purposes.

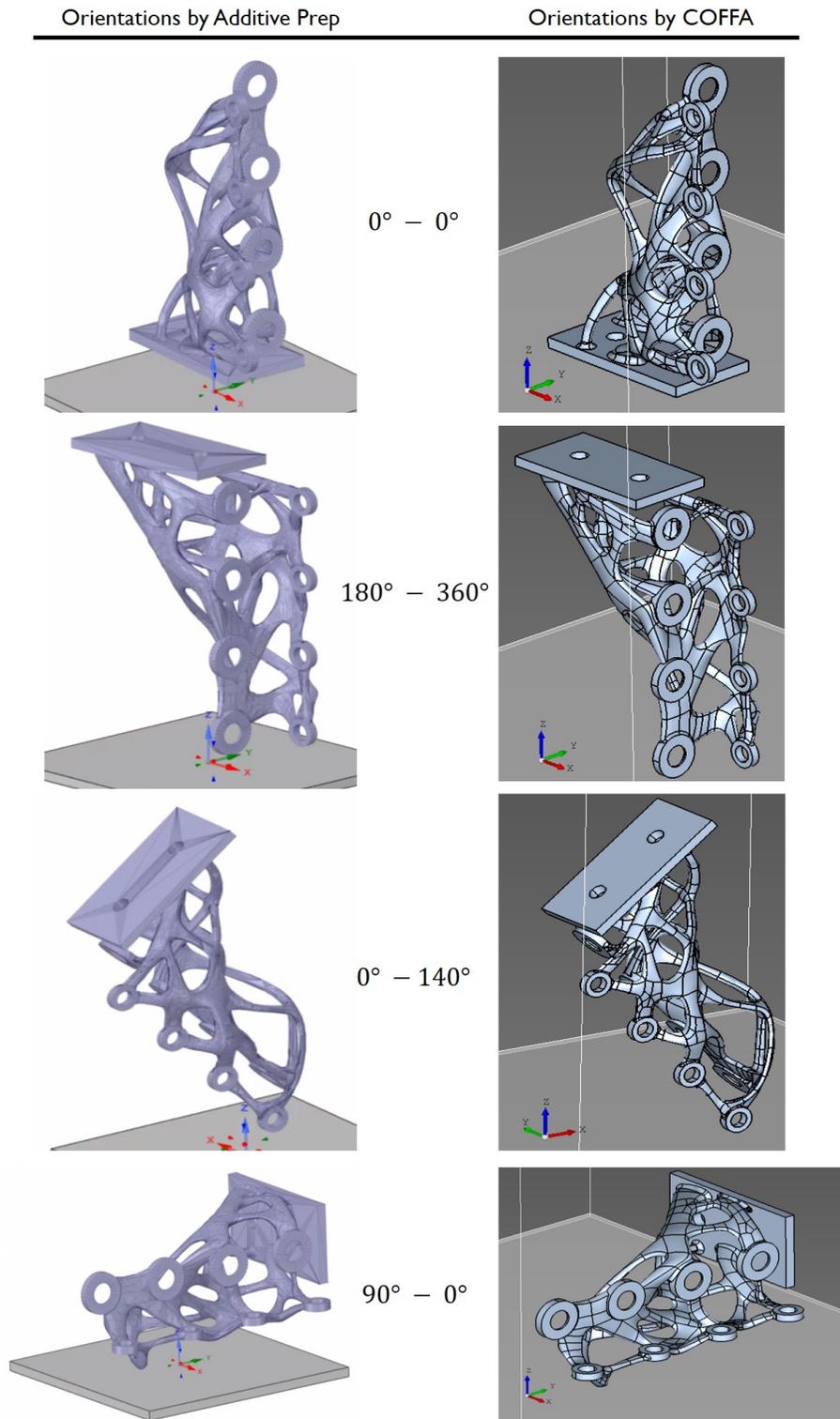


Figure 5.12: Part oriented using Additive Prep and COFFA for the scenarios compared

Scenarios	Additive Prep	Desirability Approach
$0^\circ - 0^\circ$	Very Good	Bad
$180^\circ - 360^\circ$	Very Bad	Bad
$0^\circ - 140^\circ$	Fair	Good
$90^\circ - 0^\circ$	Very Good	Fair

Table 5.5: Comparison between ANSYS Additive Prep results and the desirability approach results

5.3.2 Case of a Wavy Part: Re-Manufacturing with better Parameters

5.3.2.1 Problem Definition

For this part (made of two blocks for electrical consideration, but built as one part), the aim was to find an orientation avoiding as much as possible the support structures difficult to remove. In fact, in the first manufacturing trial, the engineer in charge of the preparation determined manually an orientation according to his knowledge (the corresponding orientation is shown in Fig. 5.13a). The rules related to support removal difficulty were not taken into account. As a reminder, this type of consideration is given by the action rule AR6 detailed in section 4.6. Owing to this, the support removal process after manufacturing this part was quite complicated. This lasted over 30 minutes, and in spite of the efforts, there still was some support impossible to remove with the available tools (see Fig. 5.13b). Moreover, the marks left on the surfaces were difficult to finish and would cause extra cost and time. Hence, for the second trial, the approach and algorithms developed in this study are used to check whether a better set of orientation parameters could be used to avoid the SSDR. Additionally, the engineer wanted to reduce the overhanging surfaces of the part (AR2), in considering that all of the surfaces are *non-machined*.

5.3.2.2 Results & Discussions

Fig. 5.14a and Fig. 5.14b respectively show the responses corresponding to the support removal difficulty and the overhanging non-machined surfaces. For the AR6, many points have a weak desirability; this is due to the action used “*Avoid*”. Remember that when a such action is used, if any local “SSDR” surface has a bad orientation, then the global desirability of this orientation for the part becomes weak. In contrast, the AR2 has several good scenarios since its action “*Minimize*”, compensates bad results. Choosing

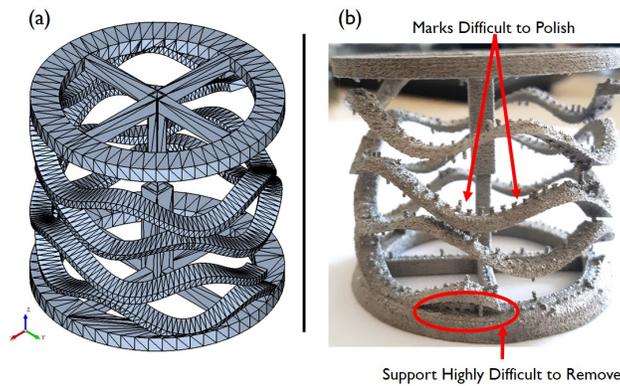


Figure 5.13: First manufacturing trial without assistance based on action rules: (a) Oriented CAD part; (b) Manufactured with marks and non-removed support block

an orientation will then be highly governed by AR6, which has less good scenarios and is the most important action rule of this problem. The total time for computing both action rules grouped is around 86 *seconds* for 700 orientations.

Some points randomly picked up among potential candidate orientations (avoiding poor desirability values) have been used to draw the bar diagram in Fig. 5.14c. By comparison, one of the scenarios that have both greater desirabilities is that having the pair of angles $\alpha = 120^\circ$ and $\beta = 40^\circ$. The corresponding desirability values are 0.97 and 0.95 for AR6 and AR2 respectively. The part has thus, been re-manufactured with that defined orientation (Fig. 5.15a). And, for this attempt the resulting component exhibited less removal difficulty. In fact, the process lasted around 3 minutes and there was no support blocks impossible to remove as in the previous case (Fig. 5.15b). However, there naturally are marks left by the supports, but, the accessibility for finishing is quite good. It can therefore be concluded that the expert knowledge has greatly helped the improvement of the part's quality, post processing cost and time. And the desirability-based method highly helped defining the parameters by simply comparing sets of parameters based on quantitative measures.

5.3.2.3 Benchmark with Commercial Tools

As the commercial tools available to this work do not integrate the removal difficulty option, only the criteria linked with the supported area and the shadow on plate are compared to the results from COFFA. The desirability of part shadow action rule was not of interest in this problem, but it has only been computed for comparison purposes.

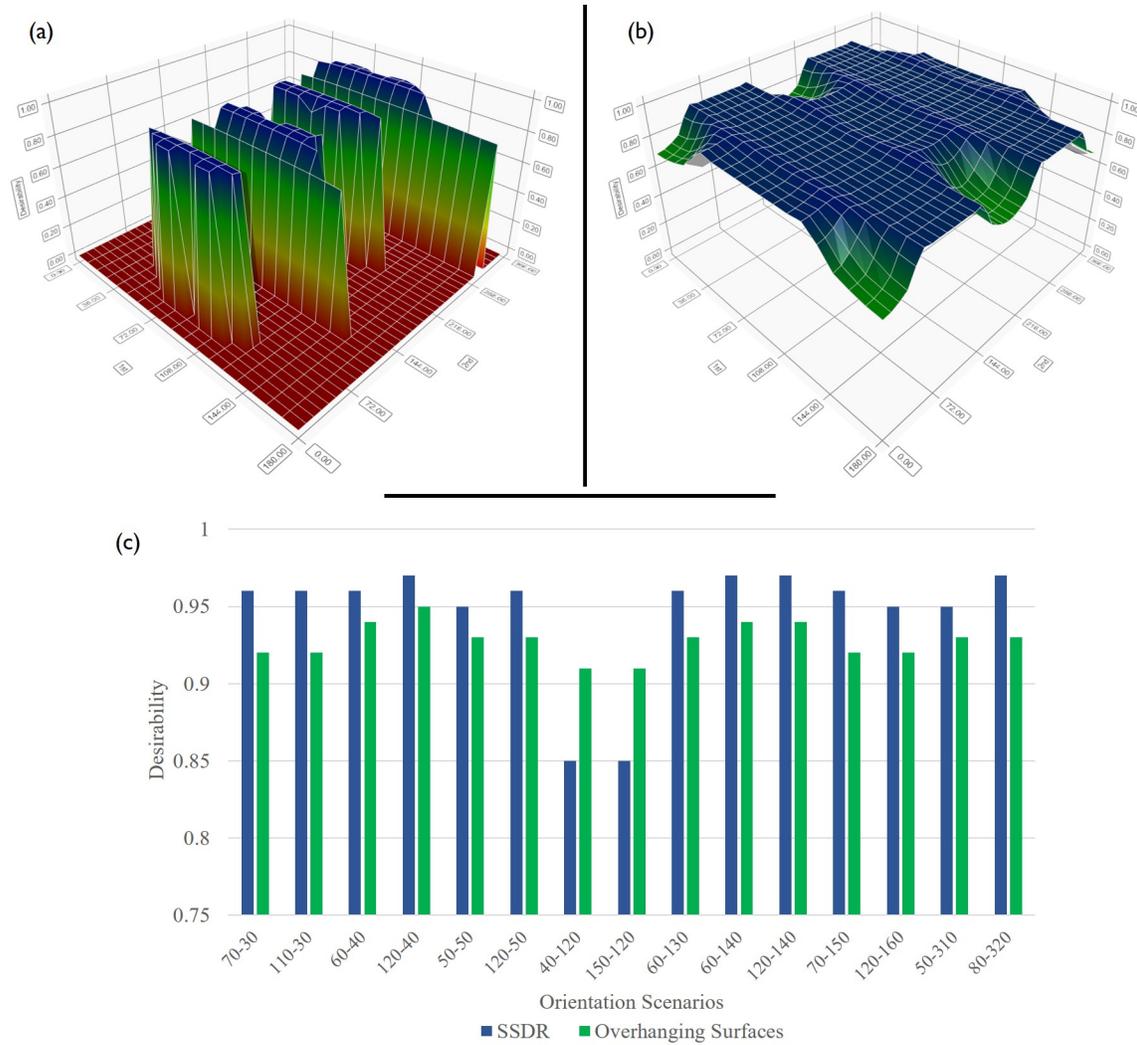


Figure 5.14: 3D response surfaces: (a) SSSR desirability; (b) Overhanging surfaces desirability; (c) Bar graph comparing SSSR and overhanging action rules for a series of orientation scenarios.

