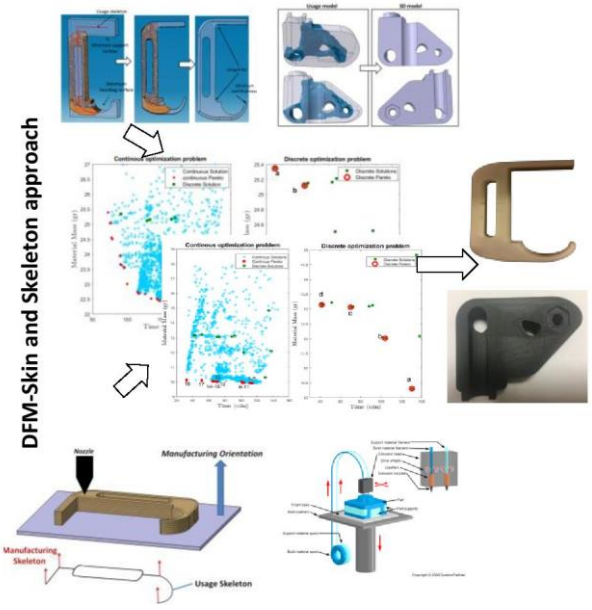
Integrated Design of Additive Manufacturing Based on Design for Manufacturing and Skin-skeleton Models

Elnaz Asadollahi-Yazdi

Thèse
de doctorat
de l'UTT

Elnaz ASADOLLAHIYAZDI

Integrated Design of Additive Manufacturing Based on Design for Manufacturing and Skin-skeleton Models



Spécialité :
Matériaux, Mécanique, Optique et Nanotechnologie

2018TROY0026

Année 2018

utt
UNIVERSITÉ DE TECHNOLOGIE
TROYES

THESE

pour l'obtention du grade de

DOCTEUR de l'UNIVERSITE DE TECHNOLOGIE DE TROYES

Spécialité : MATERIAUX, MECANIQUE, OPTIQUE ET NANOTECHNOLOGIE

présentée et soutenue par

Elnaz ASADOLLAHIYAZDI

le 21 septembre 2018

Integrated Design of Additive Manufacturing based on Design for Manufacturing and Skin-skeleton Models

JURY

M. A. BERNARD	PROFESSEUR DES UNIVERSITES	Président
M. V. DHOKIA	ASSISTANT PROFESSOR	Rapporteur
M. J. GARDAN	PROFESSEUR ASSISTANT	Directeur de thèse
M. P. LAFON	PROFESSEUR DES UNIVERSITES	Directeur de thèse
M. L. ROUCOULES	PROFESSEUR DES UNIVERSITES	Rapporteur
Mme N. TROUSSIER	PROFESSEUR DES UNIVERSITES	Examinateur

Keywords: rapid prototyping, technical design, manufacturing processes, life cycle analysis, multi-criteria decision making, mathematical optimization

Mots clés : prototypage rapide, conception technique, procédés de fabrication, analyse du cycle de vie, décision multicritère, optimisation mathématique

This thesis is dedicated to my dear husband, Mohsen, who has been a constant source of support and encouragement during the challenges of graduate school and life. I am truly thankful for having you in my life. This work is also dedicated to my parents, Asadollah and Tahereh, who have always loved me unconditionally and whose good examples have taught me to work hard for the things that I aspire to achieve.

Integrated design of Additive Manufacturing based on Design For Manufacturing and skin-skeleton models

Abstract

Nowadays, Additive Manufacturing (AM) evolves the manufacturing world by its capabilities for production of the complex shapes layer by layer. Design For Manufacturing (DFM) approach helps to overcome the AM constraints and mastering product features in product lifecycle. Several studies are devoted to integrated design approach for AM, but there is no approach that considers all product life cycle steps in optimization level for product and manufacturing process. So, this thesis provides a DFM approach for AM to investigate simultaneously different attributes, constraints, and criteria of design and manufacturing in product definition. Skin-Skeleton approach models the first definition of product and AM. It contains functional analysis, usage model, and manufacturing model. In this work, a novel interface processing engine as an interface between product and manufacturing model is developed through analysis of AM technologies and their parameters and criteria. This engine relies on a bi-objective optimization problem to minimize production time and material mass under limitation of mechanical properties and roughness of the product to obtain the optimal manufacturing parameters. This methodology permits to define the product model. The approach is implemented into Fused Deposition Modeling to verify the methodology through two case studies.

Keywords: rapid prototyping, technical design, manufacturing processes, life cycle analysis, multi-criteria decision making, mathematical optimization

Résumé

Aujourd'hui, la fabrication additive (FA) fait évoluer le monde de la fabrication grâce à ses capacités de production de formes complexes couche par couche. L'approche de conception pour la fabrication (DFM) aide à considérer les contraintes de FA et à maîtriser les caractéristiques du produit dans la gestion de son cycle de vie. Plusieurs études sont consacrées à l'approche de conception intégrée pour la FA, mais aucune approche ne prend en compte toutes les étapes du cycle de vie du produit dans le niveau d'optimisation de sa conception et de sa fabrication. Ainsi, cette thèse fournit une approche DFM pour la FA afin d'étudier simultanément différents attributs, contraintes et critères de conception et de fabrication dès la définition du produit. L'approche Peau-Squelette modélise la première définition du produit. Il contient une analyse fonctionnelle, un modèle d'usage et un modèle de fabrication. Dans ce travail, un nouveau moteur de résolution, qui agit à l'interface du modèle de produit et du modèle de fabrication, est proposé grâce à l'analyse des technologies FA et de leurs paramètres et critères. Ce moteur repose sur un problème d'optimisation bi-objectif pour minimiser le temps de production et la masse du matériau en proposant les solutions optimales pour les propriétés mécaniques et la rugosité du produit. Cette méthodologie permet de définir le modèle de produit. L'approche est mise en œuvre à travers une première technologie de dépôt par fil fondu (FDM) pour la production de deux études de cas.

Mots clés : prototypage rapide, conception technique, procédés de fabrication, analyse du cycle de vie, décision multicritère, optimisation mathématique

Institut Charles Delaunay (ICD)- Laboratory of Mechanical Systems and Simultaneous Engineering (LASMIS)

Acknowledgment

First and foremost, I would like to express my most sincere gratitude to my supervisors, Pr. Pascal LAFON and Dr. Julien GARDAN for their excellent support and guidance during my research work at LASMIS laboratory and EPF Graduating School of Engineering. Thanks to their priceless advice in scientific research, I have overcome many difficult problems of my thesis.

I would like to acknowledge Pr. Lionel RECOULES and Dr. Vimal DHOKIA who have accepted to read and examine my dissertation. Thank you for your brilliant comments and suggestions. I would also like to thank the members of the jury, Pr. Alain BERNARD and Pr. Nadège TROUSSIER for having accepted to be part of the jury and for their remarks and interesting questions in my PhD defense.

I am so grateful to the EPF Graduating School of Engineering of Troyes which provides possibility for me to study here and to use their Additive Manufacturing laboratory. I would like to show my gratitude to my EPF colleagues for their warmly welcoming and allowing me to join them.

I acknowledge my colleagues in the LASMIS lab, particularly Laurent DANIEL which helped me for 3D printing. I also thank Dr. Pierre-Antoine ADRAGNA for our discussion on Additive Manufacturing characteristics. I am thankful of my friends, Ali RIDA, Kim Trong NGUYEN, Yuchen ZHAO, and Li YIZHUO, and Van Tuan DANG for their support and exchanging knowledge and skills.

I am grateful to thank you all Iranian students in Troyes for our good time after scientific works, exchanges of knowledge, skills during my study which helped enrich the experience.

I gratefully acknowledge the Grand-Est region in France and the European Development Fund regional (ERDF) for their financial supports during this thesis.

Last but not least, I would like to thank my family and my best friends for their support and encouragement during the time far away from home. I must acknowledge my dear parents, Asadollah and Tahereh, and my lovely husband, Mohsen, without whose love and encouragement, I would not have finished this thesis.

Table of contents

List of Tables

List of Figures

List of Abbreviations

ABS	**A**crylonitrile **B**utadiene **S**tyrene
AHP	**A**nalytical **H**ierarchy **P**roces
ALM	**A**dditive **L**ayer **M**anufacturing
AM	**A**dditive **M**anufacturing
AMF	**A**dditive **M**anufacturing **F**ile
ANSYS	**AN**alysis **SYS**tem
ASTM	**A**merican **S**ociety for **T**esting **M**aterial
CATIA	**C**omputer-**A**ided **T**hree-dimensional **I**nteractive **A**pplication
CILP	**C**ontinous **L**iquid **I**nterface **P**roduction
CJP	**C**olor **J**et **P**rinting
DDM	**D**ough **D**eposition **M**odeling
PLM	**P**roduct **L**ifecycle **M**anagement
CAE	**C**omputer **A**ided **E**ngineering
CAD	**C**omputer **A**ided **D**esign
CaCODE	**C**omputer **a**ided **C**onsumer **DE**sign
CDFAM	**C**ustomized **D**esign **F**or **A**dditive **M**anufacturing
CE	**C**oncurrent **E**ngineering
CT scan	**C**omputed **T**omography scan
CMM	**C**oordinate **M**easuring **M**achine
DFA	**D**esign **F**or **A**ssembly
DFAM	**D**esign **F**or **A**dditive **M**anufacturing
DFM	**D**esign **F**or **M**anufacturing
DFX	**D**esign **F**or **X**
DFS	**D**esign **F**or **S**afety
DLP	**D**igital **L**ight **P**rocessing
DMD	**D**irect **M**etal **D**eposition
DMLS	**D**irect **M**etal **L**aser **S**intering
DOE	**D**esign **O**f **E**xperiment
ERP	**E**ntreprise **R**esource **P**lanning
FBS	**F**uncTion **B**ehavior **S**tructure
FDM	**F**used **D**eposition **M**odeling
FFF	**F**used **F**ilement **F**abrication
FRs	**F**unctional **R**equirement**s**
FTI	**F**ilm **T**ransfer **I**maging
FV	**F**unctional **V**olume

HPGL	**H**ewlett-**P**acked **G**raphics **L**anguage
HSM	**H**igh **S**peed **M**achining
IFF	**I**on **F**usion **F**ormation
IGES	**I**nitial **G**raphic **E**xchange **S**pecification
JSON	**J**ava**S**cript **O**bject **N**otation
LENS	**L**aser **E**ngineered **N**et **S**haping
LMJ	**L**iquid **M**etal **J**etting
LOM	**L**aminated **O**bject **M**anufacturing
MAT	**M**edical **A**xis **T**ransformation
MATLAB	**MAT**rix **LAB**oratory
MCDM	**M**lti **C**riteria **D**ecision **M**aking
MD	**M**anufacturing **D**irection
MES	**M**anufacturing **E**xecution **S**ystem
MOGA	**M**ulti-**O**bjective **G**enetic **A**lgorithm
MPM	**M**anufacturing **P**rocess **M**anagement
MRI	**M**agnetic **R**esonance **I**maging
NSGA-II	**N**on-dominated **S**orting **G**enetic **A**lgorithm-**II**
PC	**P**oly**C**arbonate
PDM	**P**roduct **D**ata **M**anagement
PLA	**P**olyLactic **A**cid
PPSF	**P**holy**P**henyl**S**ul**F**one
PSO	**P**article **S**warm **O**ptimization
RAM	**R**andom **A**ccess **M**emory
RSM	**R**esponse **S**urface **M**ethodology
SADT	**S**tructured **A**nalysis and **D**esign **T**echnique
SPEA	**S**trength **P**areto **E**volutionay **A**lgorithm
SLA	**S**treo**L**ithogr**A**phy
SLC	**S**tre**L**ithography **C**ontour
SLM	**S**elective **L**aser **M**elting
SLS	**S**elective **L**aser **S**intering
STL	**S**tandard **T**essellation **L**anguage
TO	**T**opological **O**ptimization
UV	**U**ltra **V**iolet
XML	e**X**tensible **M**arkup **L**anguage
3D	**Three D**imensional
3DP	**Three D**imensional **P**rinting
NP-Hard problem	**N**on-deterministic **P**olynomial-time Hard problem

List of Symbols

$\boldsymbol{x}_{inf}$	Lower bound of decision variables	-
$\boldsymbol{x}_{sup}$	Upper bound of decision variables	-
$\boldsymbol{f}(x)$	Optimization objective function vectors	-
p	Numbers of optimization objective function	-
m	Numbers of optimization inequality constraint function	-
l	Numbers of optimization equality constraint function	-
$f_i(x)$	Optimization objective function for i=1,...,p	-
$c_j(x)$	Optimization constraint function for i=1,...,m,..,l	-
$\boldsymbol{x}^*$	Optimal solutions vector	-
D	Solution space	-
D_f	Pareto front	-
w_i	i^{th} Weight for Objective function	-
L_t	Layer thickness	mm
α	Deposition angle	°
θ_x	Orientation angle along x-axis	°
θ_y	Orientation angle along y-axis	°
θ_z	Orientation angle along z-axis	°
$\boldsymbol{x}$	Decision variables vector	[°, °, °, mm]
$\boldsymbol{u_b}$	Upper bound of AM decision variables	[°, °, °, mm]
$\boldsymbol{l_b}$	Lower bound of AM decision variables	[°, °, °, mm]
R_1	Radius of fillet in layers	0.045
R_2	Radius of corner in layers	0.01
w	Dimensionless parameter of roughness	0.2
d	Nozzle diameter of printer	1.75 mm
σ_{Max}	Maximum mechanical stress	
ρ_{ABS}	ABS density	$1.04\,\mathrm{g/cm^3}$
R_{a}	Surface roughness	µm
e	extrusion width	mm
E	Extruded material	mm
F	Speed	$\mathrm{mm\,min^{-1}}$
L	Coordinate distance	mm
$y(x)$	Roughness profile value	-
l	Evaluation length	mm
y_c	Center line position	mm
T_j	j^{th} traingle of STL file	-
$\boldsymbol{n}$	normal vector	-
$\boldsymbol{z}$	Vertical direction vector	-
$\boldsymbol{n}_{\boldsymbol{T}_{\mathrm{j}}}$	normal vector of triangle j	-
$\boldsymbol{\alpha}_{\boldsymbol{T}_{\mathrm{j}}}$	Deposition angle of triangle j	-
R_x	Rotation matrix along x-axis	-
R_y	Rotation matrix along y-axis	-
R_z	Rotation matrix along z-axis	-
R	Rotation matrix	-

r	radius filament	mm
f	spacing filament	mm
Ω	Filament semicircle for vertical walls	-
Σ	Filament semicircle for inclined surface	-
h	Profile height	mm
Δh	Dimensional deviation	mm
V_1, V_2, V_3	A triplet of the vertices for a triangle of STL file	-
V_{1j}, V_{2j}, V_{3j}	A triplet of the vertices for a triangle j of STL file	-
$\boldsymbol{F_{T1}}$	Total force for first case study	N
M_f	Bending moment	N m
I	Second moment	N m
$a \times b \times h$	Hook bag dimensions	mm*mm*mm
$\boldsymbol{F_F}$	The force applied to front wheel	N
$\boldsymbol{F_B}$	The force applied to back wheel	N
m	Kid weight	20 kg
$\boldsymbol{G}$	The force created through kid weight	N
a_s	The distance between front wheel and car seat	200 mm
b_s	The distance between back wheel and car seat	275 mm
d_w	The distance between back and front wheels	475 mm
$2c_s$	The distance between two front wheels	325 mm
$2d_s$	The distance between two front wheels	295 mm
e, f, L	Spindle dimensions	43.42 mm, 39.8 mm, 33.6 mm
$\boldsymbol{F_L}$	Triangular distributed force applied to spindle along L	N m^{-1}
$\boldsymbol{F_{T2}}$	Total force applied to spindle (second case study)	N
$\sigma_{\text{yield(ABS)}}$	ABS tensile stress at yield	39 MPa
$\sigma_{\text{yield(Steel)}}$	Steel tensile stress at yield	250 MPa

Part I

English Version

Introduction

Outline of the current chapter

Background and motivation

Nowadays, it is essential to respond to industrial challenges towards shorter lead times, lower cost, higher product quality, and better customer satisfaction. Concurrent Engineering (CE) became more important in the success of the companies as a solution for these issues. CE is a systematic approach which performs different tasks in the product and production development process which are then integrated and performed at the same time in parallel rather than in sequence. Integration of design and manufacturing constraints makes it possible to decrease the development lead time and enhances the product quality [1].

On the other hand, Additive Manufacturing (AM) which is derived from rapid prototyping, revolutionizes the industrial world. It creates the possibility to produce different versions of a product with a range of material with specific technologies. The product is manufactured from a 3D model through layer-by-layer manufacturing technology. The unique characteristics of AM encourage the producers to use these technologies, but there are some drawbacks that affect the production performance [2].

The product design and manufacturing for AM are different compared to the traditional

manufacturing processes and it creates new issues and concerns for industrial implementation. Until now, the link between design and manufacturing of additive techniques is often a STL format which does not contain the fabrication information. So, it is necessary to find a methodology to consider all these aspects together.

In the context of Concurrent Engineering and AM, this thesis is motivated to present an integrated design approach of AM.

Problem statement

In the research area of manufacturing of the products by AM, it is intended to investigate the following general problems:

- Suggest a general approach to formulate how to take into account the usage and AM constraints simultaneously in the product definition level.
- Provide an approach to analyze and model the AM process.

To investigate these problems, we encounter some questions:

- How to model and optimize the product to fulfill the customer's requirements?
- How to integrate the manufacturing step and its constraints in the design step to improve the product model in terms of cost, time, and quality?
- Which attributes and criteria are important in the product development process of the fabrication with AM?
- Which parameters of additive technologies have significant effects on the AM attributes, criteria and constraints and how to find the best manufacturing parameters?
- How to integrate all steps of the product development process in a general integrated design approach?

To handle the defined problems and answer to all these questions, it is necessary to present an integrated and complete approach addressing the attributes, capabilities, criteria, and constraints concurrently to provide an interoperable process in product life cycle management for AM.

Integration of design and manufacturing related to AM can facilitate its implementation as it is intended to consider the manufacturing process early in the product definition as an integrated design approach. The product model is completed through a 3D model, manufacturing information, and defined attributes through Design For Manufacturing (DFM) approach.

For this purpose, it is necessary to find a methodology toward an integrated design approach for AM. DFM approach was applied to traditional manufacturing processes through Skin-Skeleton approach in some studies [3, 4]. In this study, this skin-skeleton approach is chosen to model the first definition of the product as a usage model and manufacturing process as manufacturing model. This approach will be completed through an interface processing engine which is an interface between design and manufacturing in order to define the final product model. It is developed through the analysis of all AM technologies and identification of their parameters, criteria, and drawbacks to find the optimized product model.

Objectives

The objectives of this study are summarized as follows:

- Study and analysis of scientific researches related to concurrent engineering, design process and integrated design, Design For Manufacturing, and modeling the product in a general way.
- Investigate the different performed studies related to AM and its technologies.
- Present the contribution regarding the method and new scientific and technological directions in the integrated design approach for AM. The integrated design approach is provided in the product definition level and it gradually maps the product sepecifications to the final product model. It creates an interface between product model and manufacturing model which is a support for the designer in order to select the manufacturing process and to integrate its constraints and attributes as soon as possible during product development process.
- Implement the proposed approach into some case studies to verify it.

Dissertation outline

This thesis is presented in the following four chapters:

Chapter 1: Integrated Design and Additive Manufacturing: State of the art

This chapter introduces the Additive Manufacturing and Integrated Design as the basic concepts of this thesis including background and status of the Concurrent Engineering, AM and product development in the industry. The presented approaches of Integrated Design for AM as the solutions to integrate AM attributes and constraints in design step to define a product model, as well as optimization approaches of AM criteria, are reviewed in this chapter. The literature analysis on the other proposed approaches is prepared which guides the research to the problems and research gaps.

Chapter 2: DFM-Skin and Skeleton approach for AM: Proposed methodology

This chapter describes the proposed methodology as DFM-Skin and Skeleton approach for AM. It provides an integrated approach for AM to consider simultaneously the AM characteristics, criteria, and drawbacks to find the final product model which consists of 3D model and the best manufacturing parameters for production. Skin-Skeleton approach is used to model the first definition of the product and manufacturing process. This methodology is developed based on two propositions. The propositions are different in terms of the methodes that are used for defining usage, manufacturing and interface models. They are developed through analysis of the requirements, design step, AM technologies and finally integration of these steps together to define the product through multi-criteria decision-making methods and multi-objective optimization approach.

Chapter 3: Application into Fused Deposition Modeling

The reliability of the proposed approach is highlighted through two case studies which will be produced by Fused Deposition Modeling as one of the most AM technologies. Firstly, this approach is verified through a case study as a bag hook, then, a more complex case study as a wheel spindle of a child car will be studied to utilize the AM capability to reuse a product by

replacing its broken part. The second case study shows the reliability of our proposed approch for other products.

Chapter 4: Conclusion

To complete this research, the discussion section will be provided to analyze the proposed approach. Then, the key conclusions and perspectives are given in this chapter to guide other researchers to continue their studies in this domain.

1

Integrated design and Additive Manufacturing: state of the art

Outline of the current chapter

1.1 Introduction

Nowadays, Additive Manufacturing (AM) and its different technologies bring a new approach to produce many complex products with different materials. This manufacturing method is derived from Rapid Prototyping and it manufactures the products based on the 3D model in layer-by-layer manufacturing process through different technologies to process the material [5]. The advantages of AM encourage the manufacturers to use additive technologies, while it has some disadvantages and constraints [2]. These unique characteristics, advantages, disadvantages, and constraints require new design tools and practices in order to manage the design and manufacturing process. Also, designers are not completely free to create geometric shapes in this method, that is why several issues must be taken into account during design and manufacturing steps. It is necessary to choose the correct method of design and manufacturing simultaneously in Product Life Cycle Management. Also, it is essential to respond to industrial challenges towards shorter lead times, lower cost, higher product quality, and better customer satisfaction. For this aim, designers must utilize Concurrent Engineering aspects in AM implementation [6]. Concurrent Engineering (CE) helps to integrate design and manufacturing constraints to decrease the development lead time and enhances the product quality [3, 1]. Design For Manufacturing (DFM) as one of the basic concept of CE helps designer and manufacturer to investigate the constraints and attributes of the manufacturing process in the design stage. Finally, it provides a product model by analysis of all attributes and constraints of functional analysis, design and manufacturing concurrently [7].

The remainder of this chapter is organized as follows: firstly, Product Life-cycle Management is described in section 1.2. Concurrent Engineering, Design process and Design for Manufacturing are explained consequently in section 1.3 and 1.4. Then, section 1.5 discusses Additive Manufacturing

and its characteristics and technologies. Finally, Design for Additive Manufacturing approaches are reviewed in section 1.6. According to this literature analysis, the reserach gaps are identified in section 1.7. Finally, this chapter will be finished by a summary of this chapter (section 1.8).

1.2 Product Life-cycle Management (PLM)

Modern manufacturing systems are facing several challenges like shortened innovation lead-times, reduction of time to market, cost reduction, mass customization demands, more complex products, improving product quality, inventories subject to rapid depreciation and rapid fulfillment needs [8, 9]. New information systems are enabled to tackle the different challenges and allow them to show the product information over the whole product life cycle. The emergence of the PLM concept has generated these information systems. PLM is an information technology platform which is able to respond to the needs like reducing time-to-market, enhancing collaboration for global engineering teams, reducing development costs, improving customer satisfaction, and increasing the value of product portfolios [10].

The PLM concept links different product development stages including Computer Aided Engineering (CAE), Computer Aided Design (CAD), Product Data Management (PDM), Manufacturing Process Management (MPM), Enterprise Resources Planning (ERP), etc. in a unique numerical chain. The target is to improve the manufacturing systems criteria like time-to-market, cost, and quality. Actually, there is no unique method which allows managing a project for the development of a product. It is very difficult because of the vast amount of information which comes from different trades [9].

The catchword of PLM is collaborative work within product design processes to integrate all the partners and all associated knowledge efficiently. Design needs to be defined as a collaborative process and can be optimized by allowing upstream integration of data, resources and knowledge. The actual collaborative design is often reduced to asynchronous data exchanges through Product Data Management (PDM), even if some people prefer to speak about "sharing" since the product is a mutual creation. Modeling design activities implies to take into account not only product but also process planning and the processes themselves [9].

The product life cycle goes by a functional definition to a CAD design before being simulated

and manufactured. The principal strategy which modified the sequential organization of work is called Concurrent Engineering (CE) [11]. Concurrent Engineering provides a vision to organize the product development as described in the next section.

1.3 Concurrent Engineering

Concurrent Engineering (CE) is an ideal environment for product development. One of the first general definitions of simultaneous engineering is that of Sohlenius, 1992 [1] who postulates that: "Concurrent engineering means a way of work where the various engineering activities in the product and production development process are integrated and performed as much as possible in parallel rather than in sequence ".

CE is the process of taking into account the needs of each different stages of the product life cycle simultaneously. It aims to integrate product life cycle knowledge earlier during the design process and different engineering activities must be integrated together and performed in parallel [3]. So, the iteration between the design activities which create the advantages in time, quality and cost is reduced. The strategy of CE is to integrate the material and manufacturing constraints into the design procedure as well as, tool utilization must be computer-based to ensure the desired accuracy [12].

CE involves two main areas including design process of the product and the constraints of the product life cycle arising from manufacturing, assembly, recycling, and maintenance. It allows investigating the entire life cycle of the product, from the first expression of the need to final service [3] in order to define a product. So, this approach reduces the iterations between design activities which create the advantages in time, quality, and the cost. The strategy of Concurrent Engineering is to integrate the material and manufacturing constraints into the design procedure by computer-based tool utilization to ensure the accuracy [12].

The CE objectives include improving quality, reducing cost, compressing cycle times, raising productivity and efficiency, and improving the social image. For achieving these objectives, a cooperative teamwork is needed between multiple disciplinary functions to consider all interacting issues in designing product, processes, and systems [7]. The strategies are used to integrate life cycle constraints into the early stages of the design process.

To manipulate the concepts and mechanisms of Concurrent Engineering, the scientific community formalizes them with design methods and they are provided according to the product design process. In the rest of this chapter, the design process will be presented in a general way with the different types of design including systematic and integrated design. Also, it is continued with the section of design methods for manufacturing.

1.4 Design process

The design is the most important stage in the product life cycle and Concurrent Engineering. It is essential to determine the design step in detail to define a product. Also, optimizing the design stage can reduce the total cost up to 70% thereby the production cost is optimized significantly [12].

There are several approaches for design. Firstly, the design is defined as a systematic process which includes the successive steps that performed without evaluation and considering the feedbacks. The second one is an integrated design which provides the design process as the integrated steps [12]. These types of design are defined as follow:

1.4.1 Systematic design

The systematic design is introduced by Beitz et al. 1996 [13] which classified the design process in four evaluation levels:

- **Requirement analysis:** This approach is started with the determination of the customer requirements and product specifications.
- **Conceptual design:** This step consists of definition of the specifications, determination of functional structure, functional principles, and evaluation of conception choices.
- **Embodiment design:** It is including the definition of size and form, model and analysis of these aspects of the product with together, optimizing the functions, evaluating and choosing the plots.
- **Detailed design:** It contains the detailed analysis of the components, selecting the

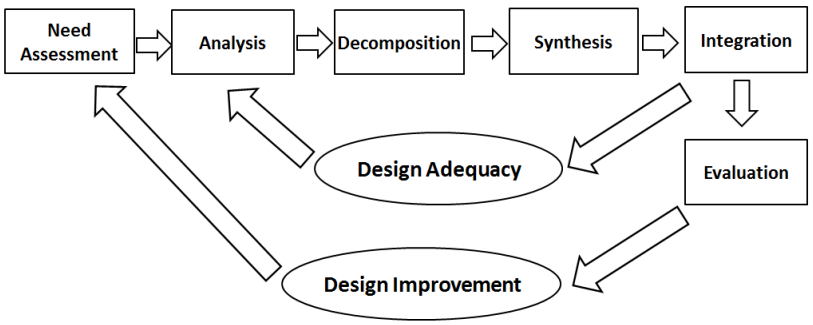


Figure 1.1 – Comprehensive version of general integrated design model [15]

fabrication methods, optimizing the performance and cost, preparing detailed drawing definition.

1.4.2 Integrated design

Integrated design is an approach considering all aspects of the product life cycle in its design like functions, analysis, manufacturing, assembly, recycling, etc. [14]. The general model of integrated design contains two activities of analysis and synthesis as loops. The analysis loop concerns the reasons which analyze and provide the design features due to the product specifications and functional constraints, and the synthesis loop is related to the identification of possible design solutions, as well as evaluation of the validity of the solutions due to the functional requirements [15]. This general model consists of a lot of iterations for designer which should returns to the back for developing the design regarding product specifications as shown in Figure 1.1.

In this approach, the design solution is based on the material constraints, attributes, and designer experiences. Compared to the traditional design process, the integrated design needs less iterations due to the intervention of an actor in all the stages. This integrated design is illustrated in Figure 1.2.

According to Figure 1.2, indeed the simultaneity is demonstrated by overlapping stages of the design process and integration through the involvement of professional actors and stakeholders on each step. Part a and b of this figure are related to systematic design and integrated design respectively. In part c, the integrated design approach is presented according to the work of

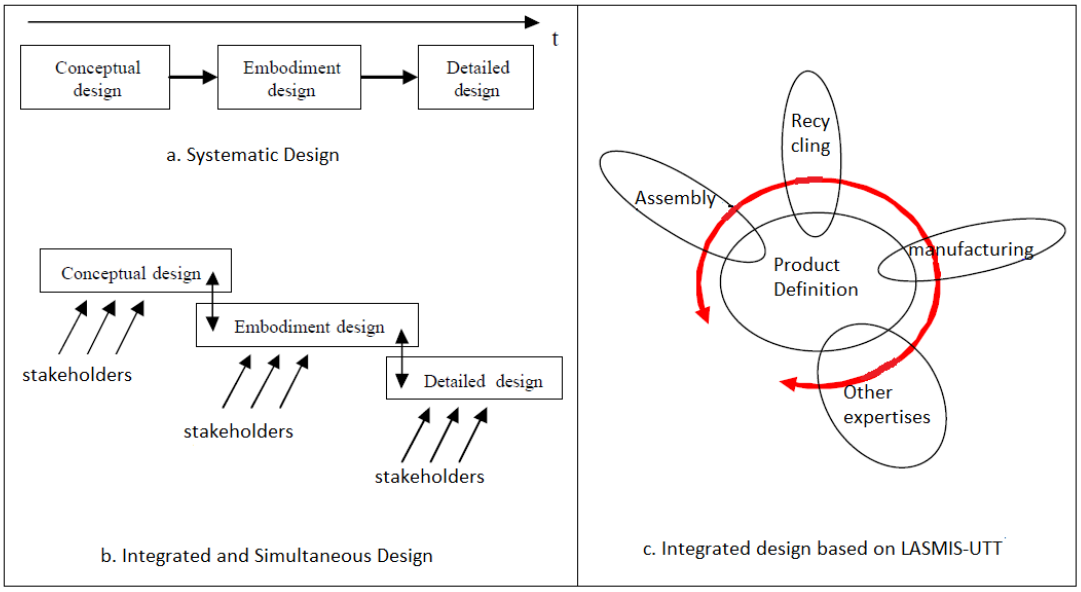


Figure 1.2 – Different design process- a) Systematic Design b) integrated Design c) Integrated design presented by LASMIS [12]

the Laboratory of Mechanical Systems and Simultaneous Engineering (LASMIS). The latter emphasizes the intervention of different expertise profession in the product definition. This approach is known as Design For X (DFX) where X represents the different professional activities. These approaches are classified into two groups of life cycle and virtue (Table 1.1). They provide qualitative design guidelines for a specific stage in product life cycle (e.g. Design for Manufacturing (DFM), Design For Assembly (DFA), Design For recyclability) as $DFX_{lifephase}$, or a specific virtue (e.g. Design For Environment, Design For Safety (DFS)) as DFX_{virtue} [16].

Therefore, DFX which is linked to the Concurrent Engineering and it is used for assessing and integrating "x-field" information independently. Figure 1.3 shows the status of DFX in Concurrent Engineering framework. This DFX approach provides an information model due to design and manufacturing analysis, as well as an interface model which is an interface between design and manufacturing model. Collaborative activities are used in terms of mechanical optimization and analysis to provide this information and interface model.

The problems and defects of product quality are derived from three factors of design, material, and process. These problems are including part fracture, tolerance defects, manufacturing diffi-

Design For X (lifephase)	Design For X (Virtue)
Design For Quality	Design For Assembly
Design For Reliability	Design For Manufacturing
Design For Environment	Design For Service
Design For Logistics	Design For Disassembly
Design For Maintainability	Design For Recycling
Design For Safety	
Design For Re-manufacturing	
Design For User-friendliness	

Table 1.1 – Design For X classification [17, 16, 18]

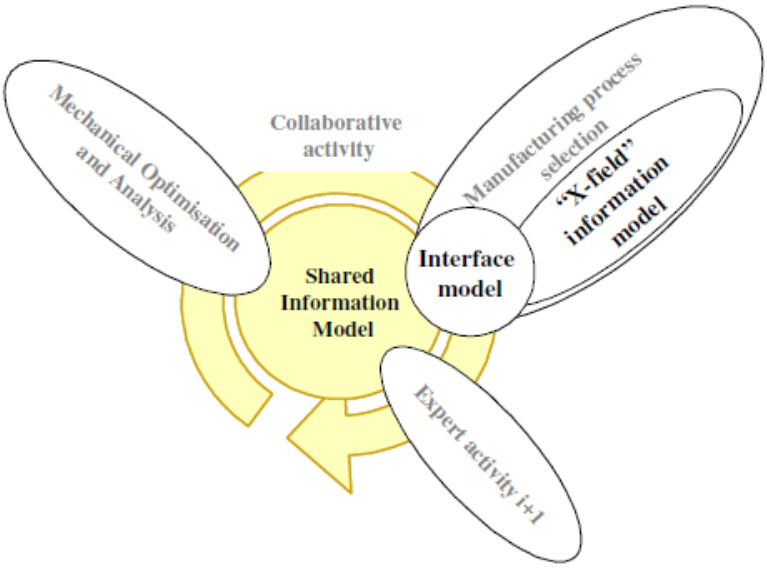


Figure 1.3 – Design For X [3]

culties, assembly difficulties, quality and ergonomic problems, etc. Integrated design approaches can help us to solve these problemes in the design stage. Also, since manufacturing is a sequence of processes for transforming raw or partially processed material into a final product that has value for the customer [19], the manufacturing process is chosen during the conceptual design of the product. All predefined design constraints including the manufacturability of the part, using the companies or suppliers existing machines and processes must be met in the design phase [20]. Also, various studies demonstrated that detecting and rectifying the errors in the design phase of the product cost less than when rectifying at manufacturing or further downstream stages. So, manufacturing must be taken into account during product design as early as possible in the design cycle [12]. Since, about 70% of manufacturing costs of a product (cost of materials, processing, and assembly) are determined by design decision, therefore, handling manufacturing problems in the design stage has an influences on cost, time, and quality. These issues put emphasis on the need for approach of Design For Manufacturing (DFM) to integrate the product design, process planning and manufacturing into one common activity to design a product that is easily and economically manufactured [21]. So, the DFM approach will be explained in the next section.

1.4.3 Design For Manufacturing (DFM)

Design For Manufacturing (DFM) involves simultaneously considering design goals and manufacturing constraints in order to identify manufacturing problems while parts are being designed; thereby reducing the lead time for product development and improving product quality [22, 23]. Actually, it as a methodology which aims to simplify the manufacturing process, increase the productivity and minimize cost while maintaining the product quality in a desirable level [20]. This technique is used to optimize the product and process concepts during the design phase of a product to ensure ease of manufacture [24] by optimizing the manufacturing, quality, productivity, reliability, cost, time of production, and time to market [12]. Generally, the products which are designed based on the DFM approach contains less number of parts that can be assembled more easily in a shorter time and with higher quality [12]. The benefits of DFM can be summarized as follow [12]:

- Improving the product quality during product life cycle development including design,

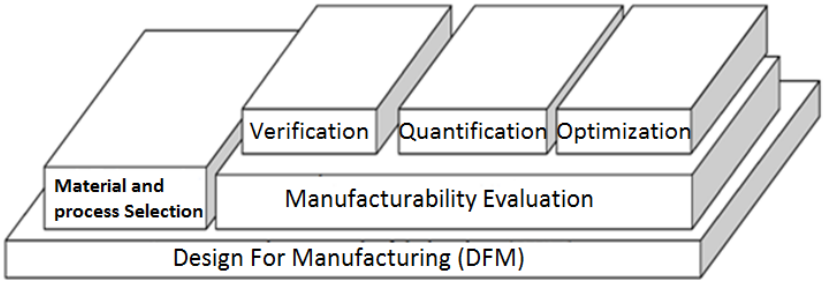


Figure 1.4 – Design For Manufacturing [3]

technology, manufacturing, service, etc. [25].

- Cost reduction, including the cost of design, technology, manufacturing, delivery, technical support, discarding, etc. [25].
- Reduction in development time for new products including the time of design, manufacturing, preparing, and calculation [25].
- The manufacturer participation in the upstream process [26].
- Improving the communication between the departments [24].

DFM is considering the limitations related to the manufacturing at the early stage of the design; the design engineer can make the selection among the different materials, technologies, and schemes to estimate the manufacturing time and the product cost quantitatively. They compare all kinds of the design plans and technology plans, then, design team will make revision as soon as possible at the early stage of the design period according to this feedback information and determine the most satisfied design and technology plan [25].

The systematic DFM approach involves the range of activities such as process selection, material selection, and manufacturability evaluation of a product which is shown in Figure 1.4. This systematic DFM contains some steps as follow:

- **Material and process selection:** Selection of the process and material are the most important factors in providing the design solutions for manufacturing. It is necessary to consider the design optimization during the selection of process activities [27, 12].

- **Manufacturability evaluation:** The evaluation of manufacturability consists of analysis and evaluation of the ability to produce and design with the necessary requirements by spending minimum cost and time. For this purpose, it is necessary to decompose the product to sub-elements (for example, the surface, dimension, tolerance, etc.) due to the manufacturing data. This evaluation is performed through three steps as follow:
  - **Verification:** This step is determining the product manufacturability including identification of the design and manufacturing capacities, accepting the compatible design with the existed solutions of manufacturing for the complex products, and rejecting the design which requires expensive changes in the production system [28].
  - **Quantification:** The parameters like cost, time, and quality must be quantified [26].
  - **Optimization:** Optimization must be performed in three levels of human (competence), means (machines, tools and software) and product (design) [29].

The Skin-Skeleton approach, which has been used in some studies [3, 4] and is applied for the traditional manufacturing processes, can be used to implement the DFM approach. In the next section, skin-skeleton approach as the basic concept to provide a product definition with an integrated design approach is described.

DFM Implementation: Skin-Skeleton approach

In the product development process, several tasks should be performed to gradually map the customer requirements to the final product model. The product is designed according to the constraints related to the whole product life cycle (materials, structural analysis, recycling, etc.). Hence, Concurrent Engineering can help to consider and analyze manufacturing constraints in the product development. This integration in product definition is carried out from sub-model representing common design and manufacturing modeling [30]. For this purpose, a skin-skeleton approach is used to depict the product features by usage model and the information model for manufacturing process by manufacturing model, provide an interface model which allows to synthesize and compare the usage and manufacturing model in order to define the product model. Actually, the product model is an evolved usage model that is developed by considering the manufacturing model information through an interface model.

The Skin-Skeleton approach allows modeling the product and manufacturing process from functional analysis to production step. Generally, skins must describe the product's functional surfaces and skeleton shows the flow trajectory as shown in Figure 1.5. This Figure illustrates an example of usage and manufacturing skins and skeletons to define the product model of a "U" magnet. The usage model coming from customer requirements and manufacturing one is an information model for manufacturing. The required solution is not totally determined and it is constrained by manufacturing model, as well as interface modeling coming from the design and manufacturing. Several design solutions are then available. Specific sets of attributes are associated with the skin such as shape, tolerance, roughness, and material direction which is dependent on the form. Skeleton attributes are initial section form, final section form, section variation, and neutral fiber (line, curve, plate, etc.). Also, an extra attribute defines the material flow direction for manufacturing skeletons. According to this simple concept, final product definition will be provided and analyzed based on manufacturing process selection. Indeed, the final 3D model of a product (made of manufacturing skins) is constructed by sweeping or deforming the skeleton section on the skeleton trajectory. The initial model described with "usage" skin and skeleton must be compared to the "manufacturing" one [3].

This approach consists of Function-Behavior-Structure (FBS) model, usage model (i.e. design requirements), manufacturing model (manufacturing features) and interface model which are described comprehensively as follow:

Function-Behavior-Structure (FBS) model: Gero et al. [32] conceptualizes the design objects as Function (F), Behavior (B), and Structure (S) as FBS model as shown in Figure 1.6. According to the FBS model, designing a product involves a series of elementary steps including transformation of the desired product function into its expected behavior and the expected behavior into a structure [32]. The basis FBS framework is formed by three classes of variables to describe the different aspects of a design object:

- **Function (F):** The object must be described by its function, i.e. what it is for.
- **Behavior (B):** It depicts the attributes that are derived or expected from the structure (S) variables of the object, i.e. what it does.

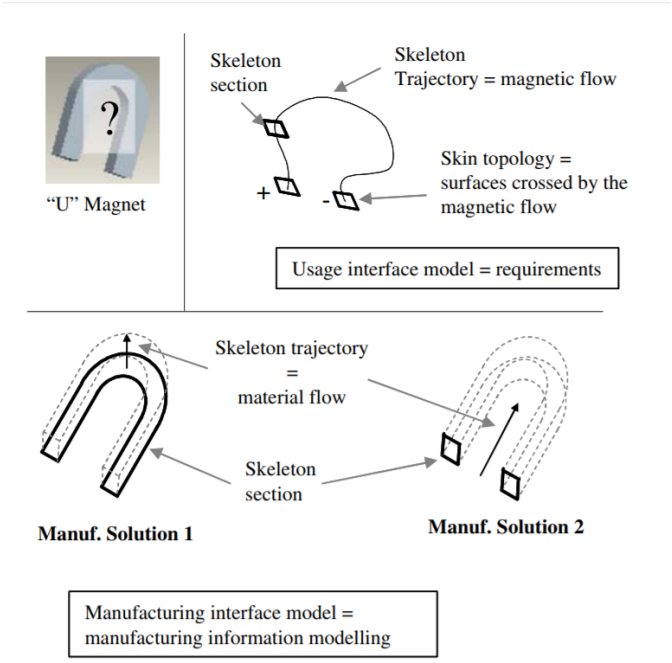


Figure 1.5 – Skin and Skeleton illustration for a "U" Magnet [31]

- **Structure (S):** It describes the components of the object and their relationships, i.e. what it is.

The connections between the function, behavior, and structure of a design object can be created through experience. Specifically, the designer ascribes the function to behavior and derives the behavior from the structure. There is a direct connection between function and structure, however, is not established. The FBS framework represents designing through a set of processes linking function, behavior, and structure together, which can now be seen as different states of the developing design. In this framework, the behavior derived from structure must be compared to the expected behaviors.

The eight processes depicted in the FBS framework (Figure 1.6) are claimed as (1). Formulation, (2). Synthesis, (3). Analysis, (4). Evaluation, (5). Documentation, (6). Reformulation type 1, (7). Reformulation type 2, (8). Reformulation type 3 [32].

In this approach, FBS model provides an initial structure for the product which satisfies its function and behavior. So, it helps to recognize the material flow and identify the usage skin and

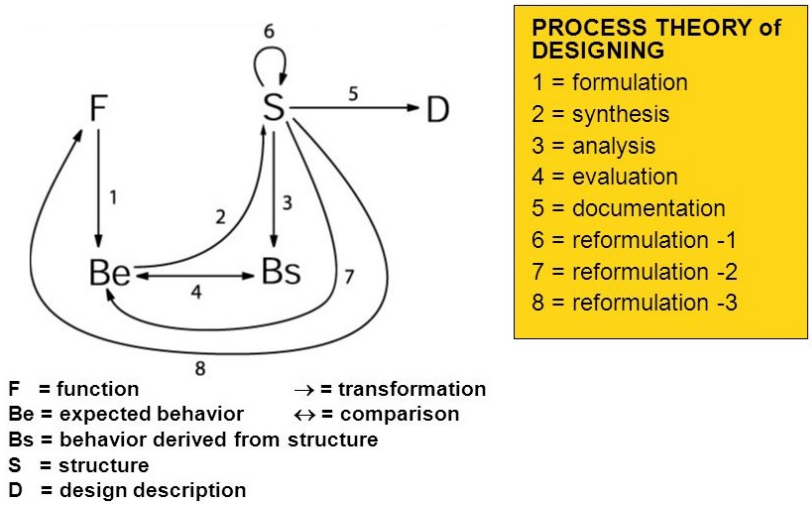


Figure 1.6 – FBS model framework [32]

skeleton by its initial design space.