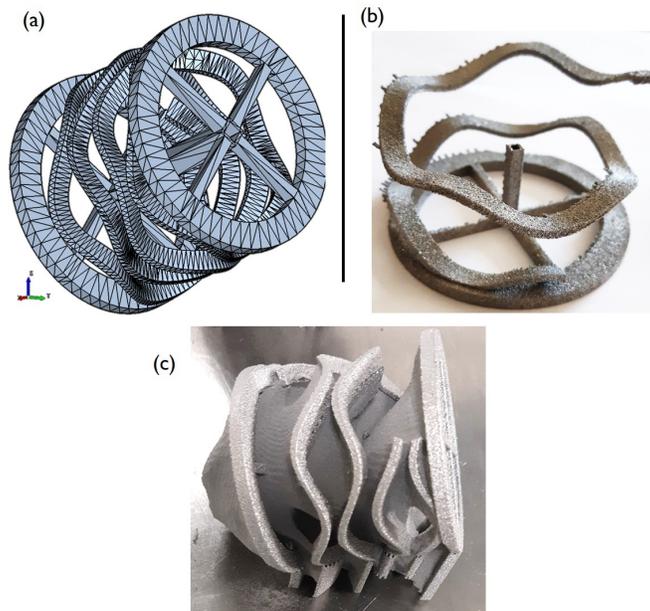


Figure 5.15: Second manufacturing trial with assistance based on action rules: (a) Oriented CAD part; (b) Manufactured cleaned part; (c) Manufactured part before powder and support removal

First, the optimum orientation given by Magics corresponds to the pair of angles $\alpha = 90^\circ - \beta = 50^\circ$. In terms of desirability, the action rules about overhang and shadow respectively return 0.93 and 0.85 which are the maximum values they can return. So, it can be concluded that the result of COFFA approach is in this case compliant with that from Magics. However, the chosen orientation ($\alpha = 120^\circ - \beta = 40^\circ$) for the manufacturing are not the same, since Magics does not include support removal criterion.

For the Additive Prep tool, many solutions can be compared with respect of the supported area (as this software does not include support removal difficulty and part shadow criteria). It has to be reminded that the minimization of supported area is equivalent to the overhanging surfaces minimization. The grammatical ratings in Fig. 5.16 are used to build the Table 5.6 for some scenarios of orientation. Globally, the results are varying in same direction even if these are only approximate comparisons. The commercial tools do not provide quantitative evaluations, but simply maps of colors generated by black boxes in which the user does not have any control nor criteria understanding.

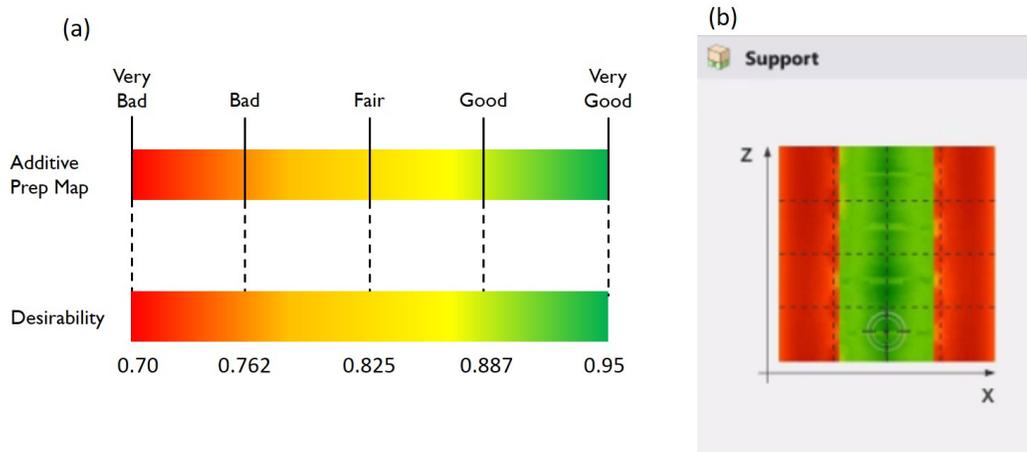


Figure 5.16: Approximate correspondance between results

Orientation Scenarios	Additive Prep	Desirability Approach
$0^\circ - 0^\circ$	Very Bad	Very Bad
$50^\circ - 90^\circ$	Good	Good
$80^\circ - 110^\circ$	Very Good	Good
$20^\circ - 30^\circ$	Very Bad	Bad
$90^\circ - 210^\circ$	Very Good	Good
$160^\circ - 180^\circ$	Bad	Bad

Table 5.6: Comparison between ANSYS Additive Prep results and the desirability approach results

5.4 Testing COFFA with Students

COFFA tool for part orientation have been used with students in the context of their practice class about *Advanced Manufacturing*. Indeed, the prior aim of making tests arose from the fact that the teacher wanted to draw their attention on the significance of part orientation in PBF. Their examination topic was about the topology optimization of and fabrication in EBM of a simple mechanical clamp assembly (Fig. 5.17a). An example of one of the topology optimization results is shown in Fig. 5.17b.

The first feed back received from the students with whom the tool has been tested



Figure 5.17: Tests with engineering students: (a) Generic clamp; (b) Topology optimized clamp; (c) Manufactured considering optimal orientation; (d) Manufactured without considering optimal orientation.

is that they did not know that defining good orientation would be so important to ensure good quality products. The six action rules discussed earlier in this work have been explained to them, so that they understand each objective. In the context of their practice they were interested in the minimization of overhanging non-machined surfaces and the avoidance of surfaces with potential support difficult to remove. The orientation desirability has been separately evaluated on each part.

Globally, all the manufactured parts had an acceptable quality (an illustration is given in Fig. 5.17c). Only one group of students did not test the strategic orientation before manufacturing. As a result some of their components exhibited major problems related to the surface quality due to the support removal difficulty as depicted in Fig. 5.17d. On the one hand, the position they chose did not minimize the overhanging surfaces. On the other hand, they put support structures on surfaces without taking account of the removal intricacy. Therefore, it could not be cleanly operated, leaving thus big marks on surfaces.

This experimentation has shown how a knowledge-based manufacturability analysis is also able to help uninitiated users of manufacturing systems when the experts are not available to intervene. In the view of its interesting integration in education, it has been planned to put a version of the tool online for students.

Conclusion

Providing decision making assistance tools was of major concern in this work. That is why, this chapter proposed some tools for facilitating to decision makers, the selection of the suitable processing parameters. Most of the tools are based on the comparison between multiple alternatives and multiple action rules visualized at the same time. However, one of the solutions allows the aggregation of the different action rules responses into one single output by using a weighted geometric mean. Tests performed with engineering students showed that this knowledge-based tool can be very useful where experts are not available to support the decision making.

This chapter also presented some applications of the COFFA approach to part orientation problems. The first case treated the orientation of a complex geometry obtained by topology optimization. In that problem, all the six action rules were considered to find out an optimal orientation. It has been noticed that for a set of orientations some of the rules give desirability values evolving in opposite direction. This makes it mandatory to make decisions based on compromises. The computation times were very low for action rules AR2, AR2, AR4 and AR6 (less than one minute) and a little bit high for AR1 (27 minutes) and AR5 (90 minutes).

In the second case that was about re-manufacturing a part with a better orientation avoiding support removal difficulty and minimizing support structures, compliant results have been found. The re-manufactured part presented a better quality with no support difficult to remove.

Regarding the comparisons with commercial software, the results were mainly compliant for the comparable criteria. Benchmarks with Magics only considered the minimization of supported area and shadow criteria. For Additive Prep, comparisons were only achieved with respect of supported surfaces. However, the second case study showed that the integration of other orientation criteria (such as the difficulty of access to surfaces for the removal of supports) could be critical in some rooms. The approach proposed in COFFA then made it possible to manufacture this part under conditions acceptable to the customer. Globally speaking, the knowledge based approach is helpful for defining part orientation. Another main advantage is that several quantified results are proposed and the user can create new rules when necessary.

Conclusions, Contributions & Perspectives

Conclusions

This thesis arose from collaborative works between G-SCOP and I2M laboratories, and is the continuity of previous works led on the elicitation and structuring of additive manufacturing (specially powder bed fusion methods) knowledge. **This work's aim was to provide means of mathematizing expert knowledge in order to assist manufacturing pre-processing operations, among which part orientation have been identified to be one of the most important.**

In manufacturing processes, expert knowledge has been used in various ways in order to assist the decision on strategic choices leading to efficient production. So far, the methods proposed to leverage knowledge were relying on procedural testing mainly based on inference engines. Moreover, the manufacturability assessment systems used feature recognition techniques to evaluate knowledge on geometries. However, through this presentation, it has been demonstrated that these methods were not relevant in the case of additive manufacturing. The main issue that has been noticed, is that to assess knowledge on parts, they need to be decomposed into simple shapes using feature recognition techniques. And, this is difficult to realize in additive manufacturing since the shapes are most of times very complex. This work has then brought a contribution to the field by proposing a novel manner to quantitatively integrate and evaluate expertise on products in the context of CAM operations basing on desirability function approach.

From the investigation of knowledge typologies presented in Chapter 2, **action rules have been identified as the knowledge entities, that can guide the choice of manufacturing parameters.** Then, a review of the additive manufacturing part orientation literature and industrial practice has allowed collecting a set of knowledge resources. Differences between the research and industrial approaches to define part orientation have been emphasized in that chapter. The approach of the industry prac-

titioners was not considering directly quality, cost and time but the action rules leading to them. No tool able to evaluate the compliance level of those rules on parts to produce were proposed yet. For this reason, **a modeling approach combining geometry and knowledge has been presented** here in Chapter 3.

The modeling process made possible **the transformation of action rules in literal form into unit functions** for which the values are bounded between zero and one. The first step was to **codify the action rules** with respect of a common grammar in order to make visible the objectives they include. Inside action rules, **concepts were classified in three classes which are the action, the part (shape with attributes) and the evaluation concept**. A mathematization process led by achieving an analysis of the codified action rules, resulted in relational functions that show the link between the involved shape entity variable and the evaluation concept. The desirability function, that corresponds to a given rule, is built (on the basis of the relational function) in order perform the evaluation. This thesis developed a way to assess the compliance level of the rules on geometries regardless their complexity, without need of performing feature recognition on them.

The proposed mathematical representation model of the rules has a good suitability regarding additive manufacturing as shown in Chapter 4, where **the computation of part orientation desirability** is presented. A demonstration software has been developed in this project to facilitate the desirability evaluation on geometries and to support the process planer activities. It also includes tools for decision-making assistance. The use of the software has been illustrated through case studies of industrial parts benchmarked with commercial tools, and through tests carried out with engineering school students. One of the case studies illustrated a special requirement from a customer who wanted to eliminate support removal difficulty on his part. That was not possible with the commercial tools, but COFFA tool made it possible. This possibility of adding rules to the tool as needed is probably one of the great advantages of the COFFA approach.

Globally, **the idea of integrating workers expertise not only helps but also harmonizes the company's practices**. The decision-makers are able to justify the choices they do based on desirability values. The COFFA approach might be different from some other expert systems. Here, the application of the rules on parts is done simultaneously rather than being procedural. This probably reflects better the human expert "thinking", who tend to check whether all the requirements are satisfied at the same time.

Extensively, the desirability method has another advantage that is the possibility to go back to design stage with a fixed orientation that attaches a desirability to each surface. Those with low conformity values can be detected and re-optimized.

Perspectives

Assisting the edition expertise resources

This work has presented a knowledge mathematical representation technique to support additive manufacturing pre-processing operations. When knowledge assets are transformed into desirability functions, they are stored in an expertise resources description framework (xrdf) file in which, all the necessary information about the rules are described. A simple tool assisting the modeling has been proposed in Chapter 3. In that tool, an expert or knowledge engineer can write a new action rule that is scanned to automatically find out the included concepts and propose a set of variables that could link the shape entities with the evaluation concept (see Appendix A). However, this process remains manual and requires a certain level of comprehension. Therefore, intelligent tools need to be developed in the future. Those must be able to infer the data related to the shapes and handle the creation of new evaluation concepts. In fact, the suggested mathematical representation model of rules assumes that in each of them there is an evaluation concept which is linked to a shape entity through a variable that is to be measured on that shape entity. Hence, the automated identification of the variable, the way to measure it on CAD elements and its evolution have to be assisted in future works.

Quantification of the desirability functions

For each desirability function encountered in this work, the involved experts have indicated the threshold and the shape of the function. Nevertheless, there is still a need for a process to properly guide the function description. For this purpose, a short term perspective is to experimentally determine the values and the refined shapes of the desirability functions with respect of the manufacturing processes.

Testing the COFFA tool with experts

In this documents, tests with students in engineering school have been presented. Now, extended tests need to be performed with industry and academic experts to:

- Prove that the tool helps making better choices of parameters,
- Investigate, what is the best way to present the computation results and to assist the decision-making.

Integration to other additive manufacturing technologies and in traditional manufacturing

The desirability-based assistance for part orientation selection in powder bed fusion has attracted the interest of experts that tested the proposed tools. Therefore, it would be interesting to expand this work to other additive technologies such as SLM, WAAM, FDM, DMLS, SLS etc. The main adjustment rely on the process expertise elicitation and rules definition. In this purpose, works are being achieved on collecting knowledge for wired arc additive manufacturing and machining.

Redesigning parts based on desirability

An ongoing study in the same context of COFFA is building a methodology of re-designing parts based on the distributed desirability. Here, topology optimization is used for the geometrical modifications. In fact, the idea is to attach a desirability value to each surface of the part in a fixed orientation. Then, the principle of re-Topology Optimization will manage to improve the surface's topology in order to obtain a better desirability. As illustrated in Fig. 5.18, a bi-dimensional geometry is considered; the aim is to modify the topology of the surface E cause of its poor desirability in the current position of the part regarding a rule that requires the minimization of total overhanging surfaces.

A NURBS based topology optimization method developed by Costa et al. (2019) and Costa et al. (2017) will be used, since it has the ability of handling geometrical entities directly. The part to optimize is sent with the desirability function and the distributed desirability attached to each of the surfaces. The non-design space will include all the functional surfaces and those having satisfactory desirability. In the example, the surface A has a very poor desirability, but it cannot be re-designed cause of its functional attribute. Therefore, only the surface E can be modified. One of the possible final shape is illustrated in Fig. 5.18. In fact, the size of the overhanging area of E has been reduced by modifying its upper semi-circle. The latter is cut by two segments taken from tangent points. The desirability value of E has then been improved from 0.68 to 0.89.

There are many challenges regarding the implementation of this in topology optimization routines. Among those can be cited, the management of the connection between the surfaces, the integration of the desirability function, the aggregation in case of many surfaces to optimize and so on. Research efforts are needed for future works.

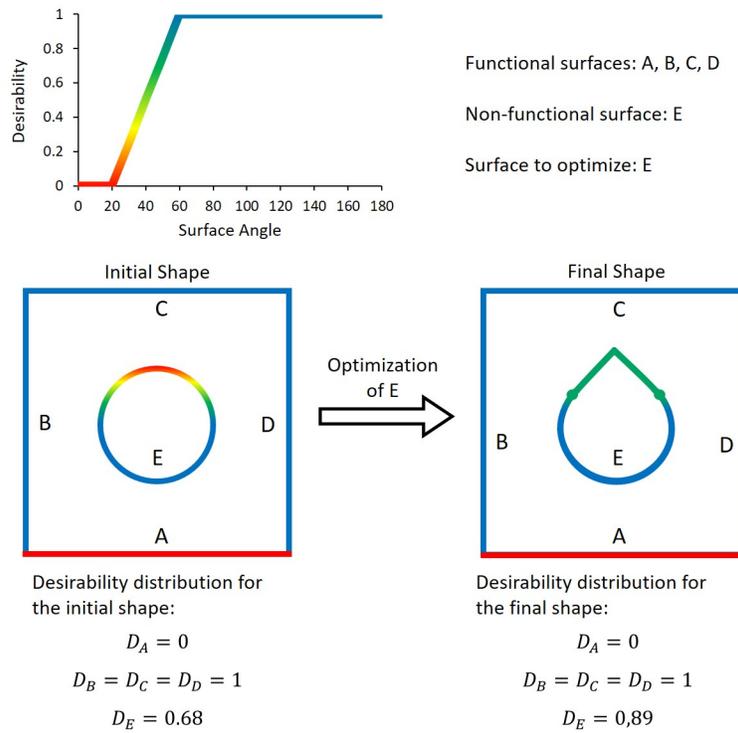


Figure 5.18: Desirability-based re-design of oriented part

Contributions

The results of this thesis have led to the development of a software made of two modules. The first one helps the modeling and storage of the rules in expertise resources description files; it is dedicated to the expert teams or knowledge engineers. The second one is made for CAM engineers and operators. It allows the evaluation of part orientation desirability based on expertise and has also different tools to support the decision making.

The publications and communications below have also been achieved.

Journal papers:

1. C. Grandvallet, Mbow M. M., T. Mainwaring, F. Pourroy, F. Vignat & P. Marin. *Eight Action Rules for the Orientation of Additive Manufacturing Parts in Powder Bed Fusion: an Industry Practice*. International Journal on Interactive Design and Manufacturing, 2020.

2. M. M. Mbow, C. Grandvallet, F. Vignat, P. Marin, N. Perry & F. Pourroy. *Mathematization of Experts Knowledge: Example of part orientation in additive manufacturing*. Journal of Intelligent Manufacturing, 2021.

Conference papers:

1. M. M. Mbow, F. Vignat, P. Marin & N. Perry. *Calcul d'Orientation en Fabrication Additive Métallique sur Lit de Poudre-Une Nouvelle Approche Quantitative par Fonction de Désirabilité*. 16e Colloque National S-mart, April 2019, Les Karelis(73), France. hal- 02355161.
2. C. Grandvallet, M. M. Mbow, T. Mainwaring, F. Pourroy, F. Vignat & P. Marin. *Criteria for the Orientation of Additive Manufacturing Parts in the Powder Bed Fusion: an Industry Practice*. International Symposium on Precision Engineering and Sustainable Manufacturing (PRESM), 2019.
3. T. H. T. Tran, M. M. Mbow, F. Vignat, D. S. Nguyen. *Surface Accessibility Detection in CAD environment for Additive Manufacturing*. The Second International Conference on Material, Machines, and Methods for Sustainable Development (MMMS) 2020.
4. M. M. Mbow, P. Marin, N. Perry, F. Vignat & C. Grandvallet. *Knowledge-based Evaluation of Part Orientation Desirability in Powder Bed Fusion Additive Manufacturing*. International Conference on Engineering Design (ICED21) 2021.

**Version Résumée : Aide à la
décision basée sur l'expertise
métier dans le domaine de la FAO
pour la fabrication additive : une
approche par mathématisation
des règles**

Introduction

Depuis les spécifications de conception du client jusqu'aux pièces finies, les méthodes traditionnelles de fabrication (fraisage, tournage, moulage, forgeage...) nécessitent généralement le développement d'un outillage individuel et spécifique à chaque famille de produits. Cependant, avec l'introduction innovante de la fabrication additive (FA) et en particulier des méthodes de fabrication additive métalliques telles que la fusion sur lit de poudre (FLP), le développement de nouvelles pièces ou de nouveaux assemblages est devenu plus rapide. Ces technologies offrent une liberté de conception qui a rendu possible le développement d'approches de conception plus flexibles telles que la conception basée sur la fonction du produit Klahn et al. (2015), qui permet de générer des produits plus compétitifs et plus adaptés à leur fonction. Cependant, les pièces fabriquées avec les systèmes FLP présentent souvent des problèmes liés à la répétabilité et à la fiabilité de la production. En raison du processus couteux, les pièces doivent être bien conçues et bien fabriquées dès la première tentative afin de réduire les pertes de temps et de matières. Ainsi, durant le processus de conception des pièces, les concepteurs doivent tirer parti des libertés de forme permises par la FA tout en prenant en compte les limitations liées aux ressources de fabrication disponibles.

Aujourd'hui, malgré les progrès réalisés, cette tâche reste compliquée car, dans le domaine de la FA, non seulement on dispose de peu de données sur les critères et les indicateurs de fabricabilité, mais en outre, les solutions de conception commerciales n'incluent généralement pas les contraintes de fabrication. Par conséquent, la plupart des utilisateurs industriels ne se fient qu'à leurs connaissances métier. Cette expertise des différents acteurs de la chaîne de valeur (conception (CAO), préparation (FAO), fabrication, post-traitement) doit être formalisée pour assister les prises de décisions afin de garantir l'efficacité de la production.

Dans cette optique, le présent travail de thèse propose la construction d'une méthodologie pour utiliser le plus efficacement possible le savoir-faire des experts dans le domaine de fabrication additive par fusion sur lit de poudre pour soutenir les décideurs en matière de FAO. L'approche de ce travail est principalement centrée sur l'assistance dans le choix des bons paramètres de fabrication. Le contenu de ce document présentera

des méthodologies et des approches pour atteindre cet objectif.

Problèmes liés aux Opérations de Préparation (FAO) en Fabrication Additive

En FA, un produit doit souvent passer par plusieurs étapes depuis sa conception jusqu'à son contrôle qualité. La manière d'exécuter ces étapes détermine fortement la qualité, le coût et le temps de production des pièces (Metal AM Vol4, N°3, (2018)).

Le processus commence par l'étape de *conception*, où la forme de la pièce est développée sur la base de spécifications bien définies. Aujourd'hui, deux approches principales de conception peuvent être utilisées, à savoir la forme pilotée par le concepteur et la forme générée par optimisation topologique (où la génération de la forme est automatisée) Hällgren et al. (2016). Par la suite, la pièce conçue passe à l'étape de *préparation* au cours de laquelle les opérateurs FAO ajustent les paramètres de fabrication et suggèrent éventuellement des options de re-conception en cas de non-conformité avec les capacités des machines à disposition. La pièce est ensuite fabriquée et envoyée aux étapes d'*enlèvement de la poudre* et des *supports* avant d'entamer le *post-traitement* au cours duquel des opérations telles que la finition ou le polissage sont réalisées.

Dans la pratique quotidienne, pour la fabrication additive, il n'est pas trivial de tenir compte des contraintes de fabrication lors de la conception. D'une part, le concepteur (dans certains cas, en communiquant avec les agents de fabrication) peut être en mesure d'analyser la faisabilité de géométries simples, mais lorsque la complexité augmente, elle devient de moins en moins réalisable pour lui. D'autre part, le processus d'optimisation de la topologie utilise des algorithmes complexes dans lesquels il serait difficile d'ajouter toutes les contraintes de fabrication, car elles doivent être exprimées mathématiquement et avec certaines contraintes telles que la dérivabilité, la continuité, etc. Ainsi, dans les opérations de FAO, les ingénieurs de fabrication doivent se ménager pour trouver les paramètres les plus adéquats pour assurer une fabrication de qualité minimisant les coûts et temps de production. Cette thèse s'intéresse à ces étapes de FAO ou de préparation de la pièce. En effet, les paramètres FAO doivent être choisis de façon à adapter la géométries conçue aux spécificités du processus de fabrication et de post-traitement. Les différentes opérations FAO en fabrication additive par fusion sur lit de poudre sont les suivantes :

1. La définition de l'orientation de la pièce dans l'espace production.
2. La définition des régions à supporter.
3. La conception des support.
4. Le choix d'un thème ou d'une stratégie de fabrication (poreuse, compacte).