Usage model: The usage model is used to make a simplified presentation of the product which consists of usage skin and skeleton. Usage skin is defined as a functional surface which energetic flow circulates through it. It supports the geometrical attributes and design specifications. Usage skeleton is an energetic flow that can be mechanical, electrical, magnetic, etc. which circulates in the product. It is specified according to the special required behavior of the product. So, the initial forms must be determined. Then, the possible morphology of the skeleton is proposed by the designer [33, 30, 3].

Manufacturing model: Manufacturing model contains manufacturing process selection information. This information contains process type and its related parameters. Manufacturing skin is just the surfaces which are produced during manufacturing process. The skin features are created from manufacturing skeletons by a sweeping operation. Skeleton is the flow trajectory of material and it is supposed that every manufacturing process is based on the material flow. From a manufacturing point of view, the manufacturing process can be realized due to the forms and surface qualities that the process can perform [33, 30, 3].

Interface model: Identification of usage and manufacturing skin-skeleton allows determining their different parameters and attributes. Finally, integration of manufacturing constraints in the product definition is done gradually as an interface model. Interface model is an output of this approach which demonstrates the relations between the parameters of the manufacturing procedure. In fact, it presents required information that supports the synthesis of design and manufacturing. It provides functional data, the technological solution as material and process selection, and the attributes values.

Therefore, this skin-skeleton approach defines the desired product as a set of usage skin and skeleton. The desired product is a subset of produced product that is a covered manufacturing skeleton, as well as the skin that is manufactured. The product is produced by comparison of usage model and fabrication one as follow [33, 3]:

$$\begin{aligned} &\text{Desired product= Set (usage skeleton+ usage skin)} \subset \\ &\text{produced product = Set (covered manufacturing skeleton)} \\ &\text{= Set (manufactured skin)} \end{aligned}$$

Generally, the main benefit of these modeling concepts is that the manufacturing knowledge is taken into account very early in the product development process and CAD modeling instead of waiting for an initial CAD model which would be modified afterward. The results of this methodology are used in the product model including manufacturing parameters in order to define the best solution(s) for manufacturing. In this research, it is supposed to adapt this methodology for AM as an integrated design approach for AM. So, AM as our determined manufacturing process will be explained in section 1.5.

1.5 Additive Manufacturing

Additive Manufacturing (AM) which is derived from Rapid Prototyping revolutionizes the ways that the products are designed, manufactured, and distributed to the users in the academic and industrial environment over the last three decades [34].

AM is defined by the American Society for Testing Materials (ASTM) as a "process of joining the materials to make the object from 3D model data, usually layer upon layer, as opposed to

subtractive manufacturing methodologies" [35, 36].

It is known as 3D printing and free-form fabrication is commonly used for modeling, prototyping, and tooling through an exclusive machine or 3D printer in the various material types like polymers, metals, etc [37].

The main capability of AM is creating the complex geometries based on a Computer-Aided Design (CAD) model or reverse engineering methodology through layer-by-layer construction manner [37].

Overall, the 3D model must be converted to the AM standard format and it is sliced based on the manufacturing parameters in the appropriate resolution. Different technologies exist to produce the product in the different material through layers accumulation manner [37, 5].

The stage involved in the product design and AM illustrates that the cycle development is specific as shown in Figure 1.7. The engineering and manufacturing cycle is decomposed as [37]:

- Part design in CAD or reverse engineering by 3D scanning.
- Skill optimization in CAE (Computer-Aided Engineering) in order to adapt the part and its geometry to the selected manufacturing technology based on the knowledge of experts.
- Conversion of part geometry in exchange format (STL, AMF,...).
- Exchange file implementation into the specific software of the AM machine.
- Configuration and orientation of the set (parts and supports).

In the next section, the standard format and different AM technologies are described.

1.5.1 AM standard formats

As a link between the design and manufacturing stage, AM uses the standard formats which are compatible with design softwares and AM manufacturing softwares.

There are several types of files like STL (Standard Tessellation Language), Additive Manufacturing File (AMF), stereolithography contour (SLC) and SLI from 3D Systems, CLI from EOS, Hewlett-Packard graphics language (HPGL) from Hewlett-Packard, stereolithography contour

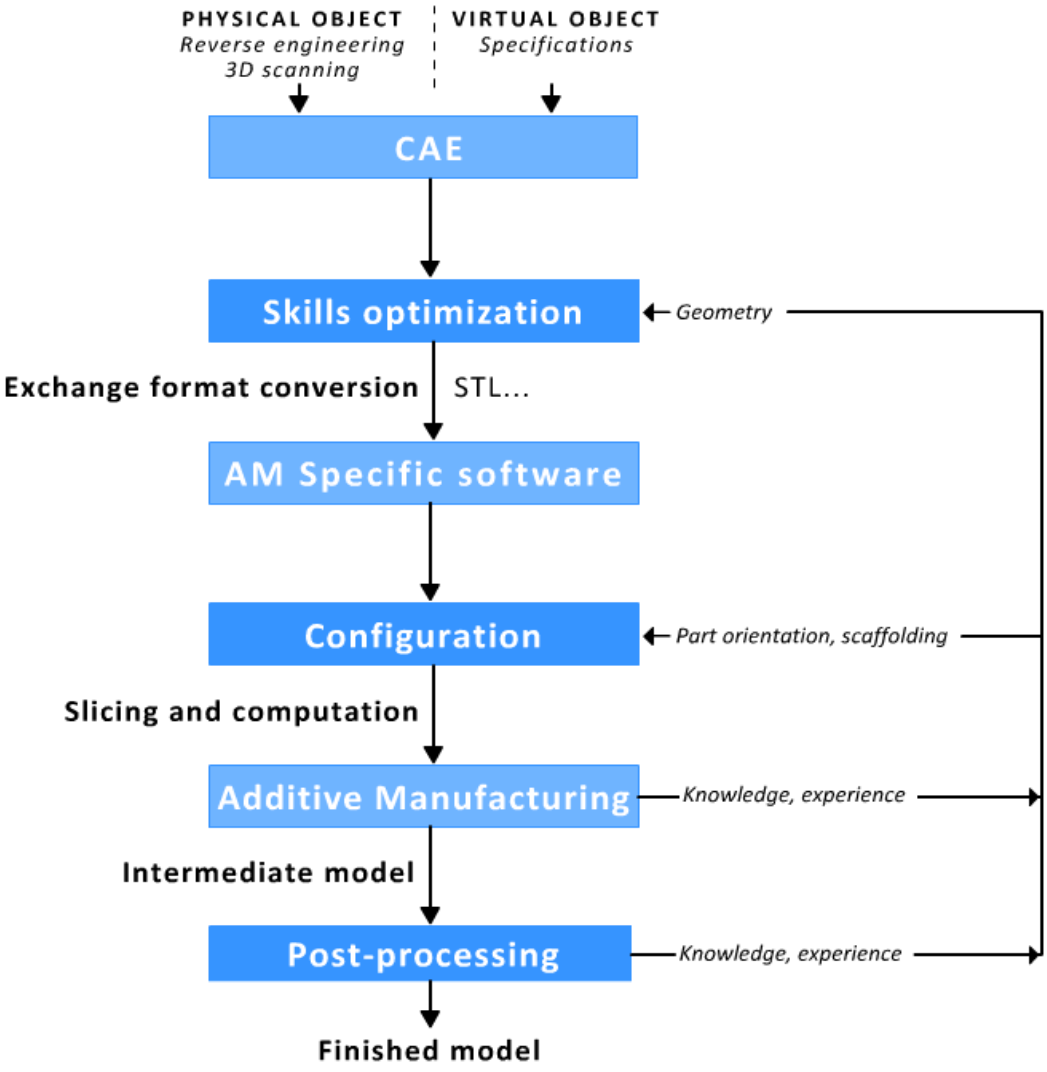


Figure 1.7 – AM engineering and manufacturing cycle [37]

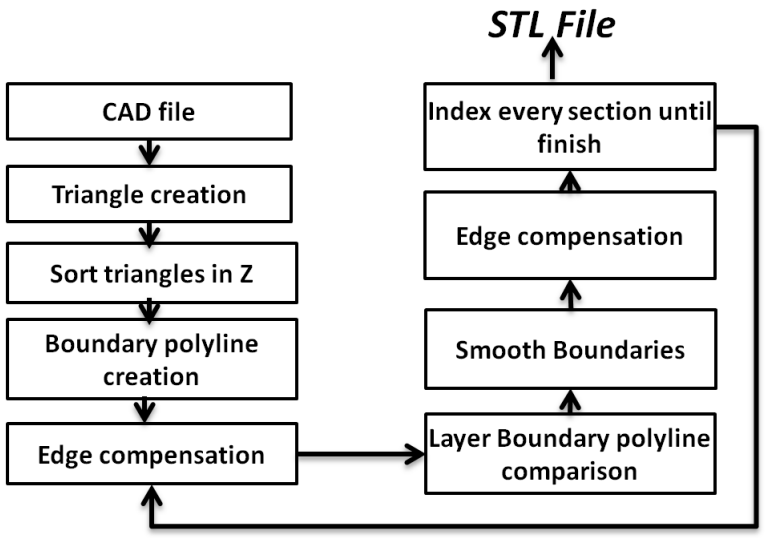


Figure 1.8 – Data flow in STL file creation [40]

from Stratasys, and F-S from Fockele and Schwarze, and initial graphics exchange specifications (IGES) [38, 39]. STL and AMF files are the most used format which will be explained comprehensively in the following:

STL:

STL (Standard Tessellation Language) becomes a standard format for 3D models as the input for AM technologies and software and it can be easily created through all CAD software. The STL file creation process is to convert the continuous geometry as CAD file into small triangles as STL format [37]. The data flow in the STL creation is shown in Figure 1.8. The accuracy of this process is dependent on the triangle numbers. A large number of triangles creates the more closed STL file to the CAD model [40]. In terms of accuracy, Δ as shown in Figure 1.9 is chordal error that illustrates the deviation between 3D model and STL format.

As shown in Figure 1.9, a normal vector $\vec{n}$ and three vertices of A, B and C are used to define each STL facet and two vertices are common in adjacent facets. The facets are the surfaces of 3D objects which consist of an unordered list of triangles [41]. Facet is a part of the boundary between the interior and exterior of the object [37, 42]. STL format is very simple to read, write and process but it contains information only about a surface mesh and has no provisions for

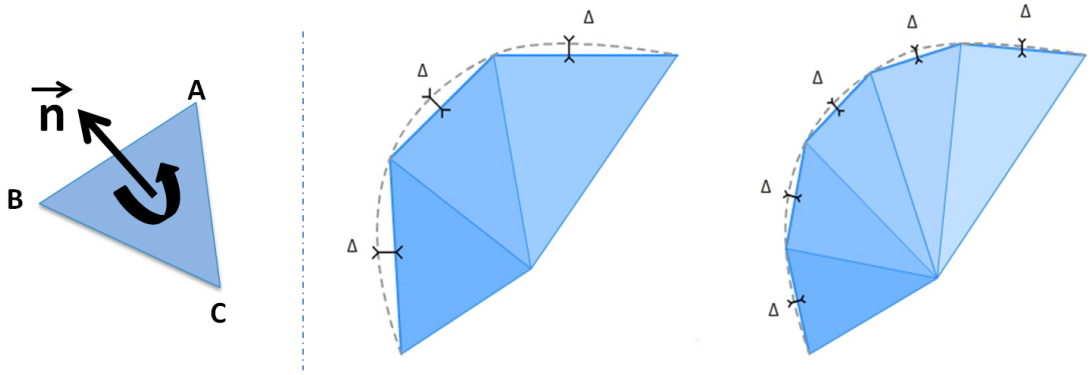


Figure 1.9 – STL format and its triangles [37]

representing colour, texture, material, etc.

STL file contains the coordinates related to the vertices and normal vector as 12 floating point numbers [41]. STL contains redundant information, as the surface normal can be calculated from the order and location of the three vertices. By default, the right-hand rule is used to define the direction of the normal based on the order that the points are encoded. Since each triangle is represented separately, each vertex must be written repeatedly for every triangle that shares that vertex (three or more times).

Also, the physical units are not defined in the STL, and AM pre-processing software determines its units between inches or mm depending on the build size of the machine but it is still ambiguous. An additional point of confusion regarding the STL file is that in fact there are two separate file formats that may be used: binary and ASCII. The ASCII version exists to make the format human readable, but the binary version is often used by mature programs to minimize the storage space. A summary of the advantages and disadvantages of the STL file format is mentioned in Table 1.2 [41].

These disadvantages encourage the researchers to provide the other formats like AMF for AM which are explained as follow.

AMF:

The new Additive Manufacturing File (AMF) format is an XML-based file format which is used to handle the complex structure and micro-structures. This format overcomes the shortcomings

Advantages	Disadvantages
Simple	Geometry leaks
Sequential memory access*	No specific units
Portable	Unnecessary redundancy
-	Incompatible with colour, multiple materials,etc
-	Poor scalability
* Does not require large amount of RAM	Lacks auxiliary information

Table 1.2 – STL format advantages and disadvantages

of the STL file including leaks, lack of multi-material support, and no provisions for surface data, with a flexible XML-based format and it has a native support for colour, materials, lattices, and constellations [41].

AMF defines the regions geometrically either using a triangle mesh, using functional representations or through a voxel bitmap. Each region is associated with a material, which may be defined as a base (single) material or hierarchically by a combination of other materials, either functionally (enabling smooth gradients) or voxel-wise (for arbitrary micro-structure). Files can be self-contained or refer to external or on line material libraries. The flexibility of the XML structure enables the additional features to be adopted as needed by CAD programs and future AM processes [41].

It is independent of the technology and it contains the target object but not how to make it. It is easy to understand and implement, as well as it is compatible with STL file for both forward and backward conversions [41].

Until now, AM is described generally and in the rest of this section, the advantages and disadvantages of AM will be discussed.

1.5.2 Additive Manufacturing advantages and disadvantages

The advantage of AM over conventional subtractive or formative manufacturing methods is coming from its great design freedom. These design freedoms enabled by AM capabilities are described in the four categories of shape complexity, hierarchical complexity, material complexity, and functional complexity as described in the following. It must be mentioned that these four aspects are not independent, e.g. functional complexity can be also achieved by adopting hierarchical

structures [43, 36].

- **Shape complexity:** It is possible to manufacture virtually any shape, which facilitates customized geometries, and shape optimization.

- **Hierarchical complexity:** Hierarchical multi-scale structures enables design and manufacturing of the parts from the micro-structure through geometric meso-structure (0.1-10 mm) to the part-scale macro-structure. It enables design and manufacturing of the features at one size scale that can have smaller features added to them, and each of those smaller features can have smaller features added.

- **Material complexity:** In AM, the material can be processed in one point or one layer, at a time, which enable the fabrication of the parts with complex material compositions and designed property gradients.

- **Functional complexity:** Since in AM manufacturing manner for building the parts, the inside of the part is always accessible. This capability makes it possible to integrate multiple design domains to realize multi-functionalities. For instance, operational mechanisms and embedded components can be manufactured directly to achieve multi-functional parts [43, 36].

There are other benefits that create appropriate status for AM as a new method for manufacturing between different methods of production which are explained as follow:

AM advantages:

- **Direct translation of design to component:** The input for fabrication with AM technologies is a 3D model that comes from the design stage [44].

- **Design flexibility:** Layer-by-layer production creates a capability for AM to produce the complex shapes [45, 5].

- **Personalized production:** AM facilitates producing the different personalized products [45, 5] due to its capability of producing any complexe shapes.

- **Material choice:** AM technologies can process a large range of materials including polymers, metals, ceramics, and composites.

- **Cost reduction [45, 5]:**

  - Low buy-to-fly ratio which is a ratio of the amount of material purchased to the amount of material found in the final component reduces the material consumption and consequently cost.

  - There is no startup tooling required for AM production contrary to the traditional methods which reduce the cost.

  - AM creates an opportunity to produce the products closer to the consumption point by geographically delocalized production and reducing the risk of supply chain source which reduce the transportation costs.

  - Contrary to traditional methods which by adding geometrical complexity the cost will be increased, AM produces almost any complex shapes without any additional cost.

- **Flexible and lightweight component:** AM allows manufacturing of the components with hollow or lattice structures which create flexible and light-weight designs [44].

- **Excellent scalability:** The path for utilizing AM and scaling them for use in production relies on new design tools for AM. AM is capable of working along the entire spectrum of build sizes in multi-scale, from the nanoscale, mesoscale, and macroscale [44, 5].

- **Time reduction:** A great reduction in overall product development and manufacturing time leading to quicker transfer to market [44] and no tooling.

- **On-demand manufacturing:** This technology can be used for the products that are demanded separately by customers [44].

- **Colour:** Full-colour products can be manufactured through some AM processes. These characteristics can be done by adding colour to the raw materials (e.g. by ink jet printing on paper or powder), by using different colour feedstocks for different parts of the model, or by inducing the colour change in a single feedstock (e.g. resin) by in-process activation of

pigments. AM parts in colour can reduce or eliminate downstream painting and decoration steps during production and reduce chipping and flaking [46].

- **Positive impact on sustainability:** Reducing the material mass and energy with additive technologies can have positive impacts on sustainability [45, 5].
- **Recyclability:** Some of the AM technologies are useful to facilitate recycling and disposal, they can permit repairing or remanufacturing, refurbishment, redesigning of ancient and obsolete or failed product and tooling rather than being replaced or disposed of with the new tooling production [45, 5].
- **No additional tooling and re-fixturing:** AM needs no additional tooling and re-fixturing for production of the product in the different geometries [45, 5].
- **Need for assemblage:** AM is enabling to produce the 'single-part assemblies' that feature integrated mechanism. The parts and joints are printed in place and are suspended by support material that must be removed in post-processing [45, 5].

While AM seems to have unlimited potential, it does not have un-limited capabilities. Like other manufacturing technologies, utilization of AM is encountered with different difficulties that can create the disadvantages for this type of production and designers must take into account many kinds of constraints which are described comprehensively in section 1.5.2.

AM disadvantages:

- **Interdependency between material and physical process:** Different technologies exist for different types of material. Each material requires a specific resolution and dedicated components which limit the choice of the technology type [45, 5].
- **Knowledge driven-based productivity improvement**: Improving the AM productivity is knowledge driven and it is related to the CAD designer-makers and it needs the high skill level [45, 5].
- **Long design process:** The design process of a complex product is more time consuming than manufacturing step [45, 5].

- **Machine constraints:** Machine-specific capabilities and requirements are the input and data file like the minimum build resolution, maximum build dimensions, the available and compatible materials, the process parameters, and the post-processing parameters. These characteristics can create limitation for production [46].

- **Process constraints:** Process-specific characteristics determine warpage, shrinkage, accuracy, and precision of the part, the dimensional stability of the part, the surface roughness of the part in x, y, and z, the minimum feature size in x, y, and z, the minimum spacing between features, the maximum aspect ratio of a feature, and the unsupported and supported feature shapes and sizes that can be produced. So, designers must choose an AM process which produces the specific part in the specific material with the required quality [46].

- **Material constraints:** In many cases, the raw material can be used for processing but some materials must be adapted before using like changing the alloy of gold for selective laser sintering to overcome evaporating. Also, AM processing can modify the material properties of the final part as increasing in tensile strength and reduction in breaking elongation for Ti–6Al–4V ELI in fabrication with DMLS than bulk material. Moreover, recycling process can affect due to material properties. Thus, the cost and waste related to AM must be weighed against any potential degradation in quality [46].

- **CAD and digitalization constraints:** Complete and comprehensive digital models of the product model must be created by the designer. It is little or no human intervention in the translation of digital models to the physical product, AM CAD models must be in higher quality and contain more complete information than the models which have been traditionally needed for other process technologies [46].

- **The impact of discretization and orientation on surface roughness and material properties:** The boundaries between the pieces, lines, surfaces, or layers of AM parts are rarely or seamless. Roughness characteristic has added a characteristic at the length scales associated with the discretization. The characteristic lengths of the raw material and process parameters such as layer thickness are often at different length scales, the surface roughness is also often multi-scale. The boundary between newly created and existing

material can act as an interface where cracks and other types of failure can initiate. Since the discretization in modern AM processes is rarely isotropic, the surface roughness and resulting material properties are also usually anisotropic [47]. One method to analyze and reduce these impacts is parameter analysis like part orientation and layer thickness which is performed by several researchers [48, 49]. Other methods include finishing operations after each layer [50], finishing operations such as chemical [51] or mechanical polishing, or post machining after the build is complete.

- **The need for support structures during production:** Unlike traditional manufacturing process, AM parts are usually strongest when complete. The orientation of the part can typically compensate these mechanical effects to maximize its strength during the build, by adding support structures to the part, or by designing the part to be self-supporting throughout the printing process, but all of these strategies can increase production cost and time. There are different methods to remove the support part that have the impact on the final part quality [46].

- **Quality control constraints:** These constraints are related to the verification of materials, geometries, and surfaces. AM parts must be inspected for defects in bulk material like undesirable grain characteristics, unexpected porosity, and larger internal void [46].

- **Through-life constraints (maintenance, repair, and recycling):** Capabilities of AM including production embedded objects and assembly parts create the constraints for maintenance, repair, and assembly as these parts cannot be disassembled for routine maintenance or repair. These problems are increased for objects with embedded components and multi-material assemblies. If part of an assembly breaks and it cannot be disassembled and reassembled, the whole assembly must be replaced. These constraints increase the cost and waste associated with the product throughout its usable life [52].