5. Le nesting pour augmenter la densité de pièces dans l'espace de production.
6. L'exportation de la pièce à fabriquer.

Le choix des paramètres de la FAO nécessite un certain niveau de compétences sur le processus. D'après une étude menée par Grandvallet et al. (2017) auprès d'un industriel utilisant les technologies FLP, on constate que les opérateurs de FAO utilisent principalement le savoir-faire ou l'expertise de leur entreprise lors de la préparation des pièces. Une fois formalisée, cette expertise de l'entreprise peut être utilisée pour aider à déterminer les paramètres de fabrication optimaux qui conduisent à la qualité, au coût et au temps de production requis. Cependant, aujourd'hui il manque clairement d'outils permettant de prendre en compte cette connaissance métier pour proposer des jeux de paramètres optimaux.

Question de Recherche Générale

Les connaissances formalisées pour les opérations de FAO peuvent être considérées comme des règles qui doivent être testées sur une géométrie donnée pour vérifier si elles sont respectées ou non et dans quelle mesure. Par exemple, les experts en FAO peuvent recommander cette règle pour l'orientation d'une pièce donnée : "Orienter les surfaces fonctionnelles de la pièce près de la verticale" ; dans ce cas précis, une bonne orientation de la pièce est celle qui place le maximum de ses surfaces fonctionnelles près de la verticale. Cette évaluation du niveau de conformité d'une règle n'est pas une tâche facile car, non seulement les géométries sont généralement complexes en fabrication additive, mais aussi l'expertise sous sa forme littérale est difficile à quantifier. En particulier, si l'on considère plusieurs règles, la complexité du problème s'amplifie et devient difficile à traiter manuellement. Ces différents besoins conduisent à une question principale qui est :

Comment intégrer les connaissances des experts dans l'assistance aux opérations FAO pour la fabrication additive par fusion sur lit de poudre ?

L'un des principaux objectifs du présent travail est de combler le gap entre les règles exprimées en langage naturel, et leur évaluation sur des géométries quelle que soit leur complexité. Un travail précédent mené par la même équipe de recherche a permis de rassembler un ensemble de ressources de connaissances sur la FAO pour les systèmes FLP (Grandvallet et al. (2017; 2017; 2020)). Le présent travail a pour but de rechercher un moyen d'utiliser ces connaissances pour assister la prise de décision. Cela passe par la possibilité de comparer des scores (c'est-à-dire le niveau de fabricabilité) de plusieurs ensembles de paramètres fabrication.

Première Partie : État de l'art

Utilisation de l'Expertise Métier en FAO

Comme montrée par la Fig. 5.19, l'utilisation de l'expertise métier passe par plusieurs étapes parmi lesquelles l'acquisition auprès d'experts du domaine. Dans le schéma industriel classique, les retours d'information depuis les ateliers de fabrication sont enregistrés dans des rapports pour être réutilisés (Molcho et al. (2008)). Dans le même contexte, d'autres méthodes qui consistent à exploiter des catalogues de machines et des brochures pour capturer les informations des fabricants sont également utilisées (Kumar et al. (2006)). Une des méthodes les plus efficaces pour acquérir de l'expertise métier consiste à effectuer des sessions d'élicitation. Un processus d'élicitation fait référence aux méthodes de « collecte » des connaissances de sources humaines, comme l'indique Cooke (1994).

Une fois que les ressources en connaissances acquises sont traitées et stockées, il existe différentes manières de les réutiliser (Liao (2003)). Dans certains cas, ces ressources peuvent être utilisées pour former de nouveaux travailleurs aux bonnes pratiques de l'entreprise. Autrement, elles peuvent permettre de générer des règles qui sont généralement de type « SI (condition) - ALORS (conclusion) » (IF/THEN) pour assister la prise de décision. Dans la plus part des études dans la littérature, celles-ci permettent d'évaluer la fabricabilité des pièces dans une configuration de fabrication donnée dans le but d'aider dans le choix des paramètres de fabrication. Les systèmes permettant de faire ces évaluations sont appelés système experts et sont capables de guider la prise de décision en se basant sur une démarche de déductions (système d'inférence). Plusieurs travaux ont proposés des systèmes de divers type parmi lesquels les plus utilisés sont les systèmes basés sur des règles (Chan (2003), Kusiak and Chen (1988)), les systèmes utilisant un processus de hiérarchie analytique (Ong and Chew (2000)), les systèmes basés sur la logique flou (Korosec et al. (2005), Ong et al. (2003)), les systèmes orientés objet (Horvath et al. (1999), Amalnik and McGeough (1996), Giachetti and Alvi (2001)) etc.

Globalement en FAO traditionnelle, l'évaluation de la fabricabilité respectant un certain nombre de règles passe par la décomposition en éléments simples de la géométrie

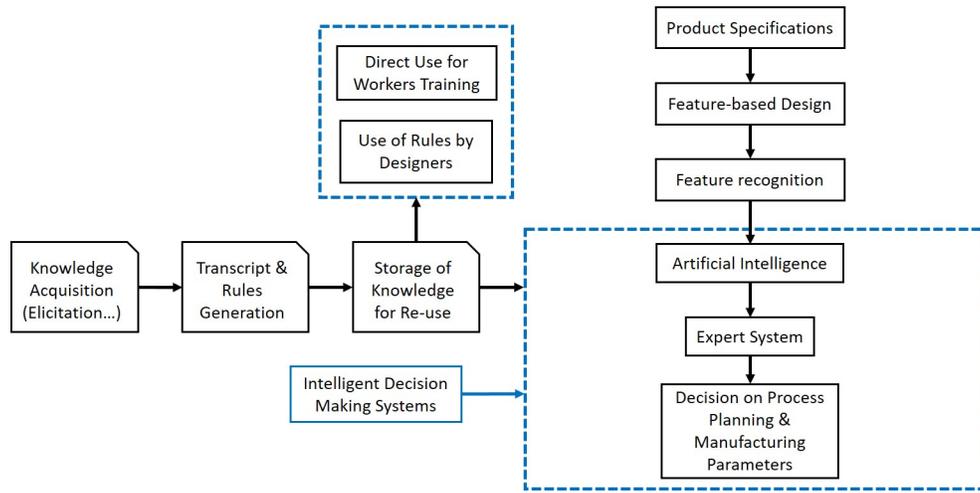


Figure 5.19: De l'acquisition à l'utilisation de la connaissance en FAO (schéma adapté de Kumar (2017))

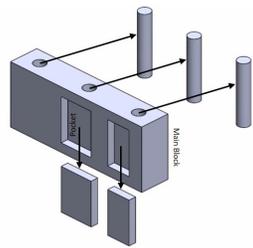


FIGURE 5.20 : Décomposition de géométrie – Feature Recognition

considérée afin de faire leur correspondance avec des éléments prédéfinis dans une base donnée. Par exemple, pour analyser la fabricabilité de la pièce de la Figure 5.20, celle-ci est décomposée en entités simples ; ensuite, la fabricabilité de chaque élément est évaluée séparément. Ceci n'est généralement pas possible en fabrication additive d'autant plus que les formes sont complexes et souvent organiques.

Ressources en Connaissances Disponibles en Fabrication Additive

Typologies de Connaissances

Les connaissances collectées par élicitation ou d'autres méthodes peuvent être de différents types (Lundvall (2004)), ainsi que de différents niveaux (profond ou superficiel comme mentionné par de Jong et Ferguson-Hessler (1996)). Cependant, même si elles sont de natures diverses, les connaissances ont le plus souvent été classées comme procédurales, déclaratives ou conditionnelles (Nonaka (1994), Alexander et Judy (1988)). La connaissance déclarative est définie comme une information factuelle correspondant au « savoir quoi » (Alexander et Judy (1988)). La connaissance procédurale fait référence à une compilation de connaissances déclaratives en unités fonctionnelles correspondant au « savoir comment » (Gorman (2002)). La connaissance procédurale décrit les actions à effectuer dans un domaine précis pour des objectifs spécifiques ; il s'agit donc d'une connaissance méthodologique (Nonaka (1994)). La connaissance conditionnelle indique « quand » et « où » appliquer une procédure particulière ; il s'agit donc d'une connaissance procédurale qui s'applique lorsque des conditions spécifiques sont vérifiées.

Plus concrètement, dans le domaine de la fabrication additive, Grandvallet et al. (2017) ont identifié cinq sous-catégories de connaissance déclarative qui sont les *définitions, exemples, influences, lois* et *règles d'état*, et une sous-catégorie de connaissance procédurale nommée *règle d'action*.

Exemples :

- Règle d'état : Si utilisation de supports, alors existence de marques sur les surfaces et besoin d'effectuer une finition.
- Influence : L'utilisation de supports a une influence sur la qualité d'une surface.
- Loi : Qualité de surface = f(quantité de marques de supports)
- Règle d'action : Minimiser les marques de supports sur les surfaces non-usinées.

Pour des perspectives de prédiction dans la prise de décision sur des paramètres FAO, les règles d'action apparaissent comme étant très appropriées. Dans cette étude elles sont utilisées pour décrire les connaissances d'experts pour la prise de décisions. La section suivante présente quelques règles d'action utilisées pour l'orientation des pièces dans un contexte industriel.

Connaissances d'experts industriels sur l'orientation des pièces

À ce jour, les travaux d'élicitation de connaissances en fabrication additive sont encore rares. Cependant, des travaux récents menés par Grandvallet et al. (2017) et Grandvallet et al. (2020) ont permis d'identifier quelques données d'élicitation pour l'EBM. En effet, ils ont utilisé une technique d'élicitation appelée "iterative limited information task" pour acquérir des connaissances d'experts sur la sélection de l'orientation des pièces et la construction des structures de support. Quelques règles d'action (extraites de Grandvallet et al. (2020)) sont présentées ci-dessous.

- *AR1. Minimize part shadow on start plate*

La surface projetée de la pièce sur le plateau de construction doit être minimale pour permettre un nesting maximale, et donc augmenter la quantité de pièces fabriquées dans un lot. L'étendue de l'ombre varie en fonction de l'orientation de la géométrie.

- *AR2. Minimize total of overhanging non-machined surfaces*

Selon sa topologie et son orientation, une pièce peut comporter différentes zones en surplomb. En fabrication additive en général, ces surfaces surplombantes présentent des déformations résultant du retrait et du « warping » dus aux contraintes résiduelles (Körner (2016)). Pour altérer ou éliminer ces effets néfastes, des supports sont ajoutés au cours du processus de fabrication pour ancrer la surface (Hussein et al. (2013)). Cependant, après leur enlèvement, ces structures de support laisseront à leur tour des traces indésirables qui auront un impact sur la qualité de surface. C'est pourquoi, la plupart du temps, des opérations de post-traitement telles que l'usinage ou le meulage sont effectuées pour améliorer la finition. Cette règle vise alors, à minimiser ces coûts supplémentaires de finition en trouvant une orientation globale qui minimise les surfaces en surplomb.

- *AR3. Orient part priority surfaces (PPS) close to vertical*

Les surfaces prioritaires constituent les surfaces les plus importantes d'une pièce donnée. Selon les experts, une surface est dite prioritaire lorsqu'elle doit être de bonne qualité dès l'étape de fabrication additive (FLP), c'est-à-dire qu'aucune opération de post-traitement (finition, polissage) ne sera effectuée sur celle-ci. En bref, une surface prioritaire doit être acceptable ou bonne "en l'état". Pour atteindre une certaine qualité, ces types de surfaces doivent être orientées verticalement ou à proximité de la verticale.

- *AR4. Orient machining datum surfaces (MDS) out of horizontal*

Comme le post-traitement est généralement nécessaire pour les pièces FLP (en particulier l'usinage des surfaces fonctionnelles), il est nécessaire pour les ingénieurs CAO ainsi

que pour les ingénieurs FAO de penser au positionnement isostatique. C'est pourquoi, dans l'activité d'orientation des pièces, ces surfaces doivent être clairement indiquées; elles sont appelées surfaces de référence d'usinage. Les imprécisions liées au parallélisme, à la perpendicularité, à la planéité (principalement), etc. doivent être évitées. Les experts ont indiqué que ces surfaces de référence d'usinage devraient être orientées hors de l'horizontale afin d'éviter de telles inexactitudes.

- *AR5. Minimize shape deformation risks*

Les pièces fabriquées par fusion sur lit de poudre présentent généralement des déformations liées au processus de solidification des couches de métal en fusion. Par expérience, si un certain nombre de longues couches sont empilées, il peut y avoir des risques de déformation par retrait progressif (Vo et al. (2018)). Par conséquent, la forme finale s'écarte complètement de celle conçue par la CAO.

- *AR6. Avoid support structures and support removal difficulty on surfaces with potential support difficult to remove (SSDR)*

La formulation de cette règle d'action peut sembler complexe, mais en bref, il signifie "ne pas mettre de structures de support sur une surface si vous ne pouvez pas ou avez des difficultés à les enlever après la fabrication". Ce type d'exigence n'est généralement pas traité dans la littérature. Un support mal situé peut nécessiter de grands efforts ou prendre beaucoup de temps et peut même être non-retirable. Pour ces raisons non rentables pour une entreprise, les ingénieurs FAO procèdent généralement à cette analyse, mais manuellement, ce qui n'est pas toujours facile avec les formes complexes dont il est question.

Conclusions sur l'état de l'art

Les systèmes experts basés sur des règles (de type IF/THEN) et la reconnaissance des fonction CAO (décomposition de géométrie) restent les méthodes les plus utilisées aujourd'hui pour assister le choix des paramètres de fabrication. Ces solutions peuvent présenter des limites par rapport aux objectifs du présent projet. D'une part, parce qu'elles sont généralement procédurales. Cela signifie que l'application d'une règle dépend de l'application d'une autre règle spécifique suivant une condition. Ce type de raisonnement ne convient pas avec les règles d'action. Les experts essaient souvent d'évaluer parallèlement les règles d'action pour une configuration de fabrication donnée afin d'évaluer leur niveau de conformité.

D'autre part, l'évaluation passe par la décomposition géométrique des pièces en formes de base reconnues par le solveur du système. Les limites de son utilisation dans la

fabrication additive sont liées à la grande complexité des formes. Dans la plupart des cas, la décomposition n'est pas possible sur les formes organiques (issues de l'optimisation topologique).

Selon les experts, les règles d'action sont appliquées simultanément pour voir dans quelle proportion la géométrie concernée est conforme lorsque les paramètres de la FAO sont appliqués. Pour cette raison, les moteurs d'inférence (utilisant des règles IF/THEN) ne seraient pas adaptés à l'évaluation du niveau de conformité (valeurs quantitatives) des règles d'action. À l'heure actuelle, il est difficile de trouver des outils permettant ce type d'évaluation pour la fabrication additive. Les évaluations quantitatives passent par la représentation mathématique des règles. À cet égard, la question de recherche affinée de ce travail est la suivante :

Comment mathématiser les règles d'action des experts pour assister la prise de décision dans les opérations de FAO pour la fabrication additive par fusion sur lit de poudre ?

Deuxième Partie : Approche de mathématisation des règles d'action

Approche générale

Cette partie propose d'utiliser les fonctions de désirabilité (issues des approches de prise de décision) afin de mathématiser les règles d'action. L'approche mathématique vise à transformer une règle donnée (sous forme littérale) en fonctions de désirabilité (forme mathématique). De cette façon, le niveau de conformité de chaque AR est obtenu par le calcul de sa valeur de désirabilité.

La Figure 5.21 résume les étapes générales de la méthodologie. Pour une règle d'action donnée :

- La première phase codifie son contenu afin de le mettre sous forme d'objectif (si nécessaire) en utilisant une grammaire commune.
- La deuxième phase procède à une mathématisation de la règle d'action en réalisant un certain nombre d'étapes qui seront décrites.

Dans toute la phase de mathématisation des règles d'action, les connaissances sont générées avec la collaboration des experts. Par conséquent, ce processus fait partie du processus d'élicitation et implique les experts ainsi que l'équipe de recherche.

Codification des Règles d'Action

Les règles d'action acquises auprès des experts sont exprimées sous différentes formes avec des structures grammaticales différentes. C'est la raison pour laquelle, ce travail propose de codifier les règles d'action sous forme d'objectifs en utilisant une grammaire commune

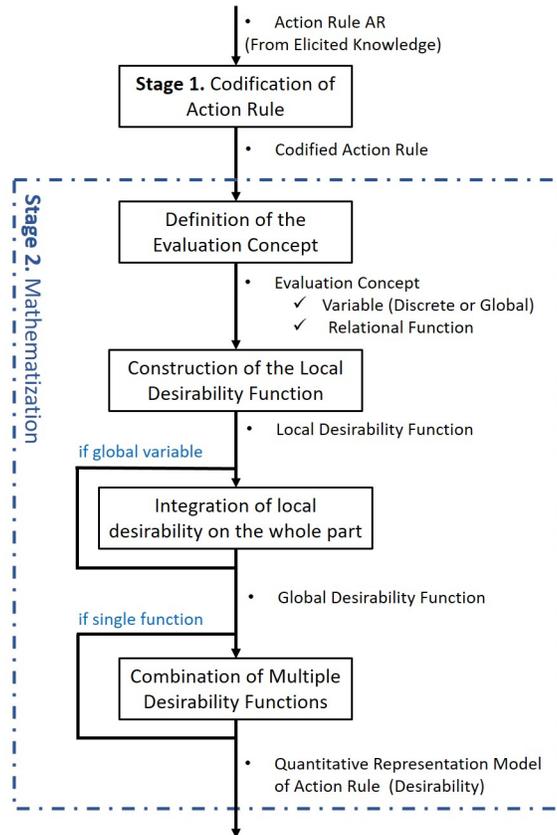


Figure 5.21: Approche de modélisation des règles d'action en fonctions mathématiques

composée de mots classés dans différentes catégories de concepts liés au domaine. Chaque règle d'action comporte implicitement un objectif à atteindre. La codification vise à montrer explicitement cet objectif en remplaçant son verbe d'action. Par exemple, la règle « Orienter les surfaces de référence d'usinage hors de l'horizontale » cherche à obtenir le maximum de surfaces de référence d'usinage possibles hors de la position horizontale. Par conséquent, la version codifiée de cet exemple pourrait être soit « Maximiser les surfaces de référence d'usinage hors de l'horizontale » ou encore « Exiger les surfaces de référence d'usinage hors de l'horizontale ». La Figure 5.22 montre un exemple de classification des concepts d'une règle d'action.

Les concepts sont classés en trois catégories à savoir *Pièce (Part)*, *Concept d'Évaluation (Evaluation Concept)* et *Action*. La classe Pièce regroupe les différentes informations

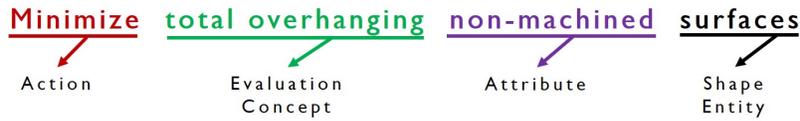


Figure 5.22: Codification des concepts d'une règle d'action

liées à la géométrie en question. Les concepts d'évaluation sont la base de la prise de décision par le biais d'une règle d'action puisqu'ils permettent d'évaluer et de comprendre les conséquences d'une action sur les exigences finales, à savoir la qualité, le coût et le temps de traitement des pièces. Les actions sont introduites pour normaliser les règles afin de les exprimer explicitement en tant qu'objectifs en utilisant les mots suivants : minimiser, maximiser, éviter ou exiger. Minimiser et maximiser sont utilisés lorsque des cas intermédiaires sont acceptés, c'est-à-dire que ces termes permettent de compenser le niveau de conformité des règles. En revanche, les termes éviter et exiger sont utilisés lorsque les cas non acceptables (désirabilité nulle) ne peuvent être compensés.

La Figure 5.23 fournit quelques éléments de grammaire en accord avec les règles d'action proposées dans la partie une.

de l'élément géométrique, est faite. La première étape de la mathématisation consiste à identifier cette variable \hat{y} ; ensuite, la manière de mesurer la valeur de \hat{y} sur l'entité géométrique en question est définie. Enfin, l'évolution du concept d'évaluation en fonction de \hat{y} est établie. Les résultats attendus sont la variable elle-même, la façon de la mesurer et la fonction qui la relie au concept d'évaluation.

Identification de la variable

L'identification implique l'avis d'experts sur la variable quantifiable de l'entité géométrique qui a le plus grand impact (ou qui a un impact significatif) sur le concept d'évaluation. En effet, chaque élément géométrique a ses variables caractéristiques; par exemple, pour une surface, l'angle, l'aire ou l'aire projetée peuvent être identifiés. La variable ayant le plus d'impact sur le concept d'évaluation sera indiquée comme \hat{y} .

Mesure de la variable sur l'entité géométrique

Comme mentionné au point précédent, l'ensemble des variables mesurables est limité et dépend également des capacités de l'outil CAO utilisé.

Dans certains cas, une méthode de discrétisation spécifique pour l'évaluation locale est nécessaire. Par exemple, pour trouver l'angle local \hat{y} d'une surface complexe par sa normale, il est de bonne pratique de trianguler cette dernière pour la transformer en surfaces élémentaires triangulaires planes. Lorsque cette discrétisation se produit, un opérateur de combinaison permettant d'agréger les valeurs locales individuelles peut être nécessaire dans certains cas. En effet, le preneur de décisions doit disposer de la désirabilité globale sur l'ensemble de la pièce au lieu de l'avoir pour chaque élément de surface de la pièce.

Établissement de la fonction relationnelle

Cette étape vise à établir la relation entre \hat{y} et le concept d'évaluation (EC). Cette analyse est l'une des étapes les plus importantes qui permettent de passer d'une vue conceptuelle à une vue mathématique des règles d'action. Le résultat attendu pour chaque variable identifiée est une fonction relationnelle montrant l'évolution du concept d'évaluation en fonction de la variable \hat{y} comme indiqué dans Eq. 5.3.

$$EC = f(\hat{y}) \quad (5.3)$$

Illustrons ceci avec l'exemple ci-dessous :

Étant donné la règle d'action représentée à la figure 5.22, une codification, selon les catégories discutées, permet d'abord d'identifier les concepts sur lesquels l'analyse est

effectuée. Pour rappel, l'attribut *non usiné* indique que la règle d'action ne s'applique qu'à un sous-ensemble des surfaces de la pièce.

Selon sa définition, le fait qu'une surface soit en surplomb dépend de son inclinaison. Ainsi, l'angle de la surface (θ) peut être identifié comme la variable géométrique qui fait le plus varier le concept d'évaluation (surplomb). La mesure de θ n'est pas globale sur la pièce, donc une tessellation (discrétisation) est nécessaire afin de la calculer sur chaque surface triangulaire élémentaire. Ensuite, l'évolution du surplomb en fonction de θ est donnée par les équations ci-dessous (Eq. 5.4) et tracée à la Figure 5.24. En effet, la fonction relationnelle est une sorte de fonction d'existence qui dicte à quel point une surface est en surplomb lorsque son θ varie. Si cette dernière est inférieure à θ_1 , la surface est considérée comme en surplomb. L'intervalle entre θ_1 et θ_2 est une zone d'incertitude pour les experts dans laquelle, la surface devient de moins en moins surplombante. Les valeurs θ_1 et θ_2 peuvent être égales, et dans ce cas la transition entre surplomb et non surplomb n'est pas progressive. Au-dessus de θ_2 , la surface n'est plus en surplomb. Les valeurs seuils θ_1 et θ_2 doivent être indiquées par les experts. Notez également que l'on peut utiliser des fonctions plus complexes.

$$\begin{cases} EC = 1 & \text{if } \theta \leq \theta_1 \\ EC = \frac{\theta_2 - \theta}{\theta_2 - \theta_1} & \text{if } \theta_1 < \theta < \theta_2 \\ EC = 0 & \text{if } \theta \geq \theta_2 \end{cases} \quad (5.4)$$

Par la suite, les fonctions de désirabilité sont construites sur la base des connaissances structurelles établies (variable, fonction relationnelle). Comme le montre la Figure 5.24, les fonctions relationnelles sont représentées entre 0 et 1 sous la forme de fonctions floues, mais pour certains concepts d'évaluation, une fuzzification est nécessaire (voir la section 3.3.3.2 de la version complète du document). Dans le cas de plusieurs concepts d'évaluation, des relations mathématiques (voir la section 3.3.3.3 de la version complète du document) sont utilisées pour réaliser des combinaisons logiques.