- **External and regulatory constraints:** The AM benefits led to widespread interest and early adoption of AM for end-use parts in the aerospace and medical industries [46]. These industries are highly regulated and require parts to gain regulatory approval before being put into use. Thus, the need for testing and documentation to support the certification and

approval process creates the constraints for the designer and design [46].

These AM capabilities encourage the manufacturer to use it. So, AM applications will be explained in section 1.5.3.

1.5.3 Additive Manufacturing applications

AM is applicable to the different sectors as follow:

- **Automotive and industrial manufacturing [53]:**
  - Consolidate many components into a single complex part.
  - Create production tooling.
  - Produce spare parts and components.
  - Faster product development cycle with rapid prototyping, form and its testing.
- **Pharmacy-health care [53]:**
  - Surgery by using the anatomical models based on CT scans and MRI.
  - Custom orthopedic implants and prosthesis.
  - Medical training by using 3D printed cadavers.
  - Bio-print live tissues for testing for drug development.
- **Retail [53]:**
  - Producing custom toys, jewelry, games, home decoration.
  - Printing spare or replacement for auto and home repairs.

The AM applications are independent to the material and consequently the AM technology which will be used for material processing. In the section 1.5.4, the AM technologies are classified as Laser technologies, Flash technologies, Extrusion technologies, binder jetting technologies, Lamination and cutting technologies.

1.5.4 Additive Manufacturing technologies

There are different technologies of AM that are used to process the material and producing the product based on the CAD model. These technologies vary in terms of material type, printing ink, power source, and characteristics. These technologies are classified in ASTM international standard shown in Table 1.3.

Categories	Technologies	Printed Ink	Power source	Strengths/downsides
Material Extrusion	Fused Decomposition Modelling (FDM) Contour Crafting	Thermoplastics Ceramic slurries Metal pastes	Thermal Energy	Inexpensive extrusion machine Multi-material Printing Limited part resolution Poor surface finish
Power Bed Fusion	Selective laser Sintering (SLS)	Polyamides Polymer	High-powered Laser Beam	High Accuracy and Details Fully dense parts
	Direct Metal Laser Sintering (DMLS) Selective laser Malting (SLS) Electron Beam Melting(EBM)	Atomized metal powder (17-4PH) Stainless steel Cobalt chromium Titanium (Ti6A-4V)	Electron Beam	High specific strength & Stiffness Power Handling & recycling Support and anchor structure Fully dense parts High specific strength and stiffness
Vat Photo polymerization	Streolithography (SLA)	Ceramic powder Photopolymer Ceramics (Alumina, zirconia, PZT)	Ultraviolet Laser	High Building Speed Good Part resolution Over curing, Scanned line shape
Material Jetting	Polyjet/Inkjet Printing	Photopolymer/wax	Thermal Energy/Photo curing	High cost for supplies and materials Multi-material Printing High surface finish
Binder Jetting	Indirect Inkjet Printing (Binder 3DP)	Polymer Powder (Plaster, Resin, Ceramic Powder, Metal powder)	Thermal Energy	Low-strength material Full color object printing Require infiltration during post processing Wide material selection High porosities on finished parts
Sheet laminate-on	Laminated Object Manufacturing (LOM)	Plastic Film, Metallic Sheet, Ceramic Tape	Laser Beam	High surface finish Low material, machine, process cost
Direct Energy Deposition	Laser Engineered Net Shaping (LENS) Electron Beam Welding (EBW)	Molten Metal powder	Laser Beam	Repair of damaged/worn parts Functionality graded material printing Require post-processing machine

Table 1.3 – AM Classification provided by ASTM standard [54]

In this thesis, these technologies are categorized as Laser technologies, Flash technologies, Extrusion technologies, Binder jetting technologies, Lamination and cutting technologies [37] as follows:

Laser technologies:

Stereolithography (SLA): Stereolithography (SLA) is the first AM technology which has been commercially available to tackle the difficulty and bottleneck of the prototyping as well as, faster and better design needs and it is the most used AM technologies currently. In this technology, the layers are created through a selective exposure of a resin vat to ultraviolet (UV) light which converts the liquid photosensitive resin to a solid state. A CAD model is sliced into layers, each layer is scanned by the UV light to cure the resin selectively for each cross-section. After a layer is built through scanning by the UV light to cure the resin selectively for each cross-section, the platform descends by one layer thickness. Then, a resin-filled blade sweeps across the part's cross-section, re-coating it with one layer of fresh resin. The subsequent layer then is scanned, adhering to the previous layer as shown in Figure 1.10. The materials that can be developed by SLA are the ceramics and photo-polymers like alumina and silica [55, 37]. The prototypes which are created by SLA have the higher stiffness than a standard part and their temperature resistance are over 200 °C.
Micro-stereolithography systems are developed for having the high resolution which can create the layers with the thickness of less than 10 µm [38]. This technology utilizes the same principle like macro-stereolithography but in the different dimension and the UV laser beam is focused to 1-2 µm to solidify the thin layer of 1-10 µm in thickness to have a 3D complex micro-structures [37]. There are some errors which are occurred during this process. Since there is no fusing with a bottom layer, over curing occurs to overhang parts. Another one is the scanned line shape which is introduced by the scanning process. As the resin has high viscosity, this one can create a problem in border position control, as well as the error occuring if the part needs a surface finishing process that is normally done by hand. However, all of these errors can be minimized by using high-quality equipment during this process [39].

Selective Laser Melting (SLM): The process for this technology is started by applying a thin layer of the powder materials which is spread by a roller on the building platform, then a powerful laser is used to fuse the powder at the point which is determined by component design data exactly. The platform is then lowered and another layer is applied. Therefore, successive layers of metal powder are fully melted and consolidated on the top of each other during the process. This manufacturing can be performed by powerful double or multi-laser technologies with layers from 75 to 10 µm in thickness. The materials which can be processed by this method include steel, stainless steel, cobalt chrome, titanium and aluminum [37].

Selective Laser Sintering (SLS): Selective Laser Sintering (SLS) is a technology invented by Dr. Carl Robert Deckard in 1988 and uses a high power laser-like carbon dioxide laser beam [39] in order to fuse the small particles from the materials like polyamide, steel, titanium, alloys and ceramic powders. The SLS process is like SLM and it is repeted to complete the model by adding the layer of powder, but sintering is different with melting because the sintering does not fully melt the powder but it heats it until the powder can fuse together on a molecular level. The porosity of the material can be controlled and this porosity needs post-treatment by infiltration to harden the final model like the bronze use steel [37]. This technology is more accurate than the PolyJet and 3DP [56] but its accuracy is limited to the size of the material particles. As the main advantage of this technology, this process offers the variety of materials that could be used like plastics, metals and their combination, the combination of metals and polymers, metal and ceramic composition, moreover, the unused powder can be recycled [39]. Therefore, as the disadvantage of this process can be mentioned the accuracy based on the size of particles and also, oxidation needs to be avoided by executing the process in an inert gas atmosphere and for the process to occur at the constant temperature near the melting point [39, 37].
These AM technologies which are known as laser technologies are illustrated in Figure 1.10.

Direct Metal Laser Sintering (DMLS): This technology is similar to the SLS but it has some differences, DMLS uses powder bed fusion process by melting the metal powder locally using the focused laser beam. The product is manufactured layer-upon layer like the other technologies and this production is a long the x-axis and the powder is deposited via a scraper moving in

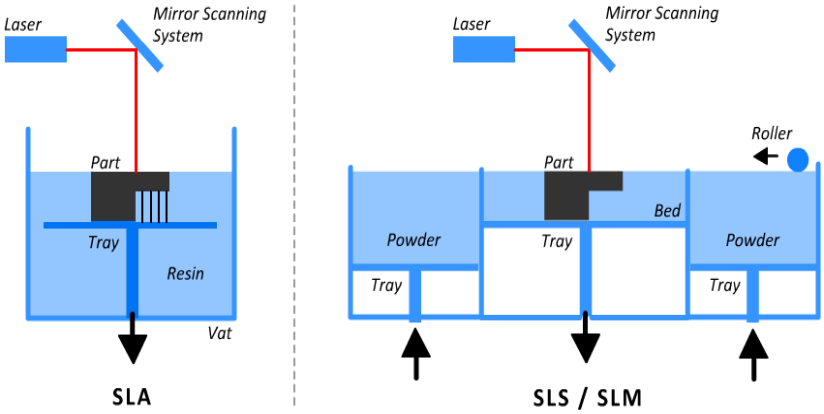


Figure 1.10 – Laser technologies (SLA-SLM-SLS) [37]

the XY plane. This process is used to fabricate the net shapes prototypes and short series tooling for plastic injection molding [37]. The DMLS is applied to metal alloys for manufacturing direct parts in industries like aerospace, dental, medical, and other industries from small to medium size for complex products and the tooling industries to make direct tooling. Nowadays, the recent developments in the powder coupled with the material durability are extending the direct manufacturing of functional prototypes for powder metallurgical and cast component [57]. Support structures are used for most geometries as powder is not enough for holding in place the liquid phase which is scanned by the laser. This power is composed of two particles which have two different melting points, the high melting point particle is used to generate the solid matrix and the low point is for binding the matrix after being melted by the laser energy [58, 37].

Flash technologies:

The new technology which is based on the flashlight power as a source is emerged to reduce the lead time and increase the building speed. This new technology is derived from SLA and it is presented by Pomerantz [37].

Digital Light Processing (DLP)-Film Transfer Imaging (FTI): Digital Light Processing (DLP) which is also known as Film Transfer Imaging (FTI) is the kind of photomask system that is used for producing 3D models by using UV photo-polymerized materials. As shown in

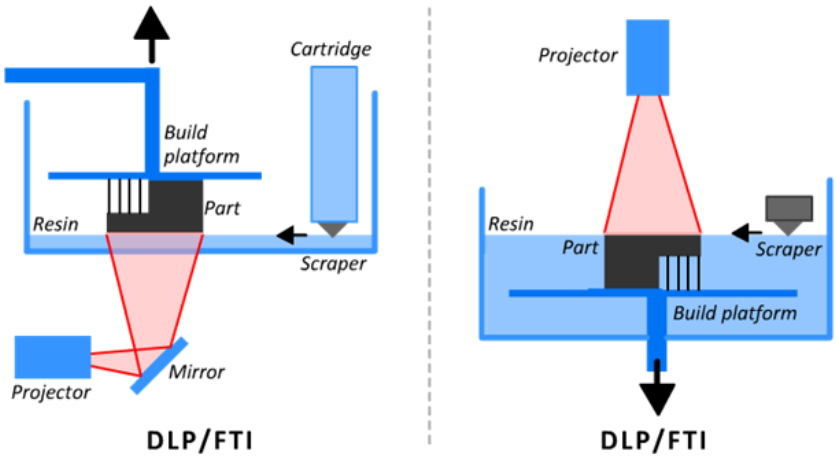


Figure 1.11 – Flash technology (Masking) [37]

Figure 1.11, the film is coated in resin which is then cured by a UV flash of light from a projector for each slice of product. This DLP projector projects the entire layer including the line and points. This technology is quicker than other methods due to the scanning time of laser. In DLP, the part is pulled upward out of the resin but in SLA the part descends downward into the resin. Also, in DLP the part must attach much more firmly to the building platform to prevent damage when newly formed layers are peeled from the basement plate after each exposure [59]. So, this technology is popular for high speed and resolution which is able to produce the layers with the thickness down to 30 µm [37].

Continuous Liquid Interface Production (CLIP): This technology is another type of flash technologies which is close to the DLP principally. It uses the photo-polymerization working continuously. The projector is able to control the oxygen levels throughout an oxygen-permeable membrane. This technology and process are 30 times faster than SLS and MJM [37].

Extrusion technologies:

This kind of technology is categorized in four groups which are explained in the following:

Fused Deposition Modeling (FDM): This technology was invented by Scott Crump in the 1980s. It is a layer AM process that uses thermoplastics filament by fused depositing. FDM is

also known as Fused Filament Fabrication (FFF). The process is printing the one cross-section of an object through a nozzle which extrudes the filament and the process is repeated to produce the layers vertically as illustrated in Figure 1.12. The materials which are used in FDM are ABS (Acrylonitrile Butadiene Styrene), PPSF (Pholyphenylsulfone), PLA (PolyLactic Acid), PC (polycarbonate) like PC-ABS blend and PC-ISO as a medical grade PC [39] and, the blend of wood and stone, as well as the filament with rubbery characteristics. The disadvantage which can be mentioned for this type of technology is the low resolution of z-axis (25 mm) compared to the other AM technologies. Therefore, a finishing process is needed to improve surface quality and thus it can takes a long time to build large complex parts by FDM. In order to save time, some models are permitted two modes, one is fully dense mode and another one is the spare mode that saves the time but the mechanical properties are reduced [39]. Since this technology is not so expensive, it is a most popular desktop 3D printer [37].

Directed Energy Deposition (DED): This technology covers a range of technologies which are described in the following:

- LENS (Laser Engineered Net Shaping)
- Directed light fabrication-Ion Fusion Formation (IFF)
- Direct Metal Deposition (DMD)
- 3D laser cladding

The printing process is complex and it is used for repairing or adding of additional material to existing components [43]. The melting methods are different for these technologies.
For LENS, the surface is melting of the target point and IFF melt the wire or powder with a plasma welding torch to form an object and it uses a very hot ionized gas to deposit a metal in small amount which is demonstrated in the Figure 1.12 and the materials solidify after cooling down. This process uses a high variety of metals and their combinations like stainless steel, nickel-based alloys, alumina, titanium-6, aluminum-4 vanadium, tool steel copper alloys, and so forth. This process is also used for repairing parts that by the other process is impossible or expensive to do. One problem with this process is residual stress by the uneven heating and

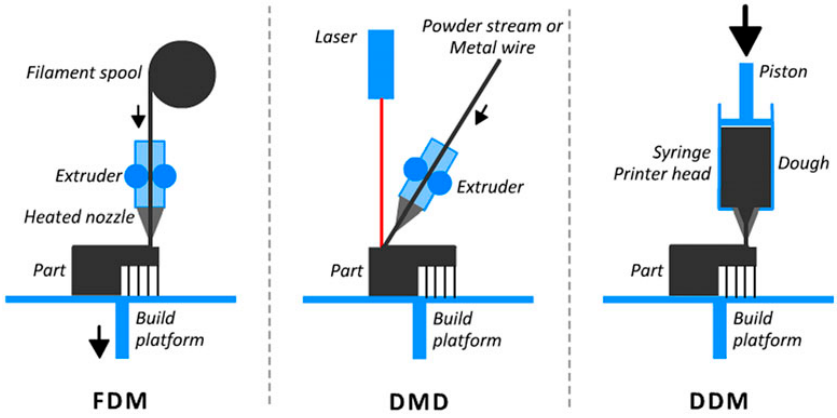


Figure 1.12 – Extrusion technologies [37]

cooling process that is important for high precision process such as turbine blades repair [39, 37]. In the DMD process (Figure 1.12), the metal is melted by an electron beam as feedstock to form an object within a vacuum chamber. Parts produced by DMD can be larger, even up to several feet long.

Dough Deposition Modeling (DDM) groups the marginal processes which is a technology based on the FDM but it uses a syringe to deposit a dough material such as silicone, food, chocolate, etc. (Figure 1.12). This technology presents a new method for the deposition of biopolymers in high-resolution structures.

Binder jetting technologies:

Multi Jet Modeling (MJM): This process deposits the photopolymer droplets of materials with multi jets on a building platform in ultra-thin layers until the part is completed (Figure 1.13). The different materials can be used in this technology for building actual model [60, 37]. The polymer layers are cured by UV lamps and a gel-like polymer supports the complexity in wrapping it and the soluble support materials are removed by water jet. This technology reproduces details more accurately with a very good surface finish [56] and smoothness. Therefore, this accuracy can reach the thickness from 50 to 25 µm and the part is produced in high resolution. Thermo-jet is also a system to produce a wax model in jetting tiny melted liquid material droplets which

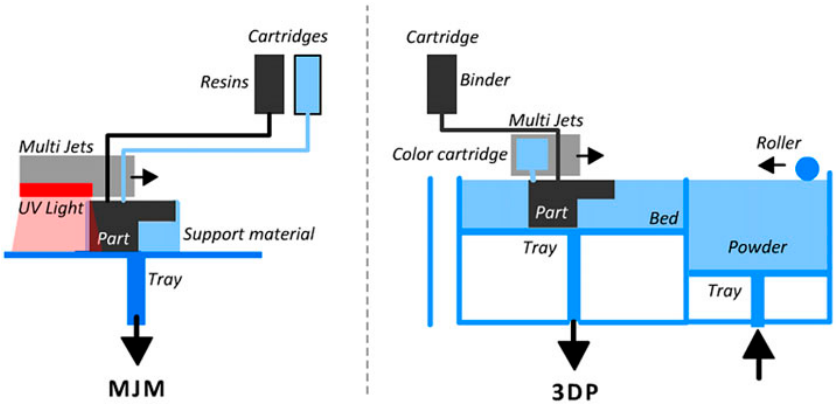


Figure 1.13 – Binder Jetting technologies (MJM-3DP) [37]

harden and cool on impact to form the solid objects.

Three-Dimensional Printing (3DP)- Colour Jet Printing (CJP): The process of this technology is to combine the powders and binders which is an MIT-licensed process. The layers are created by spreading a thin layer with a roller and this powder is linked together by ink-jet printing of a binder and the build tray goes down to create the next layer (Figure 1.13). The layer thickness is between 90 µm and 200 µm. The materials which are produced by this technology are metal, ceramic, silica and polymeric component of any geometry [61]. In another research, the other powder is used to produce a green product in wood [62]. The multicolor parts can be printed directly by this technology by entering the colors from a colour cartridge. The final model is extracted from the powder bed in order to perform infiltration with liquid glue. Mechanical behavior and colour definition are improved by infiltration. Also, 3DP is used for providing architects as a useful tool to quickly create a realistic model [37].

Prometal: It is a kind of 3D printing process which is useful for building rapid tools and dies. This is a kind of powder-based process which stainless steel is used. The printing process is performed when a liquid binder is spared out into jets to steel powder [39]. Final treatments such as sintering, infiltration, and finishing process are required to solidify the part [37].

Liquid Metal Jetting (LMJ): This technology of AM is developed at the university of Texas Arlington. This process involves the jetting of molten metal in a process like an ink jet printing. Thus, the individual droplets are ejected and connected to each other [63]. This process is not commercially available as of yet [37].

Lamination and Cutting technologies:

Laminated Object Manufacturing (LOM): LOM is a kind of process of rapid prototyping that the parts are built from paper layers sequentially. The process includes thermal adhesive bonding and laser patterning of uniformly-thick paper layers [64]. The system includes an x-y plotter device which is positioned above a work table and it is moved vertically. This plotter also includes a forming tool in order to create a layer from a sheet of material on the work table which is shown in Figure 1.14. A heat-sensitive adhesive is provided on the side thereof to bond the layers to each other and a bonding tool or fuser is mounted to translate across the work table and apply a lamination force and heat to each of the layers. Finally, the layers are superimposed to create the final object. The layer resolution is determined by the thickness of the paper sheet. Also, this printer can produce the parts in full colors [37].
The advantage of this process is low cost, no post processing and supporting structure required, no deformation or phase change during the process, and the possibility of building of the large parts. The disadvantages that can be mentioned are that the material is subtracted thus it is wasting, low surface finishing and need for machining, low mechanical properties, and complex internal cavities and hard to build. This process is used for the models with papers, composites and metals [40, 39].

Stratoconception: This is a type of rapid prototyping process with layers of sheets as shown in Figure 1.15. It consists in decomposition of the model by calculating a set of elementary layers called "strata" and by placing reinforcing pieces and inserts in strata. Rapid milling or laser cutting are used to manufacture the elementary layers and the strata are assembled with inserts in order to rebuild the final object [66]. This process is useful for milling the low cost raw materials (wood, MDF, PVC, aluminum, etc.) [37].

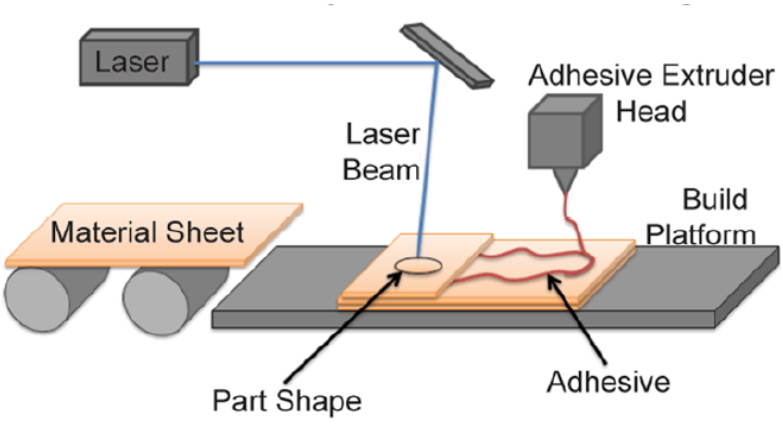


Figure 1.14 – Laminated Object Manufacturing (LOM) [65]

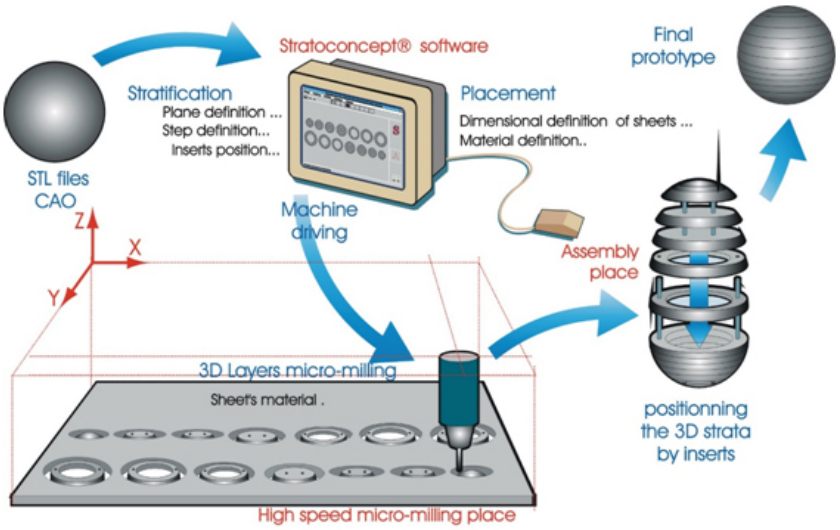


Figure 1.15 – Stratoconception [66]

Technology	Layer thickness (µm)
SLA	<10 µm
MicroSLA	1-10 µm
SLM	75-150 µm
SLS	25-92 µm
DLP/FTI	30-100 µm
FDM	100-250 µm
DDM	<1000 µm
MJM	16-30 µm
3DP	100-400 µm

Table 1.4 – AM technologies accuracy [37]

1.5.5 Additive Manufacturing attributes and criteria

In this section, the attributes and criteria of printing a 3D object will be reviewed that are important considerations for selecting an appropriate AM technology and a corresponding build layout, and manufacturing parameters. The attributes that are listed along with factors including machine selection, processes and materials, orientation and position of the geometry, and finishing can alter the resulting quality of the printed part [5].