Étape 2 : Construction de la Fonction de Désirabilité

La fonction de désirabilité DF de chaque règle d'action est construite sur la base de la fonction relationnelle issue de la définition du concept d'évaluation et de l'action contenue dans la règle d'action elle-même. Pour les actions *minimize* et *avoid*, la fonction de désirabilité correspondante est l'opposée de la fonction relationnelle (Eq. 5.5). D'autre part, pour les actions *maximize* et *require*, la fonction de désirabilité sera équivalente à la fonction relationnelle (Eq. 5.6).

$$DF = \overline{EC} = 1 - f(\hat{y}) \quad (5.5)$$

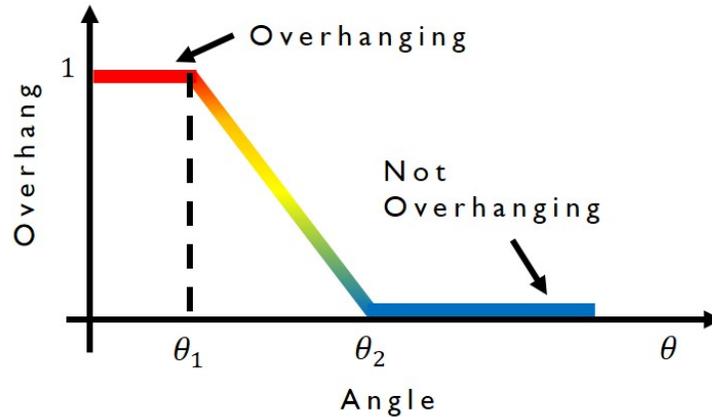


FIGURE 5.24 : Exemple de fonction relationnelle

$$DF = EC = f(\hat{y}) \quad (5.6)$$

Dans l'exemple de la Figure 5.24, la variable reliant l'entité géométrique de la pièce concernée (surface) et le concept d'évaluation (surplomb) est l'angle (θ) de la surface. Pour obtenir la fonction de désirabilité représentant la règle d'action, on utilise l'action correspondante (ici *minimize*). Du fait que cette règle d'action prescrit de minimiser les surfaces non usinées en surplomb, la situation dans laquelle celles-ci sont en surplomb n'est pas désirable et la situation inverse est désirable. Par conséquent, la fonction de désirabilité de la Figure 5.25 est obtenue en inversant la fonction relationnelle de la Figure 5.24.

À titre d'exemple, considérons la géométrie cubique simple illustrée à la Figure 5.26, pour laquelle on recherche l'orientation désirable (vis à vis de la fonction de désirabilité de la Figure 5.25). Les angles seuils de la fonction de désirabilité θ_1 et θ_2 sont respectivement de 15° et 55° . Les valeurs de désirabilité sont évaluées localement pour chacune de ses surfaces (toutes considérées comme non usinées). Un résumé des valeurs de désirabilité locales est fourni dans le Tableau 5.7.

Comme illustré, on peut voir que pour différentes orientations de la pièce, la désirabilité de chaque surface est sensible à son inclinaison. Lorsque l'orientation de certaines surfaces est bien désirable, celle d'autres l'est moins. En effet, pour cette géométrie, la typologie de la fonction de désirabilité appliquée (et ses valeurs seuils) ne permettent pas d'obtenir un scénario pour lequel toutes les surfaces ont une désirabilité maximale ($d = 1$). Pour cet exemple, le nombre de surfaces peut facilement être géré lors du choix d'une orientation. Par exemple, il est facile de voir que le scénario 3 semble être le meilleur

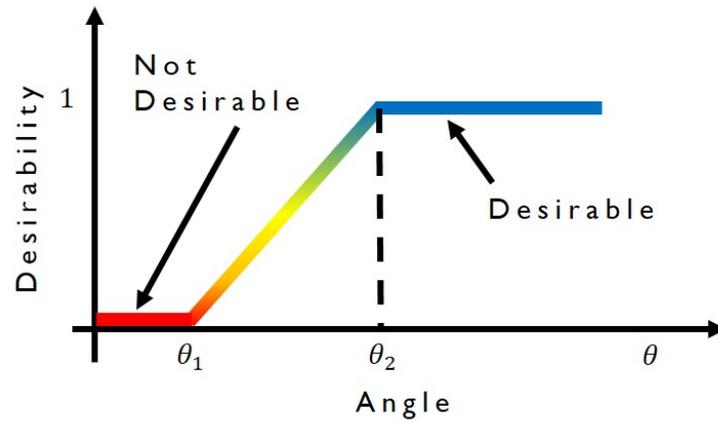


FIGURE 5.25 : Fonction de désirabilité

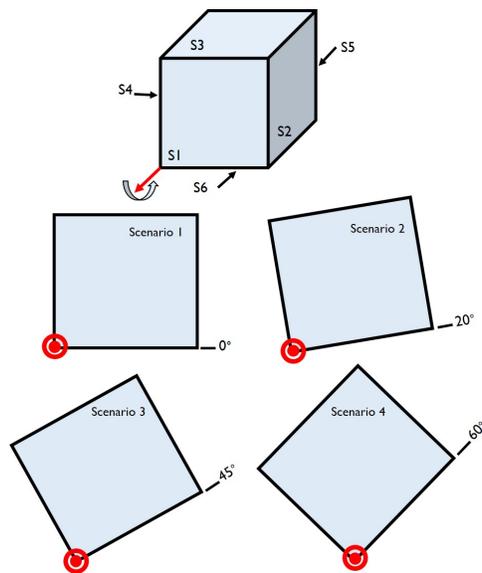


Figure 5.26: Exemple de scénarios d'orientation d'une pièce cubique

	S1	S2	S3	S4	S5	S6
Scenario 1	1	1	1	1	1	0
Scenario 2	1	1	1	1	1	0.125
Scenario 3	1	1	1	0.75	1	0.75
Scenario 4	1	1	1	0.375	1	1

Table 5.7: Valeurs de désirabilité locales pour l'exemple de pièce cubique

selon les valeurs locales. Cependant, si le nombre de surfaces est élevé, on ne peut pas facilement comparer les scénarios. C'est pourquoi, afin de faciliter l'analyse des résultats, les valeurs de désirabilité locales doivent être combinées à l'aide d'opérateurs de calcul de moyenne pour obtenir une valeur de désirabilité globale pour chaque scénario. Différents opérateurs de calcul de moyenne sont présentés dans la section suivante.

Étape 3 : Définition de l'Opérateur Mathématique de Globalisation

Dans cette étude, les sommes et produits pondérés de Hölder sont utilisés. (voir le détail à la section 3.5 de la version complète du document). Pour une pièce donnée composée de j éléments de désirabilité locale d_j la désirabilité globale D est donnée par une des relations suivantes.

$$D = \prod_{j=1}^m d_j^{r_j} \quad (5.7)$$

$$D = \sum_{j=1}^m r_j d_j \quad (5.8)$$

Si les poids r_j sont égaux, les équations 5.7 et 5.8 deviennent équivalentes aux moyennes classiques (géométriques et arithmétiques respectivement). Ici, les r_j sont liés à un paramètre caractéristique de l'élément géométrique concerné. Il peut s'agir par exemple de l'aire relative de la surface j par rapport à l'aire totale de la pièce (Eq. 5.9). Le choix de cette variable de pondération dépend des experts.

$$r_j = A_j / A_{total} \quad (5.9)$$

Le choix de l'opération de calcul de la moyenne dépend de l'action prescrite dans la règle d'action. D'une part, les concepts de minimisation et de maximisation montrent que des valeurs intermédiaires sont autorisées. En réalité, pour ces actions, les valeurs de désirabilité locales sont combinées sur l'ensemble de la pièce de sorte que les valeurs faibles sont équilibrées avec les valeurs élevées. Ainsi, ils utiliseront la moyenne arithmétique pondérée (Eq. 5.8).

D'autre part, les actions *avoid* et *require* (éviter et exiger respectivement) n'acceptent pas les cas de faible désirabilité. Cela signifie que même si une seule des entités élémentaires j a une faible désirabilité, toute la géométrie de n entités aura une faible désirabilité agrégée indépendamment des autres valeurs. La moyenne géométrique pondérée (Eq. 5.7) sera utilisée pour ces actions.

Conclusions sur l'Approche de Mathématisation

Afin d'évaluer le niveau de conformité aux règles d'action sur des géométries, cette partie du travail a présenté un nouveau modèle quantitatif couplé à une méthode d'évaluation visant à faciliter les prises de décisions basées sur des métriques. Dans l'étape de codification, l'objectif d'une règle d'action donnée est clairement indiqué par l'utilisation d'actions spécifiques. Ce résultat codifié de la règle d'action est l'entrée du processus de mathématisation global. Ensuite, le concept d'évaluation est défini ($EC = f(\hat{y})$) à l'étape 1, et à l'étape 2, la fonction de désirabilité ($DF = EC$ ou $DF = \overline{EC}$) est déduite de la définition de ce concept d'évaluation et de l'action. Enfin, si nécessaire, un opérateur mathématique de globalisation est défini en fonction de l'action. Le travail de modélisation est réalisée une fois et les résultats peuvent être utilisés pour n'importe quelle pièce à fabriquer. Dans la pratique, un jeu de paramètres FAO est appliqué, ensuite la désirabilité est évaluée sur la pièce. Si la valeur est faible ou non-satisfaisante, le calcul est répété avec des paramètres FAO différents jusqu'à satisfaction du preneur de décision. Des exemples sont exposés dans la partie suivante.

Troisième Partie : Application de la Mathématisation au Calcul de Désirabilité d'Orientation des Pièces de Fabrication Additive

Quelques Exemples de Règles d'Action pour l'Orientation

Dans cette partie, l'approche de modélisation (proposée en partie 2) sera appliquée aux règles d'action relatives à l'orientation des pièces (présentées en partie 1). Disposant d'un ensemble de règles d'action pour orienter ses pièces de manière optimale, un opérateur chercherait logiquement à évaluer si chaque règle est respectée par la pièce lorsqu'un ensemble de paramètres lui est appliqué. Ici, ce sont des paramètres d'orientation donnés par deux angles (α, β) qui sont appliqués à la pièce.

Il convient de rappeler que pour les experts, lorsque les règles d'action sont globalement conformes, la qualité requise ainsi que le temps et le coût de production optimaux sont considérés comme atteints.

Exemple AR1. Minimiser l'Ombre de la Pièce sur le Plateau (Minimize Part Shadow on Start-plate)

- **Codification**

Dans son expression, cette règle d'action inclut le concept "Minimiser" (*Minimize*) qui est classé dans la catégorie *action*. Le concept de pièce fait référence à l'ensemble de la géométrie considérée. Ainsi, sur la base de la classification proposée en Partie 2, l'entité

géométrique correspondante est le volume. La composition de la règle d'action codifiée est donnée par la Fig. 5.27.



FIGURE 5.27 : AR1 codifiée - classification des concepts

- **Mathématisation**

Cette règle d'action vise à augmenter la densité de d'imbrication des pièces sur le plateau (Grandvallet et al. (2020)). Par définition, minimiser l'ombre d'un objet sur le plateau consiste à minimiser l'étendue de son occupation. Ainsi, la variable qui est susceptible de modifier l'occupation est la surface projetée orthogonale de l'objet. Trois possibilités de projection peuvent être utilisées, comme indiquées à la Figure 5.28. Dans le contexte de la fabrication par fusion sur lit de poudre, la valeur de la Figure 5.28b est choisie car d'autres pièces ou parties de pièces pourraient occuper les zones vides.

Le concept d'évaluation "ombre sur le plateau" est mesuré par rapport à la variable A_s qui correspond à la surface projetée de la pièce, la relation correspondante est donnée dans Eq. 5.10. En faisant varier les paramètres d'orientation, la valeur de la surface projetée

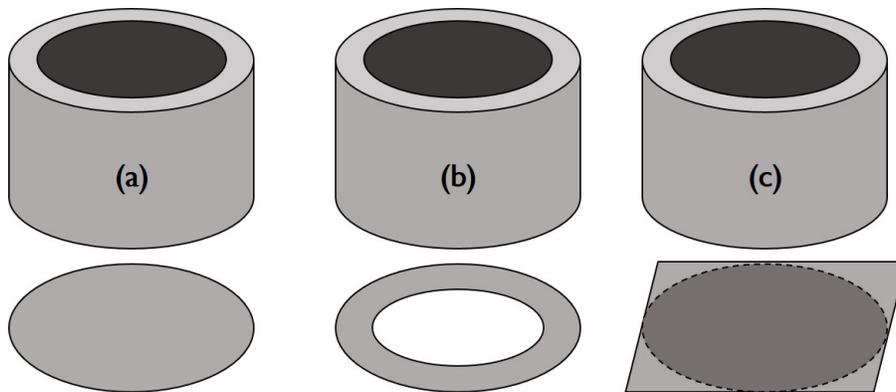


FIGURE 5.28 : Choix de la variable

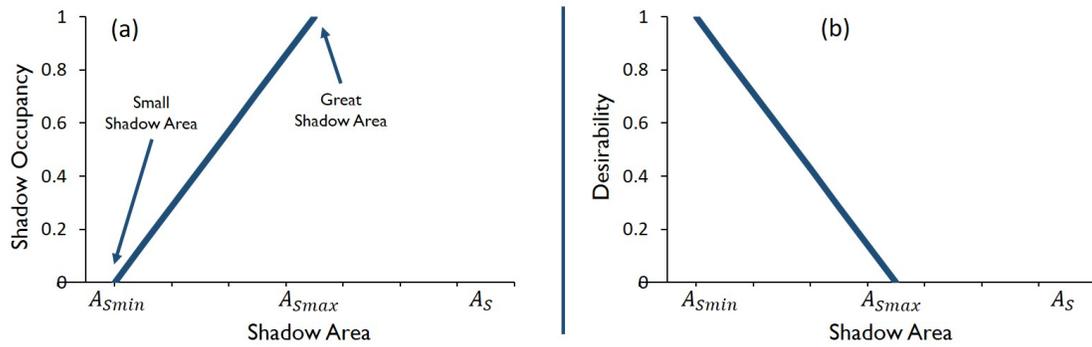


FIGURE 5.29 : AR1 - (a) Fonction relationnelle; (b) Fonction de désirabilité

A_s variera entre A_{smin} (la surface minimale projetée) et A_{smax} (la surface maximale projetée) trouvées lors du balayage du domaine.

$$EC = \frac{A_s - A_{smin}}{A_{smax} - A_{smin}} \quad (5.10)$$

La fonction relationnelle est alors une simple fonction croissante délimitée par A_{smin} et A_{smax} comme illustrée à la Figure 5.29a. En raison de l'action prescrite "Minimiser", la fonction de désirabilité résultante est la négation de la fonction relationnelle; elle est donnée par l'équation 5.11 et est représentée à la Figure 5.29b. En d'autres termes, une grande surface projetée n'est pas souhaitable, alors qu'une petite est souhaitable. Aucun opérateur de calcul de moyenne n'est nécessaire, car la règle d'action s'applique à l'ensemble du volume. Pour cette règle d'action spécifique, les valeurs seuils de la surface projetée ne sont pas prédéfinies par les experts. Elles dépendent entièrement de la géométrie.

$$DF(A_s) = 1 - EC(A_s)$$

$$DF(A_s) = 1 - \frac{A_s - A_{smin}}{A_{smax} - A_{smin}} \quad (5.11)$$

Exemple AR6. Eviter les Supports et les Difficultés d'Enlèvement de Supports sur les SSDR (Avoid Support Structures & Support Removal Difficulty on Surfaces with Potential Support Difficult to Remove (SSDR))

- **Codification**

Cette règle suggère de tenir compte de la difficulté d'enlèvement des structures de support. Dans le cadre de la fabrication par fusion sur lit de poudre, un outil est utilisé pour retirer les structures de soutien après la fabrication. C'est pourquoi il faut tenir compte de l'accessibilité. Ici, en partant du principe que le support est difficile à enlever lorsque la surface en question en a une autre devant elle, l'accessibilité de l'outil dépend de la distance entre les deux surfaces opposées. Une surface est alors qualifiée de SSDR, lorsque son accessibilité est gênée par les autres surfaces environnantes.

Aucune codification n'est requise pour cette règle. La classification des concepts est donnée par la Figure 5.30. Cette règle d'action est un cas particulier qui comporte deux concepts d'évaluation. Par conséquent, deux variables d'influence seront impliquées.



FIGURE 5.30 : AR6 codifiée - classification des concepts

- **Mathématisation**

Le concept d'évaluation A est presque le même que celui de la règle AR2 (surplomb), pour lequel l'angle de surface θ a été identifié comme variable. Habituellement, l'angle seuil à partir duquel une surface est en surplomb est le même que celui à partir duquel une surface nécessite du support lors de la fabrication.

Le concept d'évaluation B est régi par la distance minimale (l) entre la surface considérée et les autres surfaces autour. La méthode du *ray tracing* est utilisée pour mesurer les distances entre la surface élémentaire considérée et les autres surfaces. En effet, à partir de différents points d'une surface élémentaire donnée, des lignes de direction normales sont tracées (Figure 5.31).

Le fait qu'une surface soit une SSDR est donné par l'intersection du besoin de structures de support (A) et de l'existence de difficultés d'enlèvement de support (B). Les

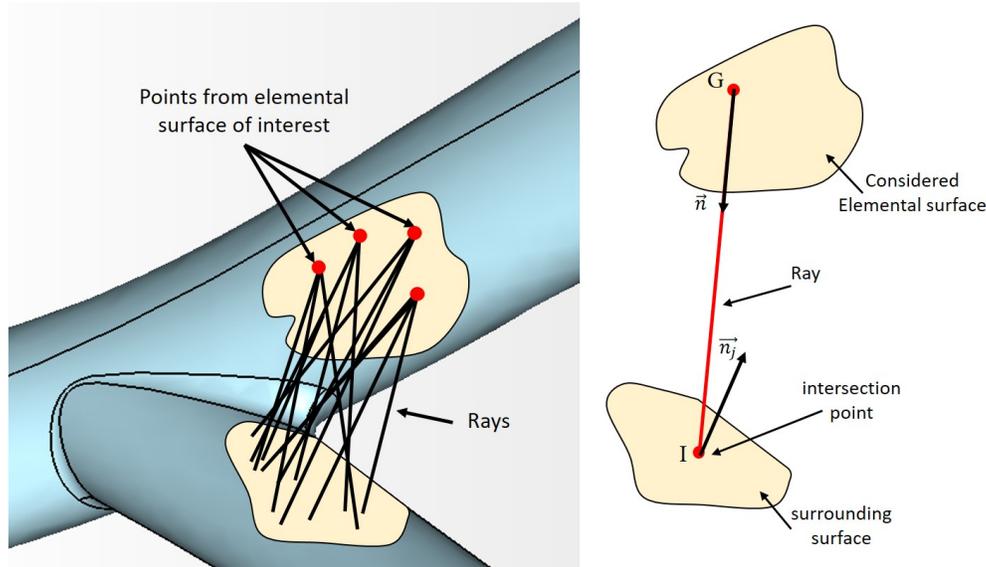


FIGURE 5.31 : Ray tracing pour la détection de surfaces

fonctions relationnelles correspondant à A et B sont représentées respectivement sur les Figures 5.32a et 5.32b. Pour obtenir la fonction de désirabilité, nous nous référons à la reformulation suivante de la règle d'action :

$$AR6 = \text{Avoid } A \text{ and } B \text{ on } SDDR \quad (5.12)$$

En raison de l'action "Eviter" (avoid), la désirabilité est la négation des concepts d'évaluation :

$$DF = \overline{A \text{ and } B} \quad (5.13)$$

En appliquant les lois de De Morgan l'équation précédente devient :

$$DF = \overline{A} \text{ or } \overline{B} \quad (5.14)$$

Pour une surface j donnée, la désirabilité (d_j) est calculée sur la base de chacun des deux concepts d'évaluation. Cependant, deux valeurs de désirabilité sont obtenues, et la valeur globale est calculée en fonction de l'opérateur dans la règle d'action (ET/OU). Ici, avec la transformation effectuée, l'opérateur est OU ; la valeur correspondante est le maximum entre la désirabilité $\overline{A}(d_{jA})$ et celle de $\overline{B}(d_{jB})$ (voir la section 3.3.3.3 de la version complète du document). Ainsi, l'Eq. 5.15 est utilisée. Ensuite, la désirabilité

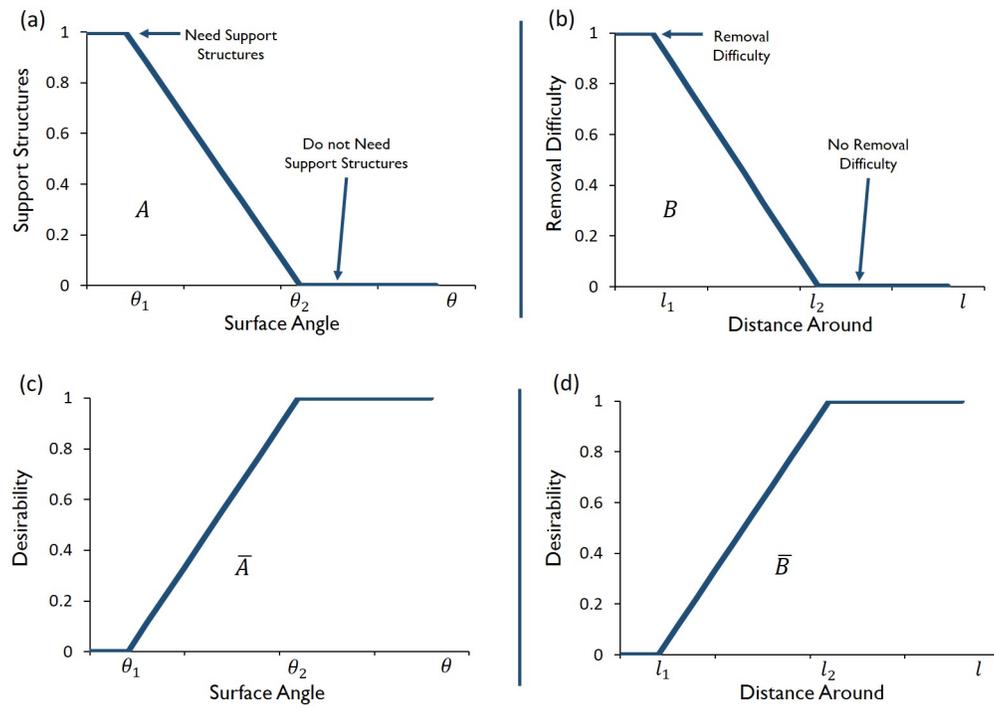


FIGURE 5.32 : AR6 - Fonctions relationnelles : (a) Support en fonction de l'angle ; (b) Difficulté d'enlèvement en fonction de la distance ; Fonction de désirabilité : (c) Négation de A ; (d) Négation de B

globale de la pièce est calculée en utilisant la moyenne géométrique (Eq. 5.16) pondérée par la surface relative $r_j = A_j/A$.

$$d_j = \max(d_{jA}, d_{jB}) \quad (5.15)$$

$$D_{part} = \prod_{j=1}^m d_j^{r_j} \quad (5.16)$$

COFFA : Outil de Calcul de Désirabilité d'Orientation

La modélisation des règles d'action a montré que différents types de variables pouvaient être évaluées sur les pièces. Il serait délicat d'évaluer manuellement les différentes règles, et c'est même impossible pour certains d'entre elles lorsqu'il est question de pièces complexes. C'est pourquoi, un outil interactif nommé COFFA a été développé durant cette thèse. Son but n'est pas de sélectionner automatiquement une orientation (α, β) optimale, mais de calculer la désirabilité de différents scénarios, afin que l'ingénieur ou l'opérateur FAO puisse les analyser et choisir le meilleur compromis. Tous les développements et algorithmes sont codés en langage C++.