- **Build Time:** Build time for an individual model or an assembly depends on printing speed, part size, layer thickness, and build orientation. It takes a long time to print a product in the larger object's height in the lay-up direction. Therefore, to reduce the build time, it is necessary to make the overall built height low for the given print speed and object size [5].

- **Feature resolution:** Feature resolution on AM systems is primarily dependent on the energy/material patterning principle [5]. The accuracy of AM system can be determined by layer thickness values as illustrated in Table 1.4.

- **Surface quality:** The quality of the printed parts surface is mainly determined by the thickness of each printed layer and part orientation [5].

- **Support material:** Creating complex geometries such as overhangs, undercuts, and printed part assemblies with moving components, all AM systems must provide some means of supporting the printed features of subsequent layers. It is obvious that support structure affects the material mass required for printing.

- **Post-processing:** Printed objects with built-in support material need post-processing operations that separate them. The methods and ease of removal are different based on the printing methods and build materials. For water-soluble materials as support, it can be washed away by gentle scrubbing. For non-soluble support materials, it can be broken and peeled away from the model using pliers or conventional cutting tools. To ensure a smooth surface finish, printed parts often need to be polished using sanding or vapor smoothing.

Therefore, several issues are coming from AM utilization, so, it is necessary to choose the correct method for design and manufacturing simultaneously in Product Life Cycle Management. For this aim, designers must consider the Design For Manufacturing (DFM) in AM implementation [6]. Several researchers proposed DFAM approach as Design For Additive Manufacturing which will be explained in the section 1.6.

1.6 Design For Additive Manufacturing

Generally, Design For Manufacturing (DFM) is used to consider manufacturing constraints and attributes in the design stage as an integrated design approach to eliminate the manufacturing difficulties and minimize costs. However, the emergence of Additive Manufacturing (AM) technologies provides an opportunity to re-think DFM to take advantage of the unique capabilities of these technologies. The term DFM has been transferred to AM and it is called 'Design For Additive Manufacturing' (DFAM). Therefore, recently different researchers have presented a DFAM approach as Design for AM approach with the objectives of maximizing the product performance through the synthesis of shapes, sizes, hierarchical structures, and material compositions, subject to the capabilities of AM technologies [67].

DFAM approaches are classified by Laverne et al. [68] as DFAM concept assessment including qualitative and quantitative analysis, and DFAM decision making which consists of DFAM guideline, design optimization, geometrical validation, and product properties. However, this classification is not mutually exclusive and there is no clear distinction between general process-focused and design-focused approaches.

Another classification was created by Kumke et al. [69] as "DFAM in the strict sense" and "DFAM in the board sense". The first one is concerned with the design process which utilizes AM

Functional DFAM	Manufacturability DFAM	Material and Process selection	Combinational DFAM
Rosen 2007a [70]	Burton 2005 [71]	D'antonio et al. 2015 [72]	Yim 2007 [73]
Rosen, 2007b [74]	Bernard, 2008 [75]	Thompson et al. 2016 [46]	Ponche et al. 2012 [76]
Chu et al. 2008 [77]	Thomas, 2009 [52]	Salonitis and Zarban, 2015 [78]	Ponche et al. 2014 [79]
Vayre et al. 2012 [80]	Kerbrat el. 2011 [81]	Zamen et al. 2017 [82]	Zhang et al. 2014 [83]
Arisoy et al. 2015 [84]	Doubrovski et al. 2011 [85]	Zamen et al. 2018 [86]	Tang et al. 2014 [87]
Yang et al. 2015 [36]	Seepersad et al. 2012 [88]		Hallgren et al. 2016 [89]
Jiang et al. 2017 [90]	Seepersad et al. 2014 [91]		Klahn et al. 2014 [92]
Vogiatzis et al. 2017 [93]	Wegner and Witt, 2012 [94]		Klahn et al. 2015[95]
Pradel et al. 2017 [96]	Adam and Zimmer, 2014 [97]		Primo et al. 2017 [98]
Leary et al. 2014 [99]	Boyard et al. 2013 [100]		Kumke et al. 2016 [69]
Rodrigue and Rivette, 2010[101]	Kranz et al. 2015 [102]		Salonitis, 2016 [103]
Ariadi et al. 2012 [104]	Bin et al. 2012 [105]		Emmelmann et al. 2011 [106]
Walton et al. 2017[107]	Ko et al. 2015 [108]		Hague et al. 2003 [109]
Tao 2016 [110]	Atzeni and Salmi 2012 [111]		Hague et al. 2004 [112]
	Boschetto and Bottini 2016 [113]		Dhokia et al. 2017 [114]
	Barclift et al. 2017 [115]		Zhang et al. 2016 [116]
			Zhang et al. 2016 [117]
			Essink et al. 2017 [118]
			Vo et al. 2017 [119]

Table 1.5 – DFAM approach classification

characteristics and is focused on the AM design rule. The board consists of strict one and process selection and production strategy, selection of parts (application), and manufacturability analysis.

According to the DFM process defined by Skandar et al. 2006 [12], DFM consists of material and process selection, manufacturability evaluation including verification, quantification, and optimization, as well as the importance of customer requirements in the product life cycle, the DFAM approaches which are presented in these researches are categorized as Functional DFAM, Manufacturability DFAM, material and process selection, and combinational approaches which are explained in the following. These different approaches are presented in Table 1.5:

1.6.1 Functionality DFAM:

The AM capabilities have inspired many people to maximize the performance of their designs, while minimizing their weight. This type of design problem could be called "functionality DFAM" and these approaches are based on the functional analysis of the product and it provide a DFM approach for AM defined by customer requirements. The design objectives are defined mathematically and typically an optimization method is used to search in a mathematically defined design space [67]. The three main types of optimization problem have been explored as:

- **Size optimization:** This type determines the product dimensions [67].
- **Shape optimization:** In this optimization type, the shapes of the part surface are changed

typically by changing control vertex positions for a curve or surface [67].

- **Topological optimization:** This optimization method permits to fulfill the design requirements like mechanical behavior and functionality, in addition, to optimize mass, structure, time and cost [120] and it explores the distribution of the materials [67].

Some researchers [80, 79, 87, 78, 98] used topological optimization in their DFAM approach to present an optimized initial model of the product. To date, no one has attempted a comprehensive solution method that integrates the AM capabilities and limitations into a topology optimization algorithm, thus, this is a research scope.

Lattice structure is also used in the DFAM approach to provide a light-weight design [77, 87, 89, 98, 110]. A lattice structure is an architecture which is formed by an array of spatial periodic unit cells including edges and faces. These structures exist in two and three-dimensions which are often linked to cellular solids [121, 110]. It is also known as lattice material as the micro architecture permits it to be viewed as a monolithic material with its own set of effective properties [122, 110]. Lattice structures have many superior properties, which make it a promising solution for various applications, such as a lightweight structure due to its high specific stiffness and strength, a heat exchanger due to its large surface area, an energy absorber due to its ability to undergo great deformation at a relatively low stress level, and an acoustic insulator due to its large number of internal pores [110].

Other approaches are also provided to consider the functional analysis in the DFAM approach. Rosen et al. [70, 74] defined a DFAM method which supports the part and specification modeling, process planning and manufacturing solution. It introduces a CAD system for DFAM which is particularly designed for the utilization of meso-structured materials. It contains a mapping between process, structure, property, and behavior, incorporating both geometry and material of an AM product.

A new design for AM approach is proposed by [77] based on the process-structure-property-behavior model like the approach which is provided in [74] and Unit Cell-Based Design approach is used to achieve the minimum weight, desired compliance distribution in order to find the optimal size by using Particle Swarm Optimization (PSO).

The limitations of SLS are investigated regarding minimal sizes of geometric features depending

on their orientation in the study of [75].

According to the initial input of design models, the DFAM methodology [36] is divided into two main steps of function integration which consists of an analysis of initial CAD model and part consolidation in functional level regarding the functional requirements and performance requirements. The second step is applying the structure optimization method in order to achieve the better performance such as lighter weight, better heat dispatch, or dynamic properties under performance requirement. The process constraints must be considered in both of these steps. Then, the design solution is found. [36]

A DFAM approach is presented in [84] as a unified computer-aided framework for design, Computer-Aided Engineering analysis (CAE) of solids with lattice structures, and topology optimization within the CAD system that enables a seamless work flow.

an Assembly-Level Design for AM is developed in [101] to optimize the functionality of the product. This approach is provided through part consolidation enabled by AM design freedom based on assembly concepts.

An investigation into the potential for the consumers designing and manufacturing of the products is prepared by using a combination of "Computer Aided Consumer Design" (CaCODE) and AM [104].

A DFAM methodology including topological optimization and genetic algorithm is used in [123] to achieve the high-strength light-weight design.

1.6.2 Manufacturability DFAM:

According to the DFM approach defined in [3], manufacturability evaluation is performed in three levels of verification, quantification, and optimization. Thus, manufacturability DFAM is categorized into these three levels:

Manufacturability verification:

As DFM aims to consider the manufacturing constraints and capabilities in the design stage, the researchers investigate the product model due to the manufacturability of AM technologies.

AM creates design potentials but geometric freedom is limited. There are restrictions which arise

from the technological principle, the processed material, and machine. This DFAM approach proposed the design rule to ensure manufacturability. These rules have been developed for various AM technologies like Selective Laser Melting (SLM), Selective Laser Sintering (SLS), and Fused Deposition Modeling (FDM) and it ranges from general qualitative guidelines, such as build orientation, to specific quantitative limitations, such as minimal wall thickness [69].

Geometric limits imposed by SLM are investigated based on the series of experiments [52]. Various quantitative constraints for geometric elements are found like radii and minimum gap features, as well as general recommendations for high-quality results like surface roughness as a function of build orientation [52].

Another method is proposed for applying the DFAM regarding AM constraints and capabilities. The approach is performed in four steps of, specification analysis, preparing the initial shape, definition of the parameters' set, parametric optimization, and validation of the shape [80].

Some studies [91, 94, 75] analyzed the limitations of SLS due to minimal sizes of geometric features such as holes, cylinders, walls, and graven fonts depending on their orientation. Moreover, the durability of functionally integrated parts like hinges and snap-fits is investigated by [94].

The experiments are performed by Adam et al. 2014 [97] on SLM, SLS, and FDM machines based on test specimens with predefined standard elements including basic geometric elements, element transitions, and aggregated structures. A comprehensive catalog is developed which is applicable to all three technologies and it is depicted that numerical values are only valid for the respective boundary conditions as the machine, material, parameter set, layer thickness, etc.

A design rule catalog was presented by [102] for the SLM-based production of [71] utilized a questionnaire approach due to the responses to questions in different design areas and it suggests part redesigns to exploit AM potentials, for example, through part consolidation. Another paper [105] is built based on this approach and it develops a digital design feature database which provides a higher number of features and an easier access.

The approach developed in [85] is presented by [105, 124] as a knowledge-based support tool as a DFAM approach. This documentation is based on the new opportunities of fabrication process, relationships between structure, performance, and optimization approaches. They provided a Wiki for documentation and using DFAM knowledge.

Customized Design For AM (CDFAM) was presented in [108] based on the formal representation

of design knowledge by considering AM constraints.

A design for rapid prototyping approach is proposed in [100]. It allows the design of parts satisfying both DFA and DFM in the earliest phase of the design but this possibility will limit a priori costly late changes.

Most DFM systems are not capable of handling multiple processes and they can focus just on one specific manufacturing. There is a need to develop a new DFM approach to handling multi-process manufacturing systems. A DFM approach which combines AM with machining process is presented by [81] in a hybrid modular vision. In fact, AM technologies must be compared to High-Speed Machining (HSM) process to choose the best way to obtain each module. Two points of manufacturability evaluation and hybrid modular optimization must be taken into account in the DFM methodology to decrease the manufacturing difficulties.

Special design rules were determined according to printability in [96]. To assess the potential quality of the products made by AM [125], a visual design for AM worksheet is utilized to identify the AM mistakes.

Topological Optimization (TO) provides an optimal product model due to functional analysis of the product by optimizing structure and mass regarding mechanical behavior of the product as its functionality. This method is used as a functional analysis methodology in several researches [78, 107, 98, 89, 87, 80, 79, 103, 106].

A computational framework is defined for computational design and AM of spatial free-form periodic meta surfaces in study of [93]. It focused on the level-set based topology approach and the conformal mapping theory. This framework creates a solution to increasing applications involving innovative meta-material designs on free-form surfaces and there is no need for reconstruction of the CAD model.

An integrated computational framework is suggested by synthesizing the parametric level set-based topology optimization method for a DLP-based SLA process [90]. This framework can be used for single material structures, multi-scale, multi-functional structures.

After verification, manufacturability evaluation must be continued in the quantification level.

Manufacturability quantification:

The best solutions for exploiting all the benefits of AM techniques by considering the limitations is focused on the study of [111]. Cost analysis is used to the compare AM and conventional processes. Finally, it concludes that AM can be economically convenient and competitive to traditional process for small to medium batch size of production.
Boschetto et al. 2016 [113] proposed a DFM approach to overcome the poor dimensional accuracy. The mathematical formulation is used to formalize the dimensional deviations as the function of layer thickness and deposition angle to operate an anisotropic offspring of the virtual model surface based on the [126, 127]. This approach allows redesigning of the component knowing the prediction of the obtainable dimensional deviation. The modifications are carried out in the design step to compensate for the deviations to improve the accuracy and this methodology is applied to the mathematical definition of the surface. For this method, there is no need to fabricate the part and perform measurement to gain the model, it is just needed to apply this method directly before CAM environment.

To complete this collaborative DFM process, it is necessary to pass from the quantification level and reach the optimization level.

Manufacturability optimization:

Optimization concerns almost all scientific fields, sciences in the living, chemistry, physics, mathematics, economics and of course engineering, in the broad sense [128].

In the rest of this section, a synthesis of some principles and methods of optimization in relation to this research problem in design and manufacturing will be explained. This section is limited to non-linear constrained multi-objective optimization with a discrete and continuous problem space.

There are various methods to formulate an optimization problem mathematically. A general formulation of a non-linear multi-objective optimization problem with mixed-variables in

engineering is as follow [129]:

$$P_{MultiObj} = \begin{cases} \text{Minimizing} \\ \boldsymbol{f(x)} = [f_1(\boldsymbol{x}), ..., f_i(\boldsymbol{x}), ..., f_p(\boldsymbol{x})] \\ \text{Under the constraints:} \\ c_j(\boldsymbol{x}) \leq 0 \qquad\qquad j = 1, ..., m \\ c_j(\boldsymbol{x}) = 0 \qquad\qquad j = m+1, ..., m+l \\ \boldsymbol{x} \in R^n, \boldsymbol{f(x)} \in R^p, c_j(\boldsymbol{x}) \in R \end{cases}$$

In this formulation, $\boldsymbol{x}$ is the variable vector of optimization which consists of n continuous scalar variables. Vector of $\boldsymbol{f(x)}$ is the set of p objective functions that must be minimized. Limitation on the optimization variables are expressed by constraint functions. These constraint functions ($c_j(\boldsymbol{x})$) are divided into m inequality constraint functions for $j = 1, ..., m$ and l equality functions for $j = m+1, ..., m+l$. Solution set of this problem (D) contains variable set of x which are defined by satisfying constraint functions of $c_j(\boldsymbol{x})$.

Actually, the nature of the physical models are utilized in formulation of the objective and constraint functions which determine the solving methods, time for searching the problem solutions. It is essential to evaluate the objective and constraint functions on the solution space (D). This space can be determined by lower and upper bound (x_{Inf}, x_{Sup}) of the decision variables. The evaluation speed of these models is an essential element which affect the computation time of solving an optimization problem. Indeed, the optimization algorithms are iterative by nature, most of the computing time is consumed by the evaluation time of the physical models.

All the optimization algorithms proceed by successive iterations so that from an initial configuration which consists of different solutions of optimization variables (x), algorithm operators evaluate the solution into an optimal one.
One of the fundamental properties of an optimization algorithm is global convergence, its ability to converge towards a local optimum $\boldsymbol{x^*}$ by evaluation of the initial solutions.

In optimization, many basic algorithms have been developed for searching the local minimum of a scalar function of several variables $f(x)$ without constraint functions. In the following, a

synthesis of the available operators is presented, synthesized in two categories according to the iterative principles put into play (deterministic and stochastic).

- **Deterministic algorithms:** In these algorithms, the operators have deterministic behavior by using objective function and constraint values, their gradient, even the Hessians of these functions. Operators manipulate a solution in the iterative process and thus generate a sequence of solutions in the space of the admissible values and converge to optimal solutions (x^*). Actually, the efficient combinations for solving these problems are as follow:
  - Augmented Lagrangian method is a combination method of penalty and Lagrange multiplier. A constrained optimization problem is replaced by a series of unconstrained problems and add a penalty term to the objective. It is based on an approximation on the second Taylor ser.
  - An approximation of the second Taylor series of Augmented Lagrangian method which Hessian is calculated by the gradients of the Quasi-Newton method.

  These algorithms are fast in convergence to the global convergence. It can be converged into local optimum due to initial configuration of the solutions. It is sensitive to the quality of gradient, as well as objective and constraint functions.

- **Stochastic algorithms:** In this algorithm, the initial solution is evaluated by heuristic operators. These algorithm can be classified in two types. The first category manipulates one solution in each iteration and in second one, a set of solutions are re-manipulated in each iteration. Tabu search, simulated annealing are the algorithms of the first category and the second group is related to the evolutionary algorithms which are inspired by evolutionary phenomena in biology and swarm intelligence inspired by the mode of movement of insect groups [129].

In a multi-objective optimization problem, the target is to simultaneously minimize often conflicting optimization criteria. Generally, this problem does not have a unique solution (even if it is a convex problem) and it has a set of solutions as a Pareto front which is the best compromise in the sense of the Edge worth-Pareto criterion and there is no difference between them in terms of optimization [129].

Figure 1.16 illustrates the Pareto front for a bi-objective optimization problem. The Pareto front corresponds to a part D_f frontiers, the image of the solution D of the optimization problem. As shown in Figure 1.16, it is illustrated that any decrease in $f_1(x)$ and result in an increase of $f_2(x)$ for $[P_2, P_2']$ and $[P_1, P_1']$.

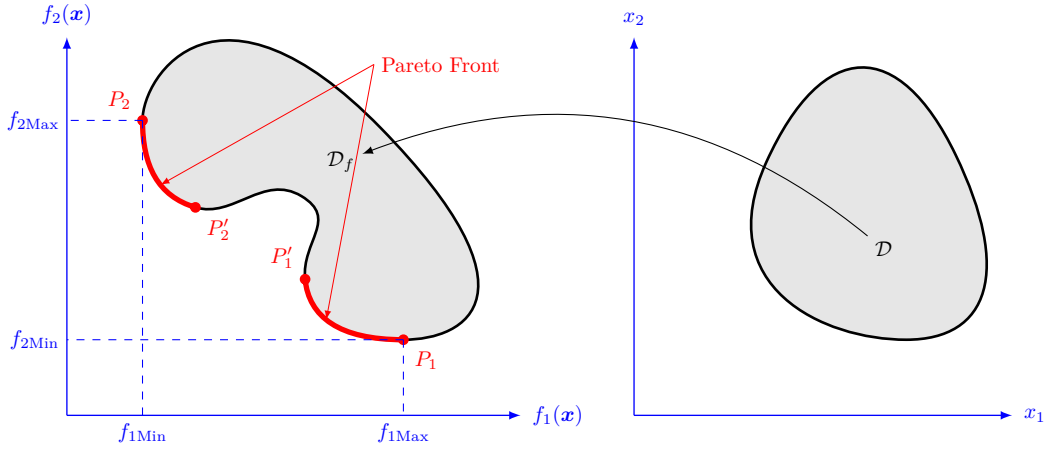


Figure 1.16 – Pareto front of a bi-objective optimization problem

There are different methods including direct and indirect method to find the optimal Pareto:

Direct methods:

- **Weighted sum method:** In this method, the special weights are assigned to the objective functions to linearize the objectives and convert the problem as a single objective to optimize the weighted sum of m objectives.

$$\min \quad f(x) = \sum_{i=1}^{m} w_i f_i(x) \tag{1.1}$$

- **ϵ-constraint method:** In this method, the problem is solved by one objective and another ones are considered as an inequality constraints to find the lower and upper bound of the objectives value. This method is better than the weighted sum technique because it

overcomes some of the convexity problems.

$$\begin{cases} \min f_p(x) \\ \text{Under the constraint:} \\ f_i(x) \leq \epsilon \end{cases}$$

- **Goal attainment method:** This involves expressing a set of design goals which is associated with a set of objectives to minimize the slackness of objectives to goal.

Indirect methods: There are different methods as meta-heuristic algorithms like Multi-Objective Genetic algorithm (MOGA), Non-Dominated Sorting Genetic algorithm-II (NSGA-II), Strength Pareto Evolutionary Algorithm (SPEA). These methods are the heuristic and evolutionary algorithms which are used to obtain Pareto front iteratively by appropriate mechanisms the least close to the Pareto front are replaced progressively by the closest individuals (the dominant ones). These methods usually have no guarantee of providing a good approximation of this front, but the tests done on many problems show an average good results [130, 131]. One of the most popular meta-heuristic algorithm which is used in this thesis is the NSGA-II algorithm, described below:

Non-Dominated Sorting Genetic algorithm-II (NSGA-II): NSGA-II is a popular modified genetic algorithm that can be used for solving multi-objective optimization problems and it is based on the non-dominating strategy. In the procedure of this algorithm (see Figure 1.17), the initial population is created and this population must be sorted based on the non-domination strategy into each front (set of solutions). The fronts are compared with together and the ranks are assigned to each individual according to the fitness value to find the optimal Pareto (as a set of non-dominated optimal solutions) [132].