Comme le montre la Figure 5.33, des outils sont proposés pour le chargement de fichiers CAO (STEP ou STL), l'importation de fichiers d'expertise contenant toutes les règles d'action et leurs modèles mathématiques, l'exportation de pièces orientées, etc. Sur le côté gauche, il y a quatre onglets ; dans l'onglet Project, on peut trouver la pièce chargée et les attributs analysés à partir du fichier d'expertise importé. L'onglet Parameters permet de définir la plage d'orientation à explorer et de définir les axes (OX, OY, OZ) autour desquels les rotations α et β vont être effectuées. L'onglet Responses montre les valeurs de désirabilité calculées sur des surfaces réponse et l'onglet Analysis fournit des outils d'assistance à la prise de décision.

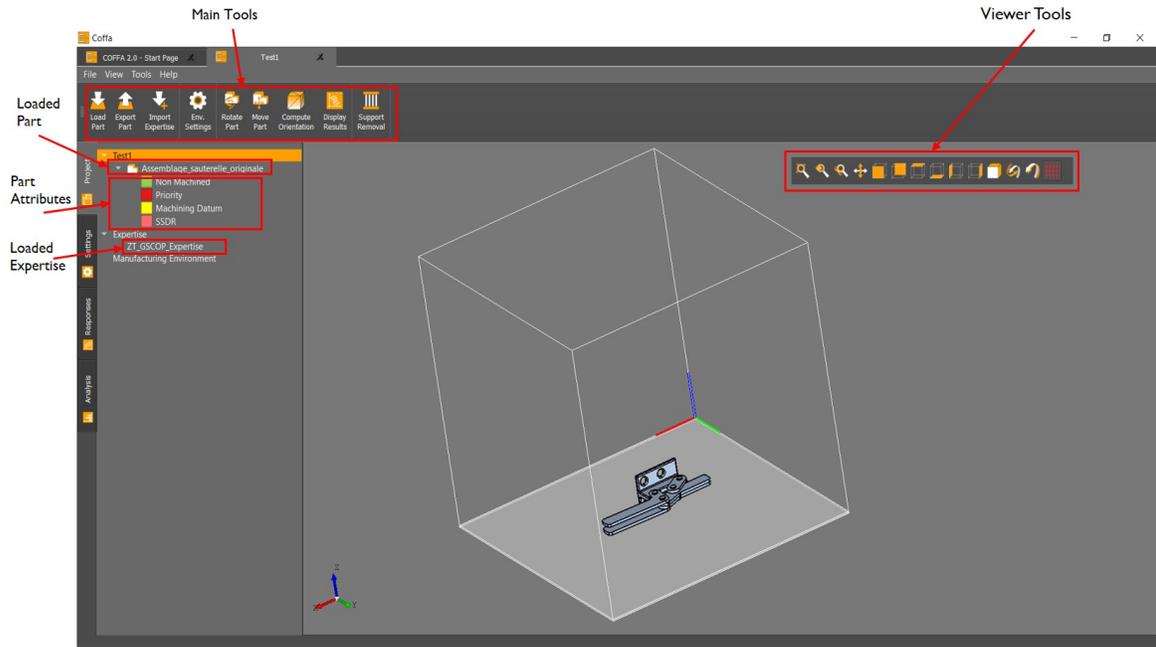


FIGURE 5.33 : Interface de l'outil COFFA

Conclusions

Cette thèse est issue de travaux collaboratifs entre les laboratoires G-SCOP et I2M, et s'inscrit dans la continuité de travaux antérieurs menés sur l'élicitation et la structuration des connaissances en matière de fabrication additive (notamment les méthodes de fusion sur lit de poudre). Ces travaux avaient pour but de fournir des moyens de mathématiser les connaissances d'experts afin d'assister les opérations de préparation de la fabrication, parmi lesquelles l'orientation des pièces a été identifiée comme l'une des plus importantes.

Ce travail a apporté une contribution au domaine en proposant une nouvelle manière d'intégrer et d'évaluer quantitativement l'expertise sur des pièces dans le contexte des opérations FAO en se basant sur l'approche par fonction de désirabilité. À partir de l'étude des typologies de connaissances, les règles d'action ont été identifiées comme les entités de connaissances qui peuvent guider le choix des paramètres de fabrication. Ensuite, un examen de la littérature sur l'orientation des pièces de fabrication additive et des pratiques industrielles a permis de rassembler un ensemble de ressources de connaissances.

Le processus de modélisation a permis de transformer les règles d'action sous forme littérale en fonctions unitaires dont les valeurs sont limitées entre zéro et un. La première étape a consisté à codifier les règles d'action en respectant une grammaire commune afin de rendre visibles les objectifs qu'elles comportent. À l'intérieur des règles d'action, les concepts ont été classés en trois classes qui sont l'action, la pièce (forme avec attributs) et le concept d'évaluation.

Grâce à l'outil COFFA proposé, les preneurs de décisions sont en mesure de justifier les choix qu'ils font sur la base de valeurs de désirabilité. De manière générale, la méthode de la désirabilité présente un autre avantage, à savoir la possibilité de revenir au stade de la conception avec une orientation fixe qui attribue une désirabilité à chaque surface. Celles dont les valeurs de conformité sont faibles peuvent être détectées et ré-optimisées.

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Appendix A – A Tool for Editing Expertise Resources Files

An Expertise Resources Description Framework (XRDF)

The modeling approach detailed by this chapter allows transforming the procedural knowledge (action rules) about one specific topic into mathematical images (desirability functions). Different information arise from the ARs transformation and can be linked with geometrical entities, types of geometrical entities, geometrical operations to perform, analytical values or actions to perform. To ensure the re-usability of these data, they need to be stored in structured files. For this reason, an expertise resources description (XRDF) framework is proposed here. The storing file must be able to describe all the necessary elements allowing the re-construction of the AR and its corresponding mathematical image.

Necessary Data

Globally, an action rule describes a shape entity on which an evaluation concept is calculated with a given objective (the action), and sometimes an attribute is applied. Therefore, the first main information are related to the structure of the AR. Then, from the modeling process, the variable of the part identified as that influencing evaluation concept, is also to be indicated. Similarly, the desirability functions constructed need to be transcribed in the file.

File Structure

Below is detailed the composition of the XRDF file. The edition of an action rule begins with its name and ends with the expression “EndAction”

1. Name: ...
2. Action rule: ...
3. Shape: ...
4. Evaluation concepts: ...
5. Attribute: ...
6. Variables: ...
7. Functions: ...
8. EndAction

The function is described by its points made of two coordinates x and y . The latter are preceded by a sharp character ($\#$). As an AR might have multiple functions, the keyword “EndFunction” is added after the last point before starting the edition of another function. The structure is shown below.

#x1

#y1

#x2

#y2

#x3

#y3

#x4

#y4

...

EndFunction

A tool has been designed under C++ and QT to facilitate the edition of the expertise resources; details about are presented in the section below. Fig. 5.34 shows an example of XRDF file.

```
Name: Overhang
Action rule: Minimize Total Overhanging Non Machined Surfaces
Shape: Surface
Evaluation concepts: Overhanging
Attribute: Non Machined
Variables: Angle
Functions:
#0.000
#0.000
#30.00
#0.000
#50.00
#1.000
#180.0
#1.000
EndFunction
EndAction
Name: Priority Surfaces
Action rule: Maximize Priority Surfaces Close to Vertical
Shape: Surface
Evaluation concepts: Close to Vertical
Attribute: Priotity
Variables: Angle
Functions:
#0.000
#0.000
#45.00
#0.000
#90.00
#1.000
#135.0
#0.000
#180.0
#0.000
EndFunction
EndAction|
```

Figure 5.34: Example of expertise resources description file

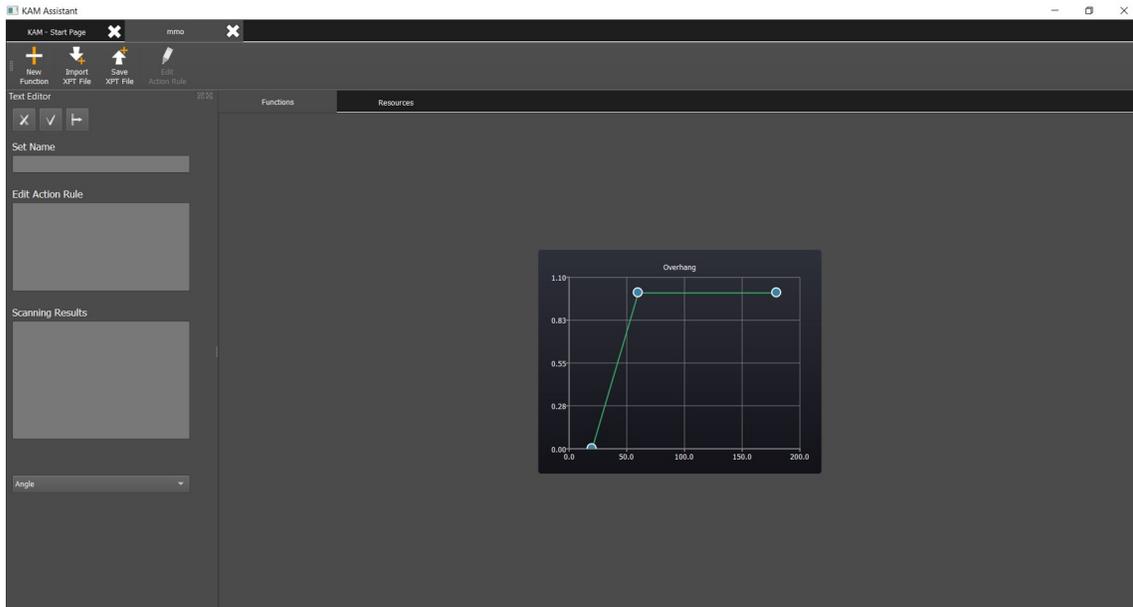


Figure 5.35: Interface for editing XRDF files

Editing Expertise Resources Files

A tool has been designed to assist the creation and the modification of XRDF files. It includes fields dedicated to the literal edition of the ARs and also an interactive interface for manipulating functions. An interesting feature is that, the user can add a small dictionary storing a set of categorized concepts related with the domain of interest. This makes it possible to automatically classify the content of an AR, whenever it is written on the field “Edit Action Rule” (Fig. 5.35). Results are then shown in “Scanning Results”. Otherwise, the user can manually provide the necessary information.

After mentioning the variables, a generate button allows adding a new function for which the points can interactively be moved. The user can also add or remove points from the graph. The tool can support as many action rules as needed. To save the data, the button “Save Expertise” is used to automatically generate a **.xrdf** file that can be also read by using a **.txt** file reader.

To provide more assistance, a perspective is to add ontological tools to help create new evaluation concepts, shape entities and so on.