1.6.3 Meta-Models, Design Of Experiments (DOE):

As the evaluation of the physical model and optimization of the process are more time consuming in calculations, there are "model of the models" or meta-models which are more simple and less

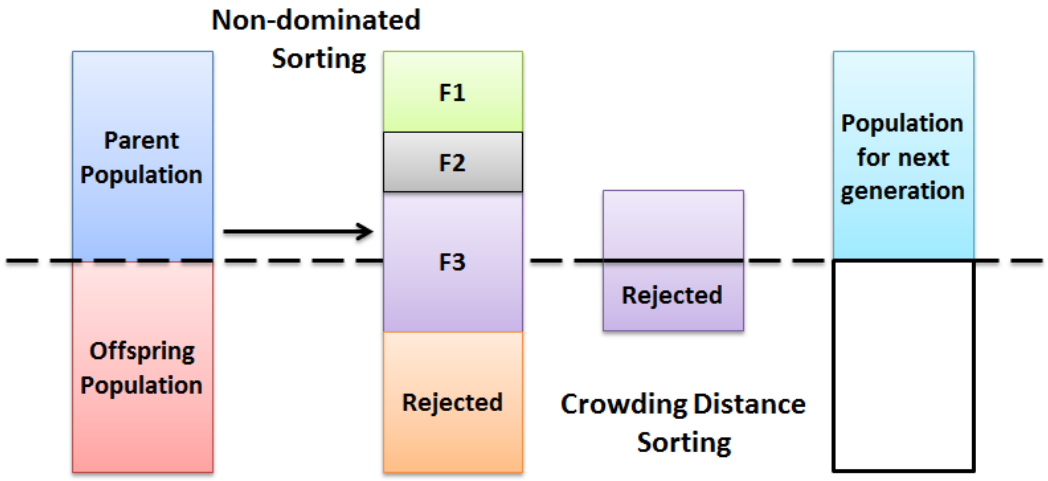


Figure 1.17 – Non-dominated Sorting Genetic Algorithm-II (NSGA-II)

expensive to evaluate. To build these meta-models, it is necessary to have a number of evaluations of the physical model to build a meta-model sufficiently close to the physical model over the entire field of D solutions of the optimization problem [133].

These evaluations needs to design the experiments as Design Of Experiments (DOE) approaches. There are several techniques to define these experiments as "Full factorial design" which permit to systematically explore the space of solutions D for large spaces, also, there are different techniques to reduce the experiment numbers which are explained in [134]. Three categories are identified to build a meta-model as regression, interpolation, and mixed techniques [133].

These meta-models can be utilized in optimization algorithms to optimize and formulate the physical models and processes. DOE can be used to define the solution space (D) and meta-models are used to formulate the physical model and finally optimization of the process based on the evaluations of meta-models [133].

Modefrontier [1] is a software for process integration and design optimization. It provides a multi-objective optimization and design environment that can easily couple with almost any CAE and CAD package. It utilizes lots of optimization algorithms and tools including response surface

[1] https://www.esteco.com/modefrontier

modeling tool, MOGA, NSGA, NASH and B-BFGS in a hybrid form instead of a single algorithm [135].

This software controls the design process and the user must create the parameterized model and specify the objectives, which they wish to attain. Therefore, Modefrontier modifies the design variables to achieve the user-specified objectives. It can be used to put forward as a mechanism for mediating conflicts. Also, there are some modules that are presented for Modefrontier including Design of Experiment (DOE) techniques, standard applications such as Excel, Matlab, Robust design optimization, Multi Criteria Decision Making (MCDM), Statistical analysis tools, mechanical software like CATIA, ANSYS, etc [135].

Design Of Experiments (DOE) permits us to define some experiments. The experiment is a series of tests, in which changes are made in the input variables in order to identify the reasons for changes in the output responses. Design of Experiment (DOE) method is used to explain the variation of information under conditions that are hypothesized to reflect the variation. Also, it is important to obtain maximum realistic information with the minimum numbers of well designed experiments. Experiments are often used to evaluate which process inputs have a significant impact on the process outputs, and what the target level of those inputs should be to achieve the desired results (outputs). Therefore, DOE techniques enable designers to determine simultaneously the individual and interactive effects of many factors that could affect the output results in any design. DOE also provides a full insight of interaction between design elements [136]. Therefore, this method permits us to create a continuous space for our input variables and their responses.

This optimization methodologies are used to evaluate the manufacturability of Additive Manufacturing (AM) in optimization level in different studies. A DFAM approach for metal is developed by [115] which consists of cost estimation and part orientation optimization. This approach is applied through a commercial 3D solid modeling program. Part orientation, functional optimization and path optimization in DFAM approaches are analyzed by Ponche et al. 2014 [79].

Also, an optimization method is presented by [99] to find the optimal build orientation by assessing manufacturing time and component mass.

1.6.4 Material and process selection based DFAM:

The importance of material type in functional analysis and specification of a product, as well as the dependency between AM technologies and material types, encourage the researchers to provide the DFAM approach in this context. Recently, Zamen et al. [86, 82] defined an integrated product-process design including material and manufacturing process selection for AM by using multi-criteria decision-making based on the functional specification, cost, and environment.
Different technologies exist for AM that create the different characteristics and attributes of AM products which must be taken into account in the DFAM approaches. A new two-dimensional approach is presented by [46] for process chains modeling for AM to support the process selection of DFAM in the early phase of design. This approach is used to investigate how AM can be incorporated into traditional manufacturing process chains. As a result, it is shown that combining AM technologies into conventional process chains increases cost and complexity and should only be done when the advantages outweigh the disadvantage of the combined methods.
A set of methods and tools which is helpful to design a product and its manufacturing process taking into account AM specificities in [72] from the early design stages with the integration of DFAM and Manufacturing Execution System (MES). This information framework is able in real-time acquire, analyze and synthesize process and product data. This framework allows improving of the product quality and process performance, and to better deal with possible criticalities, both in the prototyping and in the mass production phases.

1.6.5 Combination of functionality and manufacturability DFAM:

DFAM guidelines are presented by [109, 112] based on a comprehensive materials data survey and different analysis of AM criteria like cost and mechanical behavior.
A framework for DFM and SLA are considered in [73] which consists of four main process components and two pre-built components of the information model for representing design requirements and meta-rule taxonomy. The process components consist of representing design requirements (manual procedures), determining manufacturing rules coming from the requirements, structure the problem repository, retrieving and ranking of the DFM problems.
A multi-level design method is developed by Tang et al. 2014 [87] for AM inspirade by the work

of Rosen et al. 2007 [70]. In this approach, the topological optimization in macro-level and lattice structure in meso-level are consequently adapted. Not only the CAD models which are generated by using a CMM (Coordinate Measuring Machine) and CT scan (Computed Tomography scan) are considered as the input, but also the design requirements and manufacturability are the inputs to find the optimal structure.

A process plan for AM is suggested by [83] which includes macro and micro plan. Also, a framework for evaluating the AM is developed to analyze the design for AM. The indicators like adaption and discrimination indicators as well as, the threshold values are determined to a suitable scenario of additive process to help designers better benefit the advantages of AM processing and to avoid some potential difficulties or problems derived from the constraints or limitations in AM simultaneously to improve their designs.

Some DFAM approaches combine manufacturability analysis, functional DFAM and material selection. Salonitis et al. [78] presented a framework for re-design of Additive Layer Manufacturing (ALM) to examines the principles of AM, design guidelines, capabilities of the manufacturing processes and structural optimization using topology optimization. This approach provides different solutions for design but the optimal one must be selected based on the appropriate criteria including light-weight, strength and minimum displacements, manufacturing cost and surface quality. For this purpose, multi-criteria decision making (MCDM) method like AHP approach is used to find the best solution for design of ALM parts.

A novel approach is suggested for laser AM to create a lightweight design by incorporating structural optimization tools as topological optimization, bionic structures, and AM guidelines into one design process in [106].

A product/process optimization was studied to expand the design freedom allowed by AM for a case study through an approach combining topological optimization and lattice structures in [98]. While the results of their combined approach did not yield a global optimum solution (considering criteria such as weight, stress, displacement, etc.), at least it illustrated the feasibility of mixing these methods.

A systematic search to identify the components in series products is prepared by [92, 95] which can be designed for AM due to the criteria including integrated design, individualization, lightweight design, and efficiency. After selecting the components, the component must be analyzed due

to the different requirements for each criterion to develop the design for manufacturing in both technological and economical directions in the product development. Therefore, by this systematic search for appropriate components and by fully utilizing the geometric freedom in the re-design, performance of serie production can increase impressively.

Ponche et al. 2012 [76] proposed the novel approach with considering the new aspect to define a part's design from its functional specifications and process restrictions (particularly manufacturing direction and manufacturing trajectories) instead of using an initial CAD model for an AM-specific improvement. This approach consists of three main steps, the first one is global analysis for finding the geometrical dimensions due to the dimension constraints, the second step permits the fulfillment of the dimensional and geometrical specifications due to the AM process characterizations and capabilities, and finishing process characteristics to determine the functional volumes. Finally, the last one is determining the physical and assembly requirements based on the AM process capabilities to determine the linking volumes including Functional Volume (FV) and Manufacturing Direction (MD).

Ponche et al. 2014 [79] provided a DFAM methodology to optimize the manufacturing process through process simulation. The optimization consists of three steps which covers part orientation, functional optimization, and path optimization to balance functional requirements and process specifications. With an improved paths generation depending on process parameters and part geometry, it is possible to minimize the gap between the virtual model and manufactured part. The geometry is assessed in terms of functionality and manufacturability with defining the functional indicators and manufacturing indicators to compare the different manufacturing path. Also, the DFAM approach is classified by [89] as Process driven shape and Designer driven shape. Process-driven shape is performed through topological optimization and it focuses on reducing manual interaction with a human designer to reduce design time and/or improve design performance. Designer one is a process with a human designer driving the shape, contributing with knowledge about manufacturing to avoid costly production of the parts and it is presented through lattice structure analysis in the manufacturing domain to reduce the volume and thus printing time and part cost in this research.

AM design rules and topology optimization are combined as a DFAM approach by Leary et al. 2014 [99]. This approach illustrated that topological optimization can be modified to ensure

manufacturability without any additional support structures. The optimal build orientation is determined by assessing the manufacturing time and component mass.

Another approach on the axiomatic design method is provided based on mapping the customer needs on functions as Functional Requirements (FRs). Design parameters are determined to indicate how the object can satisfy such FRs. Finally, process variables are described for manufacturing through zigzag decomposition [103].

Previous DFAM approaches are investigated in [69] and they present a comprehensive DFAM approach which is a combination of functional and manufacturability DFAM, as well as process selection by considering the AM potential.

Multi-part production with AM is also another interesting subject that is investigated by the researchers [116, 117] to fabricate different parts simultaneously without using tools or fixtures. An optimization problem is defined to find how to optimally place multi parts into a specific two-dimensional build space by using parallel nesting algorithm. AM feature-based orientation optimization method" to optimize each build orientation to guarantee the production quality and to decrease the total build time and cost [116, 137, 138]. Also, a facet cluster-based method is used to generate alternative build orientations [139], as well as, a modified feature and rule based orientation optimization method for a new developing composite AM process [140].

Dhokia et al. 2017 [114] present a design method that mimics the behavior of termites as they build their nests, to concurrently design, structurally optimize and appraise the manufacturability of AM parts. This DFM approach is inspired by termite nest building.

A novel and disruptive approach is proposed by [118] to consider the simultaneous design and structural refinement of parts manufactured by describing the known part constraints and the mechanisms (limitations) of constituent manufacturing processes, parts are designed using a bio-inspired multi-agent system called "Hybrid Ants".

Vo et al.2017 [119] proposed a DFAM approach based on the DRM methodology. DRM is a generic and systematic methodology for improving the quality of design research. The DRM model includes 4 phases: "Research Clarification (RC)", "Descriptive Study−I (DS-I), Prescriptive Study (PS) and Descriptive Study−II (DS-II) [141]. This study contains the important steps to take into account in a design process for AM. Generally, it provided the initial 3D model based on topological optimization and Finite Element Analysis is also performed to evaluate the 3D

model. Also, the definitions of the terms "virtual model","physical model" and "Prototype" are proposed. In addition, the characteristics of a design situation are defined which will guide the choice between them in the evaluation phase of the performance of parts based on a Case Based Reasoning model.

For several years, great effort has been devoted to the study of important AM parameters like tool path optimization [142, 143], infill optimization [144], surface roughness [145, 49], dimensional accuracy [146, 147], time [148, 149], and cost [51]. According to these studies, the important parameters are build orientation, layer thickness, infill pattern and density, building temperature, material properties and process parameters like nozzle diameter,print and travel speed.

Due to AM characteristics including layer-by-layer fabrication, interior structure, part orientation, and environmental factors (building temperature, platform temperature), AM parts do not have the same mechanical properties as the products produced by the traditional manufacturing processes [150, 151].

1.7 Research gaps:

In this thesis, a statistical analysis of the performed researches is provided as shown in Figure 1.18. It is depicted that most of the studies are related to combinational DFAM (35%) which combines functionality and manufacturability analysis, so, it is the most complete and cited approach existed in literature. 30% of the researches are devoted to the manufacturability DFAM which are the studies that performed a manufacturability analysis without considering functional analysis. Manufacturability evaluation must be performed in three levels of verification, quantification, and optimization. Most of the studies are performed in level of verification (65%) but studies on the quantification and optimization levels are still lacking as 20% and 15% of all the manufacturability DFAM approaches and combinational DFAM. Also, Functional DFAM is another significant approach for DFAM which includes 26% of the studies.

According to this literature analysis it can be concluded that:
The Design For Manufacturing approach for AM is not complete like DFM approach proposed for classical manufacturing process as:

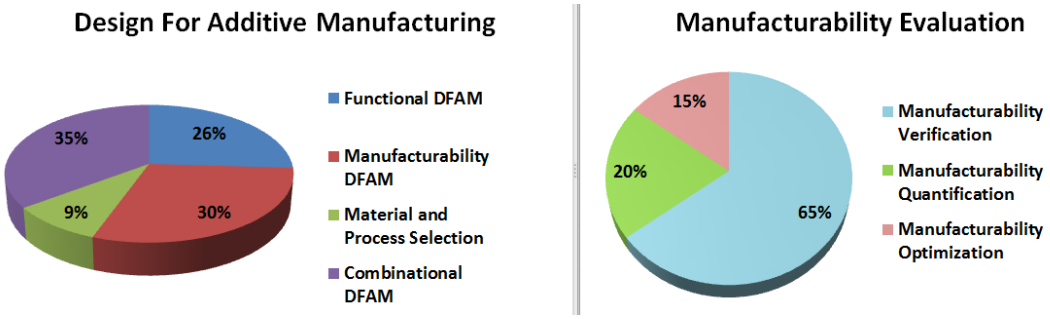


Figure 1.18 – Statistical analysis of DFAM approaches

- There is no DFAM approach in product definition level.
- There is a lack of quantification and optimization of manufacturability in the existed DFAM approaches.

Therefore, it is necessary to consider the AM criteria and parameters in the DFAM approaches to verify, quantify and optimize the manufacturability of AM as the DFM approach.
According to this literature analysis, the most important criteria which must be analyzed, quantified and optimized include time, material mass as production system cost and surface roughness as a factor of surface quality, dimensional accuracy, as well as the mechanical behavior of AM products. These criteria will be analyzed in this study through a multi-criteria decision-making approach. So, this proposed approach is the combination of functional and manufacturability DFAM by considering the AM criteria and attributes to provide an integrated approach that encompasses all the steps of the product life cycle from functional analysis to manufacturing concurrently.

1.8 Summary

Although several approaches were studied in DFM for AM with considering different criteria, the studies on the product definition level are still lacking. Since design and manufacturing of the product with AM are quite different compared to the traditional manufacturing process, it creates new issues and concerns for industrial implementation. Thus, these new studies illustrate the importance of managing the design and manufacturing process for AM technology in order to

guide the engineer and designer to an optimal solution. Therefore, it is essential to propose an integrated and complete approach addressing all attributes, capabilities, criteria, and constraints concurrently to provide an interoperable process in product life cycle development for AM.

Previous studies merely use the DFM to add manufacturing impact on the 3D model and initial design, but the process of product definition is more complex than CAD model analysis. Also, it is necessary to provide a methodology to optimize the product model through optimization of the 3D model, as well as quantify and optimize the manufacturing parameters. The design and manufacturing process of AM is quite different compared to the traditional processes. Contrary to the early promise made by some researchers, designers are not free in designing the products with every complex geometry and many analysis and investigation have to be considered in the design of products for AM processes. Therefore, it creates a major issue for the industrial implementation of AM. It is crucial to integrate the usage, design, and manufacturing attributes inside the product definition to take into account the requirements and constraints of an AM complex system.

The main objective is to propose an approach to help the designer and manufacturer in order to present an optimal solution for production with AM by managing design and manufacturing concurrently as an integrated approach of DFM for AM. Therefore, this thesis focuses on providing an integrated design approach for AM during product definition to find an optimal product model by considering all the attributes and constraints coming from the first step of design to manufacturing.

Therefore, the proposed methodology will be described in the next chapter (chapter 2) as an integrated design approach for AM through DFM-skin and skeleton approach.

2

DFM-Skin and Skeleton approach for AM: Proposed methodology

Outline of the current chapter

2.1 Introduction

In the product development process, several tasks should be performed to define the final product model based on the customer requirements. The product is designed according to the constraints related to the whole product life cycle (materials, structural analysis, recycling, etc.). Hence, concurrent engineering can help to consider and analyze the manufacturing constraints in the

product development. Importance of considering manufacturing constraints and attributes in the product definition gives the restrictions to integrate design and manufacturing as Design For Manufacturing (DFM) approach. This integration in the product definition is carried out from sub-model representing a common design and manufacturing modeling [30].

For this purpose, a skin-skeleton approach, which was used before for providing the DFM approach for classical manufacturing process, is selected to represent the usage and manufacturing model as the parts of product model simultaneously. This skin-skeleton approach is used to implement DFM approach for AM as a DFAM approach which is an integrated design approach for AM. To develop this approach for AM, the features must be adapted to AM characteristics and attributes. Two propositions are provided to implement this approach into Additive Manufacturing (AM). These propositions are different in terms of the way that usage and manufacturing skeleton are determined.

1. **Proposition 1:** To implement this approach, the usage model includes skin and skeleton are obtained by topological optimization. Then, an intermediate representation of the 3D model is achieved. Finally, the product model is the evolution of this usage model which is obtained regarding manufacturing model and interface processing engine results. In this method, manufacturing skin is layer contours and manufacturing skeleton as part orientation is determined through an optimization strategy in interface processing engine (see Figure 2.1).

2. **Proposition 2:** According to this proposition (Figure 2.2), the usage skin is obtained by topological optimization, then the skeleton is obtained by power crust algorithm based on this optimized usage skin. Consequently, an intermediate representation of the 3D model is achieved. Finally, the product model is the evolution of this usage model which is determined regarding the manufacturing model and interface processing engine results. In this method, manufacturing skin is layer contours and manufacturing skeleton as part orientation is defines based on the usage skeleton which is derived from topological optimization and power crust algorithm. It must be mentioned that the main objective of this proposition is considering geometrical constraints imposed by AM, as well as AM unique characteristics like anisotropic material and non-homogeneous structure of the product interior (different

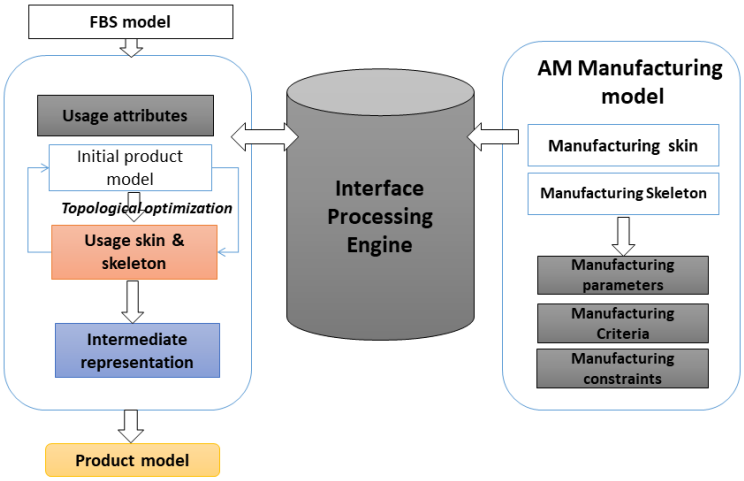


Figure 2.1 – Proposition 1

infill structure).

Firstly, the first proposition is used to implement the DFM-skin and skeleton approach for AM. Then, proposition 2 permits to define the proposed approach. In the following, the proposed approach due to the first proposition is described.

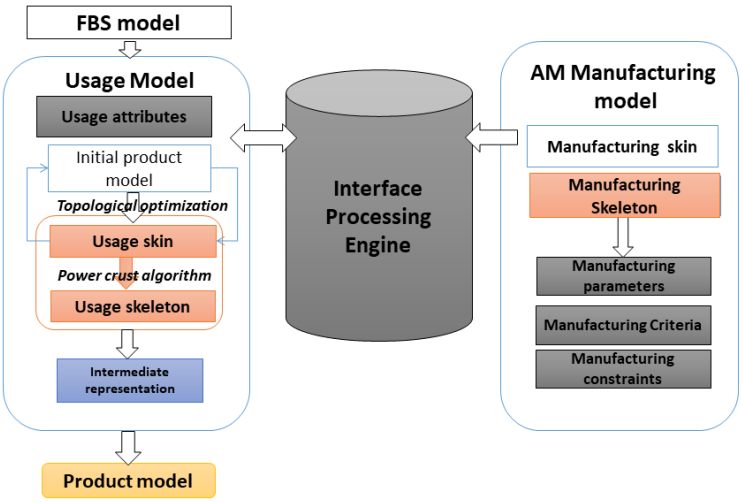


Figure 2.2 – Proposition 2

2.2 DFM-Skin and Skeleton approach for AM: Proposition 1

The first proposition allows providing the proposed methodology which relies on several models: FBS model, Usage model, Manufacturing model, and Interface Processing Engine which is a developed in section 2.2.4. Figure 2.3 illustrates the structure of the methodology. In this methodology, material data sheets and different types of AM technologies as AM database (part e and f) are important information that must be analyzed to find the desired material and suitable AM technology for production, this data must be considered in all steps of this approach. FBS model (part a) is achieved by analysis of the product specifications which are predefined due to the customer requirements. It helps to provide an initial model by analysis of the product function, behavior, and its structure. Therefore, it helps to recognize the usage model. Usage and manufacturing models are identified simultaneously as part b and c which consists of skin and skeleton. The usage model demonstrates the product features which is created through an optimized model due to mass and structure optimization regarding product function. Then, this optimized model will be modified as our 3D draft of the product due to the product features. As AM is used to fabricate the parts, the 3D model must convert to STL file as standard format

for AM. In parallel, the manufacturing model determines the process parameters and rules due to AM database. Therefore, this usage and manufacturing models help to determine usage and manufacturing attributes and criteria which are needed in providing an interface processing engine. An interface processing engine (part d) is proposed which plays an important role in completing and defining the product model by considering design and manufacturing attributes, criteria, and constraints concurrently. The main difference that distinguishes this research from other researches is the interface processing engine. This engine is derived from an interface model as an interface between design and manufacturing. This interface processing engine is a decision-making tool for the user that help to find the best manufacturing parameters in product definition regarding the manufacturing system criteria and constraints. In this thesis, it is proposed to evaluate the manufacturability in quantification and optimization levels. So, this engine contains different calculations and optimization tools to complete the final product model. This engine needs the inputs including the 3D draft of the product (which will be entitled "3D model" in this manuscript) derived from the usage model and its STL file, manufacturing parameters, and important criteria for fabrication by AM technology. It allows for defining of the manufacturing parameters for the machine to fabricate the 3D model.

Finally, this skin and skeleton concept helps to define a product. This product model derived from FBS model and usage model which define the 3D model, selected material and technology, as well as the attributes of product and the results of interface engine related to the product criteria. Therefore, it allows providing a functional DFAM and evaluation of manufacturability in the levels of verification, quantification, and optimization of AM criteria, constraints, and parameters. The product needs a redesign if the desired values of the considered criteria do not correspond to the customer requirements and product specifications, but the structure of this methodology is always fixed.

To better illustrate the proposed methodology, Structured Analysis and Design Technique (SADT) diagram is presented (see Figure 2.4) to define the activities for producing a product with AM based on DFM-Skin and skeleton approach. Node A represents the principal activity which contains sub-activities. This activity will be finished by performing all these sub-activities. This diagram consists of some activities that show how an interface processing engine is constructed to define our product model. When this engine is developed, the designer can use it even when

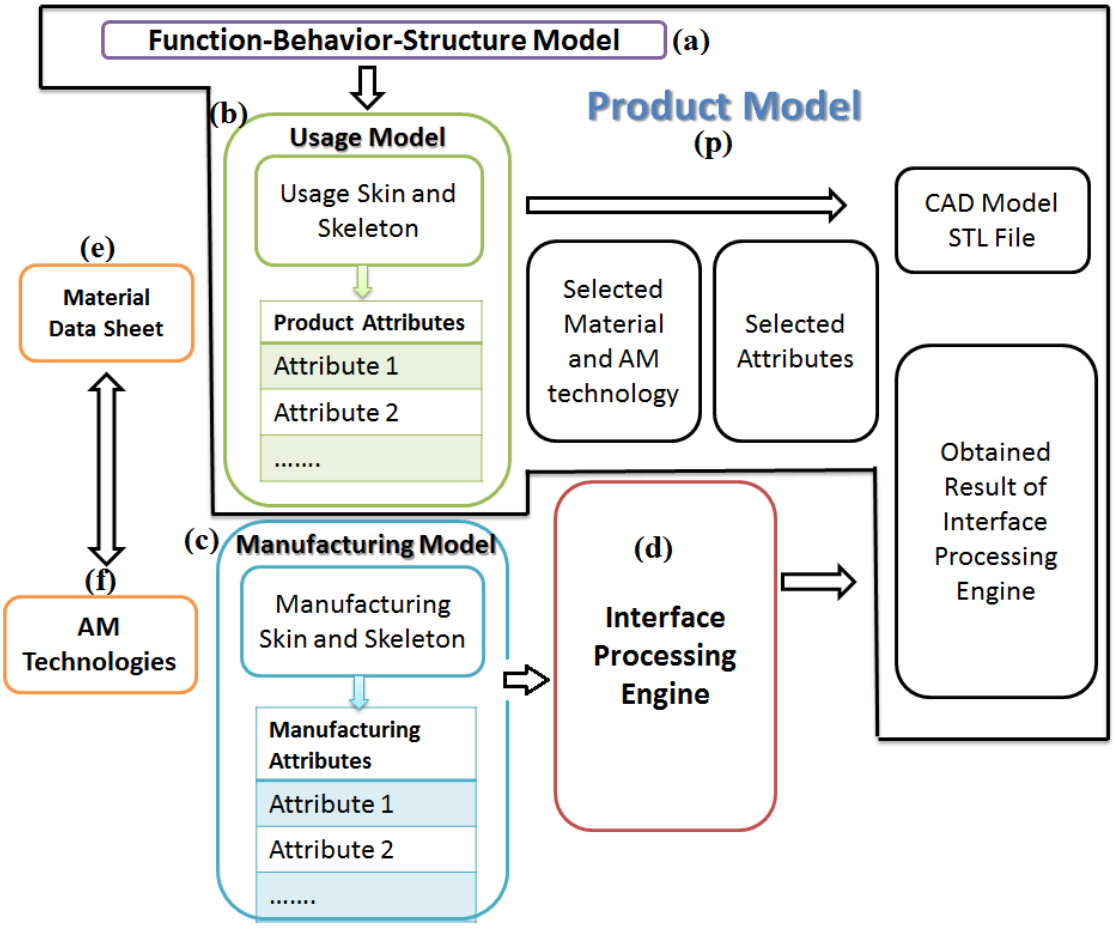


Figure 2.3 – General structure of DFM-Skin and Skeleton approach for AM

the product design must be modified. These activities are as follow:

- A1: Provide functional Analysis and FBS model
- A2: Provide initial product volume
- A3: Identify Usage model
- A4: Provide CAD model
- A5: Convert CAD model to STL file
- A6: Identify Manufacturing model
- A7: Identify manufacturing parameters
- A8: Provide interface processing engine
- A9: Provide Product model

All of these activities also contain the sub-activities that will be described in the rest of this chapter in different sections of the proposed approach: Functional analysis, usage model, manufacturing model, and interface processing engine which is derived from interface model.

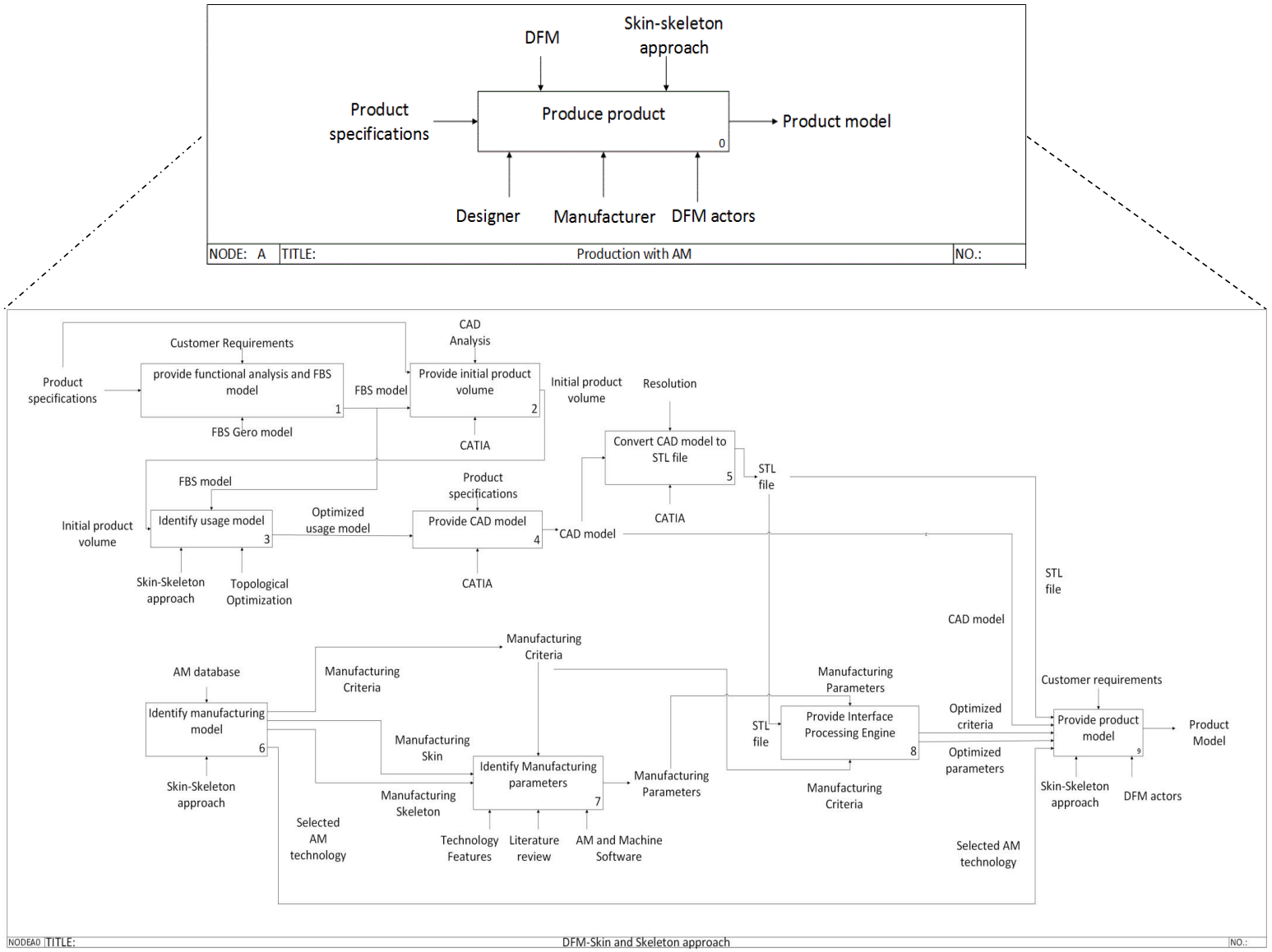


Figure 2.4 – How to produce a product due to DFM- Skin-skeleton approach

2.2.1 Functional analysis

The product specifications are already defined due to the customer requirements. The specifications consists of the mechanical performance, size and shape, weight, aesthetic aspects, and product functionality. The first step of this approach is functional analysis and requirement engineering which is determined as A1 activity in SADT diagram. In this study, Function-Behavior-Structure (FBS) model which was developed by Gero et al. [152] is considered to provide functional analysis. Design objects are conceptualized as Function (F), Behavior (B), and Structure (S) as FBS model. According to FBS model, designing a product involves a series of elementary steps including the transformation of the desired product function into its expected behavior and the expected behavior into a structure [152]. As shown in Figure 2.5, the A1 activity contains four sub-activities which are used to identify product function, behavior and structure which help us to complete the FBS model.

This FBS model is used to provide an initial volume of the product. As initial form and structure for the product must satisfy its function and behavior, also it helps to identify usage model including skin and skeleton by its initial design space. Therefore, it is necessary to provide an initial product volume as input for identifying usage model. This activity is shown in SADT diagram as A2 activity (Figure 2.6).

2.2.2 Usage model

Usage model is derived from product specifications, attributes, and FBS model. This model is used to make a simplified presentation of the product which consists of usage skin and skeleton. Usage skin is defined as a functional surface which energetic flow circulates through it. It supports the geometrical attributes and design specifications.

Since AM is used for almost all different shapes without any restriction, topological optimization is selected to obtain the usage model between various methods of optimization, such as parametric shape optimization and geometric shapes optimization. This optimization method permits to fulfill the design requirements like mechanical behavior and functionality, in addition, to optimize mass, structure, time, and cost [120]. Therefore, usage model is determined through topological optimization regarding the product function by optimization of mass and structure.

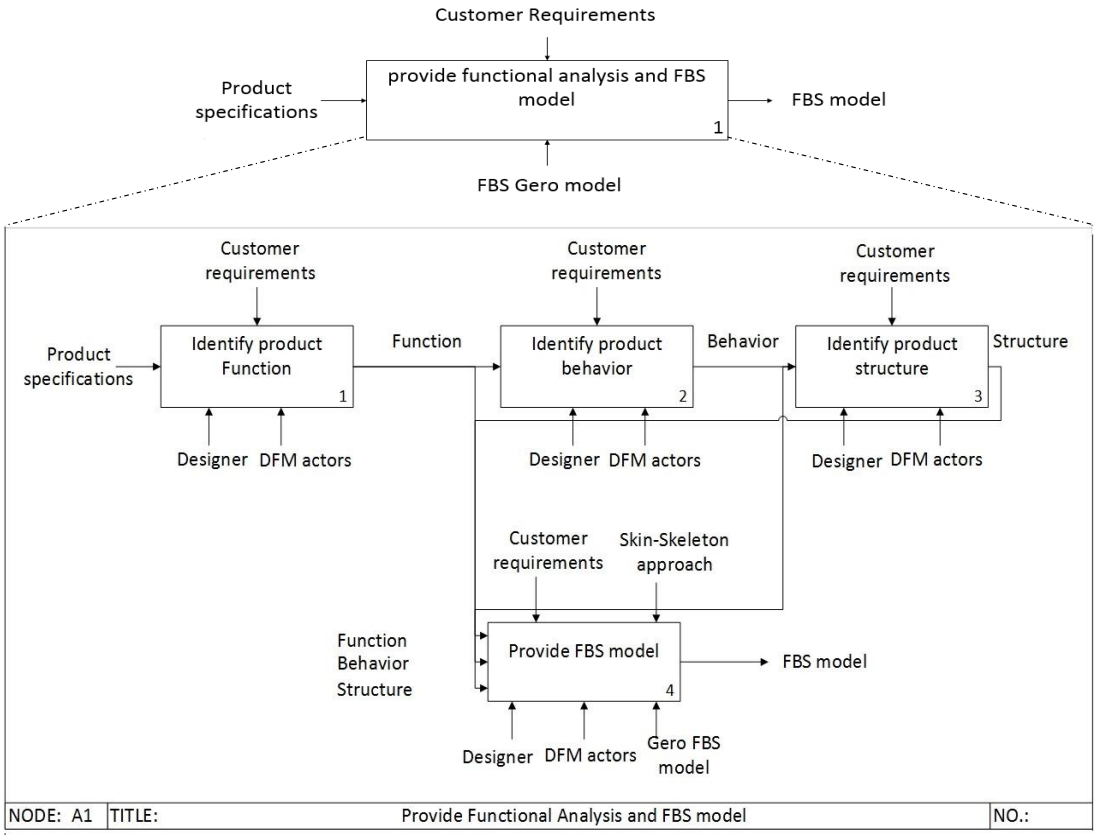


Figure 2.5 – Provide functional analysis and FBS model

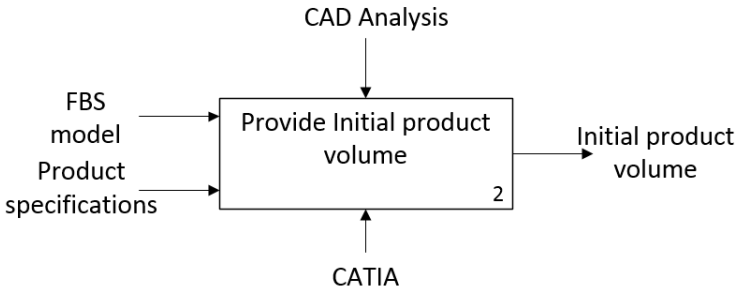


Figure 2.6 – Provide initial product model

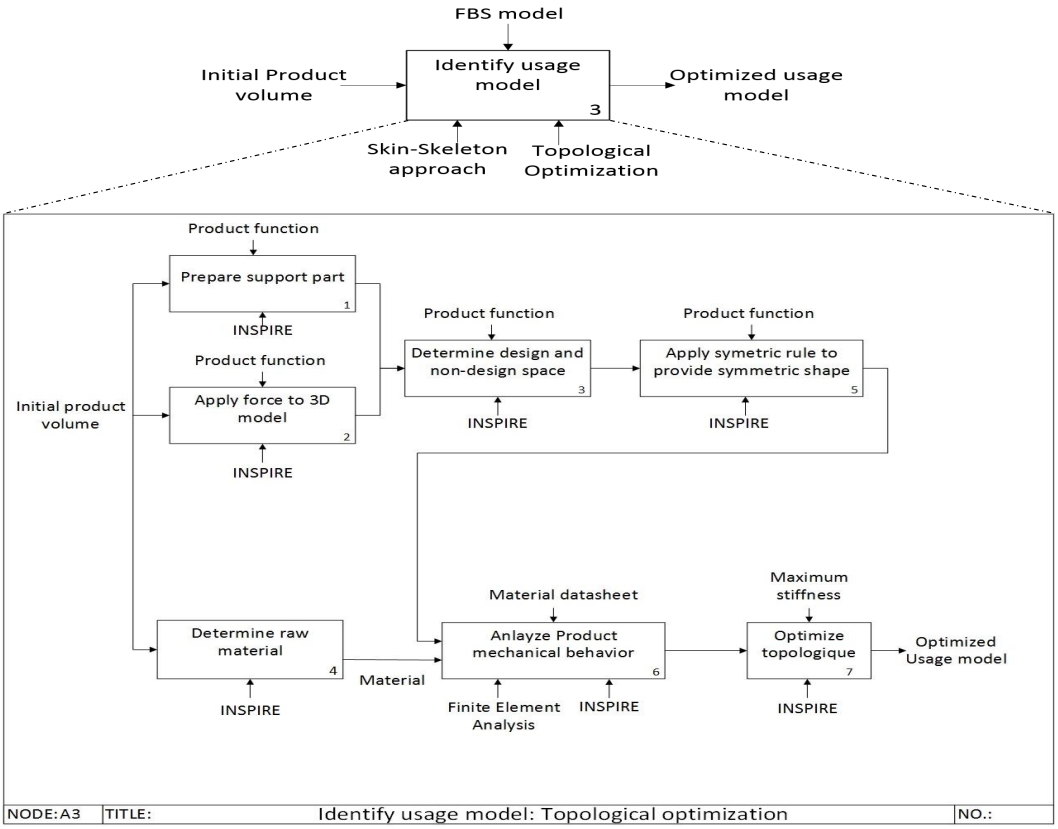


Figure 2.7 – Identification of usage model

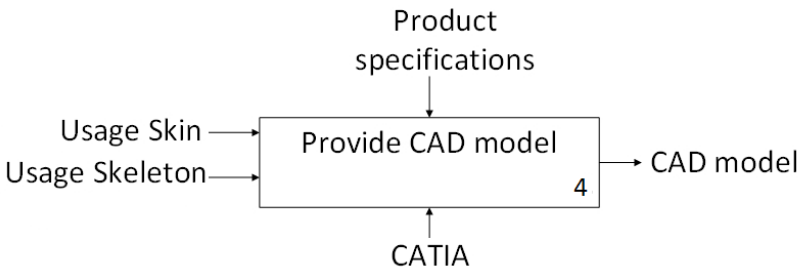


Figure 2.8 – Provide CAD model

This optimized model contains the usage skin and skeleton. Usage skeleton is an energetic flow that can be mechanical, electrical, magnetic, etc. which circulates in the product. This step as identification of usage model is presented in SADT diagram as the A3 activity. As shown in Figure 2.8, this A3 activity (node A3) is constituted from sub-activities which are needed to apply this optimization as illustrated in Figure 2.8. These activities are preparing support parts as non-design space, applying the force, determining raw material, symmetrical consideration, mechanical analysis which provides the preconditions for optimization regarding maximum stiffness of the product.

After optimization of the initial structure, the optimized usage model is a draft that must be converted to the 3D model. This optimized usage model is modified in CATIA-v5 based on the functional requirements and product functionality, as well as the AM constraints and capabilities. It is worth mentioning that products can be presented in a large diversity and the designer can select between these possible models.

Until now, one part of the product model as a 3D model is determined, but it is necessary to define the process and its parameters for production with AM technologies. Accordingly, a manufacturing model will be predicted to gather the essential information for manufacturing. In the next section, manufacturing model will be explained.

2.2.3 Manufacturing model

Manufacturing model contains manufacturing process selection information. This information contains process type and its related parameters. From a manufacturing point of view, the manufacturing processes can be realized due to forms and surface qualities that the process can

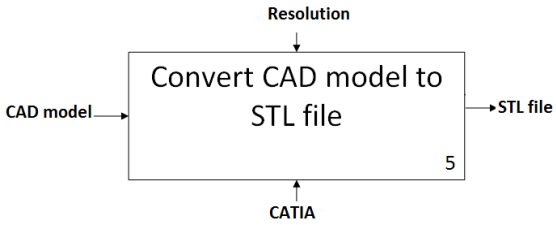


Figure 2.9 – STL file creation

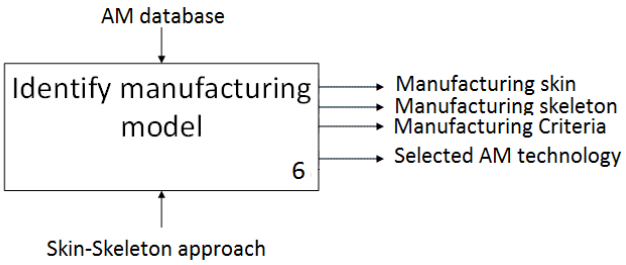


Figure 2.10 – Identify manufacturing model

perform [33, 30, 3].

In this thesis, it is supposed that product must be fabricated by AM technologies. AM produces layer-by-layer the complex products based on the CAD model. This 3D model must be converted to STL (Standard Tessellation Language) file as standard and suitable format for AM which consists of small triangles [37]. This conversion must be performed in high resolution to reduce the deviation from 3D model which is defined as the activity of A5 in SADT. Then, slicing is performed with specific software which is compatible with the machine and its technology as shown in Figure 2.9.

In this step, firstly the manufacturing model must be identified through skin-skeleton concept as illustrated in Figure 2.10 by activity A6. This identification permits to recognize the manufacturing criteria and parameters. Different parameters are identified based on these criteria through analysis of technologies, literature, and different softwares. Finally, the significant parameters of AM technology are recognized to utilize in the interface model. This steps are described comprehensively in the rest of this section. According to Skin-skeleton approach, manufacturing model consists of skin and skeleton:

Manufacturing skin: Manufacturing skin is a surface which is produced during this step. The skin features are created from manufacturing skeletons by a sweeping operation. Due to AM strategy as layer by layer production, the products produced by AM are constituted of layer accumulations. Nozzle starts the layer production from the contours of layers which are considered as manufacturing skin, then, interior structure is created that can be determined by manufacturing skeleton as described in the following.

Manufacturing skeleton: Skeleton is the flow trajectory and every manufacturing process is supposed based on the material flow.

Manufacturing tool-path shows how a product is constructed during manufacturing. Part orientation and infill structure are the parameters which determine the AM manufacturing tool-path. In this thesis, manufacturing skeleton is specified as the product orientation in the machine build platform. It is supposed that orientation is defined as an axis which is perpendicular to build platform. Orientation is presented through the angles between part and $\boldsymbol{x}$,$\boldsymbol{y}$ and $\boldsymbol{z}$-axis. It is worth mentioning that orientation along $\boldsymbol{z}$-axis creates the various infill patterns at different angles.

This slicing strategy and machine tool path are defined as G-code file for the machines. This G-code file is like a machine language that demonstrates the fabrication tool-path and parameters. Actually, it is a common numerical control planning language which is specified by the instructions on where to move, motion speed, and motion path. It is developed to guide computerized machine tools and describe the instructions about which tool-paths should be followed for AM [153].

Identification of manufacturing model helps us to recognize manufacturing parameters and significant criteria A6 activity in SADT diagram (Figure 2.11).

Additive Manufacturing parameters: To analyze manufacturing system, manufacturing parameters and produced product by AM techniques must be identified as shown in SADT diagram (Figure 2.11). The structure of the produced product by AM is illustrated in Figure 2.12.

As illustrated in Figure 2.11, identifying manufacturing parameters is performed by three activities of analysis of AM technologies, analysis of AM softwares and machines, as well as literature analysis.

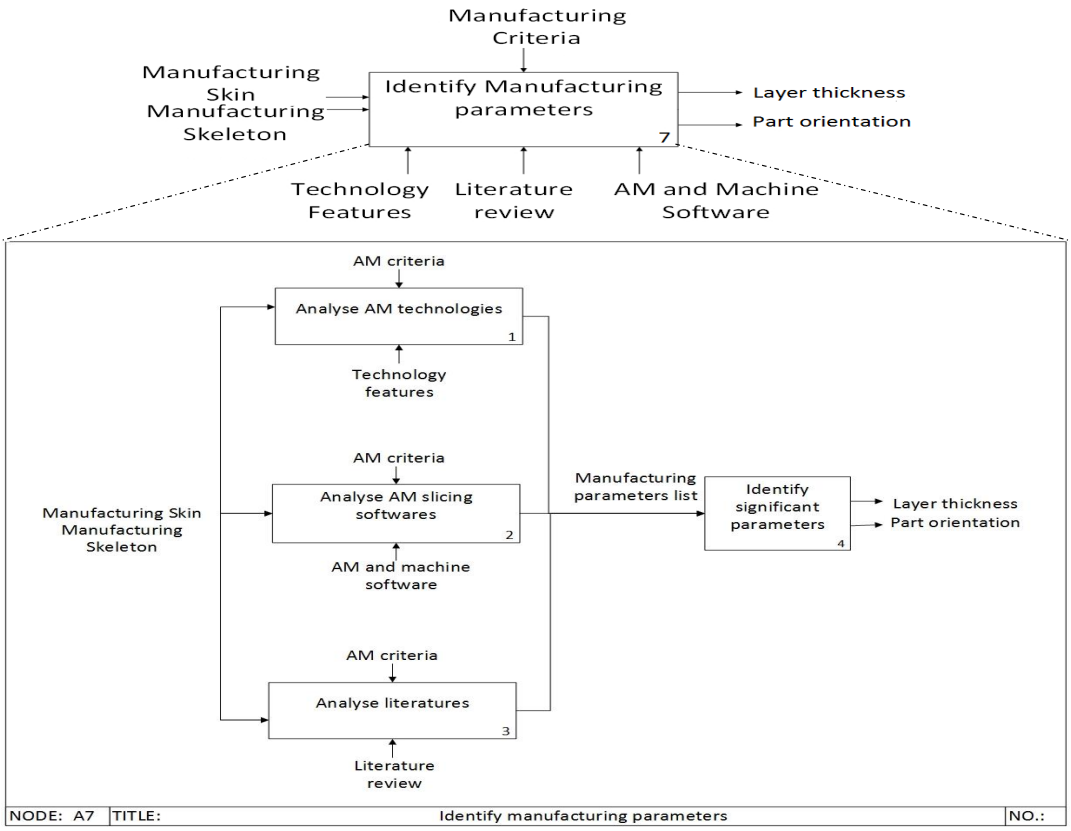


Figure 2.11 – Identify manufacturing parameters

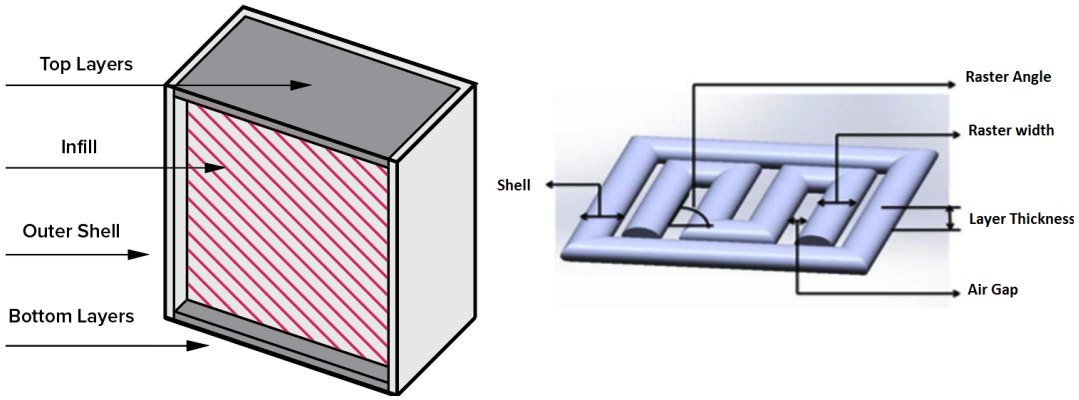


Figure 2.12 – AM product structure [154, 155]

Parameters	Technology
Layer thickness	All AM technologies
Orientation	All AM technologies
Infill density (air gap) and pattern	All AM technologies
Raster angle and width	All AM technologies
Shell width and number	All AM technologies
Support characteristics	All AM technologies
Raft characteristics	All AM technologies
Print speed	All AM technologies
Travel Speed	All AM technologies
Cooling speed	All AM technologies
Extruder and platform temperature	FDM
Laser Power	SLM, SLS and SLA
Scanning velocity	SLM, SLS and SLA
Hatch spacing	SLM and SLS
Spot size	SLS
Scan pattern	SLS
continuous wave	SLS
Pulsed wave which are defined	SLS
Heater Temperature	LOM
Platform retract	LOM
Heater speed	LOM
Platform speed	LOM
Laser speed	LOM
Feeder speed	LOM
Beam width	SLA

Table 2.1 – Different AM technologies parameters

Different AM technologies are analyzed based on their processes. Also, various slicing software like Cura, Slic3r, and MakerBot which are shown in Appendix II are investigated. Moreover, analysis of other researches [49, 156, 48, 126, 127, 157] help to find the parameters of manufacturing. These studies allow for determining of the manufacturing parameters. The most important parameters for these criteria are as follow (Table 2.1):

To find the significant parameters which affect the important criteria and constraint of AM, a literature analysis is performed on several studies (30 article) which investigate the AM technologies generally. This analysis also helps us to recognize AM criteria and constraints, as well as the parameters that affect these criteria. Table 2.2 shows the criteria, and the parameters that are evaluated, as well as the number of times that are investigated in these researches. These numbers present the importance degree of parameters on the desired criteria and constraints.

Criteria	Mechanical behavior	Accuracy	Roughness	Build Time	Quality	Cost	Material
Parameters	Material/3	Geometry/2	Orientation/3	Orientation/5	Orientation/4	Part dimension/3	Orientation
	Infill structure/2	Print speed//2	Layer thickness	Geometry/3	Geometry	Technology/3	Part dimension
	Part dimension	Orientation	Part dimension	Layer thickness/2	Part dimension	Orientation/3	Geometry
	infill density	Layer thickness	Material	Part Dimension/2	Material	Material/2	Machine
	Orientation	Extruder temperatu	Machine	Infill Density/2	Machine	Machine/2	Tehnology
	Machine	Machine	Technology	Toolpath/2	Technology	Infill density	Layer thickness
	Technology	Part dimension		Print speed/2		Geometry/2	
		Scan speed		Technology		Print speed	
				Cooling fan speed		Production volume	
						Part placement	

Table 2.2 – AM Parameters and criteria and their degree of importance derived from literature analysis (30 articles)

As shown in this table, layer thickness and orientation are the most important parameters of manufacturing and these two parameters are common between all AM technologies. They have significant effects on manufacturing system criteria and the constraints as described in the following:

Additive Manufacturing criteria and constraints

These criteria and constraints are taken into account separately in other researches [49, 48, 158, 156, 159, 160, 161, 113]. In this research, they will be analyzed together to find a solution for design and manufacturing that satisfies all these important criteria and constraints simultaneously.

Nowadays in this industrial world, time and material mass are the important criteria for all manufacturing systems as the factors that determine the manufacturing system cost. Also, mechanical behavior, surface quality, and dimensional accuracy are identified as the major issues and constraints for the industrial sectors of AM. AM characteristics like layer by layer production and the interior structure of AM products create the difference between AM products and other products which are fabricated by traditional manufacturing methods. These criteria and constraints are affected by manufacturing parameters, thereupon, final product model characteristics will be changed. In the following, these criteria and constraints are explained comprehensively:

Manufacturing time and material mass: Manufacturing time and material mass are the first criteria that should be analyzed for all production systems. For AM, these criteria are affected directly by modifying manufacturing parameters. Their modification trends can be simulated through special additive software for each machine and technology. These softwares simulate the tool-path before starting the printing according to the product geometry, build orientation, and manufacturing parameters. It creates the G-code file that contains the required time and amount of extruded material to estimate the elapsed time and material mass for printing.

Surface quality: As consequence of layered manufacturing, the surface finish of AM parts is excessively rough. Since this surface quality has the influence on the material functional properties including mechanical behavior, optical properties, and frictional behavior, the surface controlling

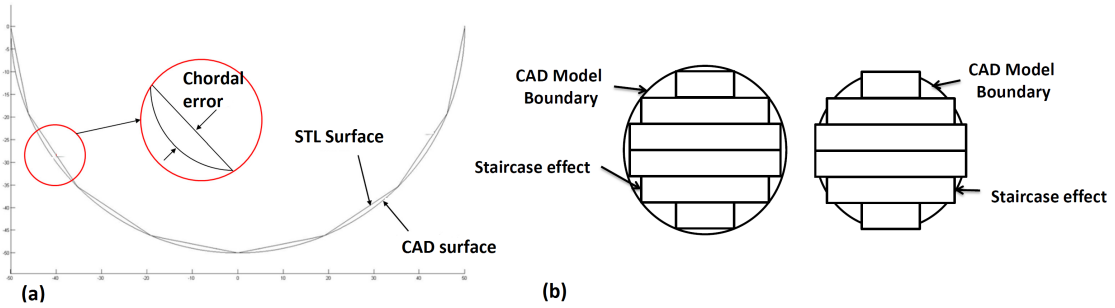


Figure 2.13 – (a) Chordal error [166]- (b) Staircase error [167]

of AM products is necessary [49, 162].

To investigate the surface quality as AM constraints, roughness can be analyzed. As described in ASME B46.1 [163]," R_a (roughness) is the arithmetic average of the absolute values of the profile height deviations from the mean line, recorded within the evaluation length. Simply put, R_a is the average of a set of individual measurements of a surfaces peaks and valleys."
Surface roughness (R_a) is defined as Equation (2.1):

$$R_a = \frac{1}{l}\int_0^l \mid y(x) - y_c \mid dx \tag{2.1}$$

where $y(x)$ is roughness profile value, l is the evaluation length, and y_c is the center line position. The areas above and below the line are equal. Therefore, $R_a$represents the summation of the areas above and below the line, divided by the evaluation length [164]. In AM process, poor surface roughness can be created by tessellation of the original CAD model (converting from CAD model to STL file) which is known as chordal error and the slicing procedure which is employed during the building process that creates the staircase effect that is created by layer deposition and it affects the surface roughness [49, 165] as shown in Figure 2.13. In this research, it is supposed that STL conversion is performed in high quality with large numbers of the triangle and its effect is ignored.

Mechanical behavior: Mechanical behavior of the AM products is not like a product that is produced by the traditional manufacturing process because of the material processing, layer by layer production, and filling structure of the additive parts. Different types of infill pattern

product and values of layer thickness create the different levels of product resistance [168]. Also, there are other parameters of manufacturing like air gap, raster width, shell number and width, raster angle and part orientation which affect the product mechanical behavior. For mechanical behavior, Ultimate Tensile Strength (UTS) is taken into account. It is measured by the maximum stress that a material can withstand during stretching or pull before breaking.

Dimensional accuracy: Obtainable desired accuracy for AM and specially FDM technology is a critical drawback which inhibits in AM utilization. A lot of parameters affect the accuracy of the product as material withdrawal and process parameters like layer thickness and orientation.

Until now, Functional analysis, recognition of usage model, and defining 3D model, as well as identifying manufacturing models include its significant parameters, criteria and constraints help to construct our novel interface model as an interface processing engine to consider design, manufacturing, and analysis of their criteria and constraints, as well as important parameters which affect them. In the following, this novel interface processing engine will be presented:

2.2.4 Interface Processing Engine

Identification of usage and manufacturing skin-skeleton allows for determining of their different parameters and attributes. Finally, integration of manufacturing constraints in the product definition is done gradually as an interface model. Interface model is an output of this approach for defining the product which demonstrates the relations between the parameters of the manufacturing procedure. In fact, it presents the required information that supports the synthesis of design and manufacturing. It provides the functional data, technological solution as material and process selection, and attributes values.

The usage and manufacturing models must be analyzed together to create the final product model by using the interface model. To define this interface model for AM and utilize these models for creating the manufacturing procedure, a novel interface processing engine is developed which is derived from the interface model but it is more complex and it contains information, models, and tools. It is a decision-making tool for the user that manages AM and product characteristics with any knowledge of its internal workings. It consists of calculation tools which

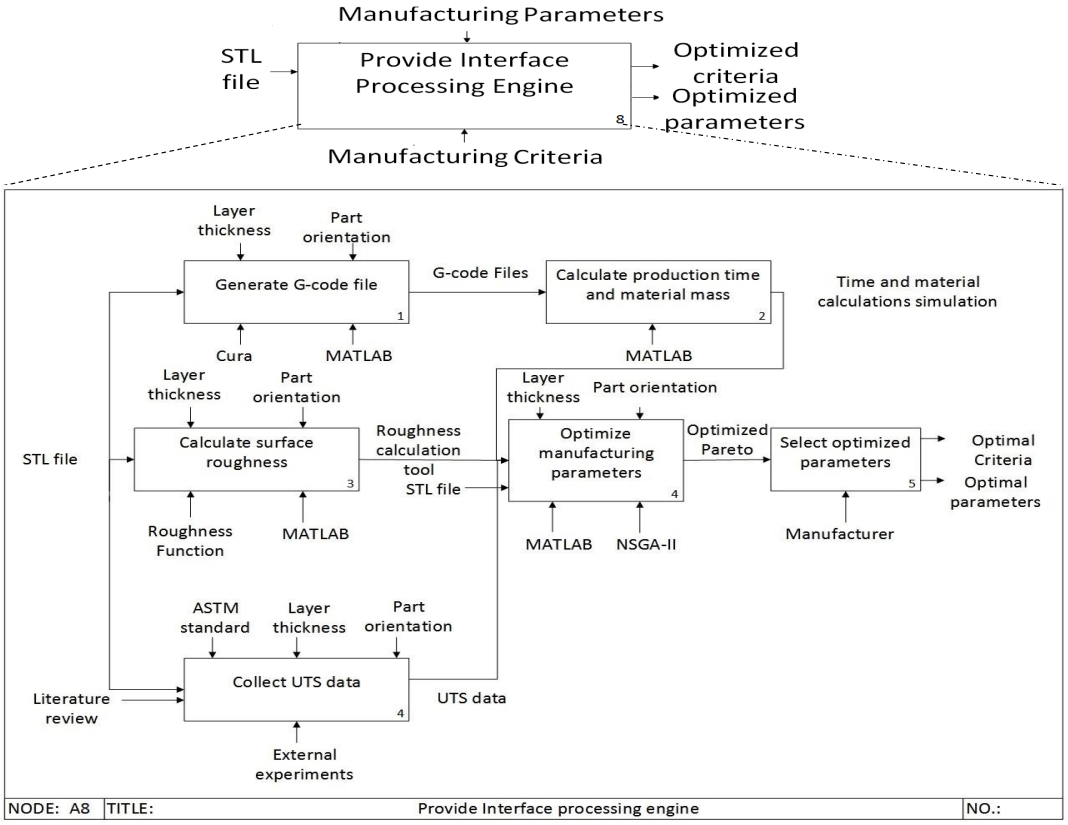


Figure 2.14 – Providing an interface processing engine

are used to integrate manufacturing constraints and attributes in the product definition. The objective is to find the suitable manufacturing parameters for production through a multi-criteria decision-making approach. Therefore, interface engine helps to complete the product model by selecting the process, machine, and manufacturing parameters for production regarding the criteria such as time, material and constraints like surface quality, and mechanical behavior of the products.

Overall, the goal is to define a generic model to be adapted to the other AM processes. This engine requires the 3D model coming from usage model, manufacturing parameters, important criteria of manufacturing, product features, and the relationships between these attributes. This interface processing engine is illustrated in SADT diagram (Figure 2.14) as activity of A7 which consists of different sub-activities. Necessary information for presenting the interface processing

engine are identified by FBS, usage and manufacturing models. 3D model of the product is also created through usage model. Moreover, analysis of AM technologies and several slicing software like slic3r, Cura, and MakerBot allow for determining of manufacturing parameters. Furthermore, it is essential to analyze the important criteria like production time, material, mechanical behavior, and the surface roughness of AM products. STL file is the main input for this interface engine.

To investigate all these criteria and constraints simultaneously, a multi-criteria decision-making approach can be helpful. To utilize this approach, this interface processing engine must be constructed as shown in Figure 2.14. As shown in Figure 2.14, the results obtained by usage and manufacturing skin-skeleton are necessary to construct this interface processing engine. There are calculation tools for time, material, and roughness. Time and material are computed by simulation through Cura software in MATLAB and generating G-code files. Roughness is presented through a mathematical model which is defined based on the geometrical study of filament, produced surface and experimental data. UTS values are collected for mechanical behavior due to layer thickness and orientation as important parameters of AM. To manufacture a product by AM, it is necessary to select the suitable values for manufacturing parameters. Parameter analysis shows that the number of variables as manufacturing parameters are more than the existed relationships between these variables. So, it is necessary to define an optimization problem to find an optimal solution of manufacturing parameters as fabrication setting by considering these criteria simultaneously.

It is decided to provide a bi-objective optimization to analyze this multi-criteria decision-making problem. This optimization is described as the fourth sub-activity of providing an interface engine in SADT diagram (Figure 2.14) to find the optimal solution for manufacturing with AM. Manufacturing time and material as the major criteria of the manufacturing system cost are considered as the objective functions for this optimization problem to minimize the total cost of the system. According to the importance of mechanical behavior and surface roughness as the drawbacks of AM products, they are considered as the constraints for optimization.

As mentioned before, layer thickness and orientation are the most important manufacturing parameters of all AM technologies, these parameters are determined as decision variables.

Decision variables, objective functions, and constraints are common for all AM technologies, this interface processing engine can be applied to all AM technologies as a general interface

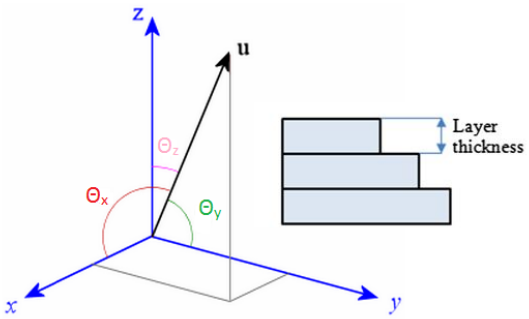


Figure 2.15 – Decision variables: angles between parts and the axis of $\boldsymbol{x}$,$\boldsymbol{y}$ and $\boldsymbol{z}$ [169]- Layer thickness

processing engine.

In the following, the mathematical formulation of the bi-objective optimization problem is explained.

Bi-objective optimization problem

A continuous bi-objective optimization problem is defined inside this engine to optimize time, material mass by considering the product roughness and mechanical behavior as the constraints.

As layer thickness and orientation are identified as significant parameters of manufacturing which affect the manufacturing criteria and constraints, they are selected as decision variables. Orientation can be defined through three angles (θ_x, θ_y, θ_z) in space. Therefore, the four component vector of decision variables ($\boldsymbol{x}$) is presented which contains the layer thickness and orientation angles as follow:

$$\boldsymbol{x} = \{\theta_x, \theta_y, \theta_z, L_t\}$$

where :

- L_t: Layer thickness.
- θ_x, θ_y, θ_z: define the orientation, i.e. the angle between part and the axis of $\boldsymbol{x}$, $\boldsymbol{y}$, and $\boldsymbol{z}$ (see Figure 2.15). These angles demonstrate the orientation of the part in platform as well as, infill angle of the part which is determined through rotation along the $\boldsymbol{z}$-axis by θ_z.

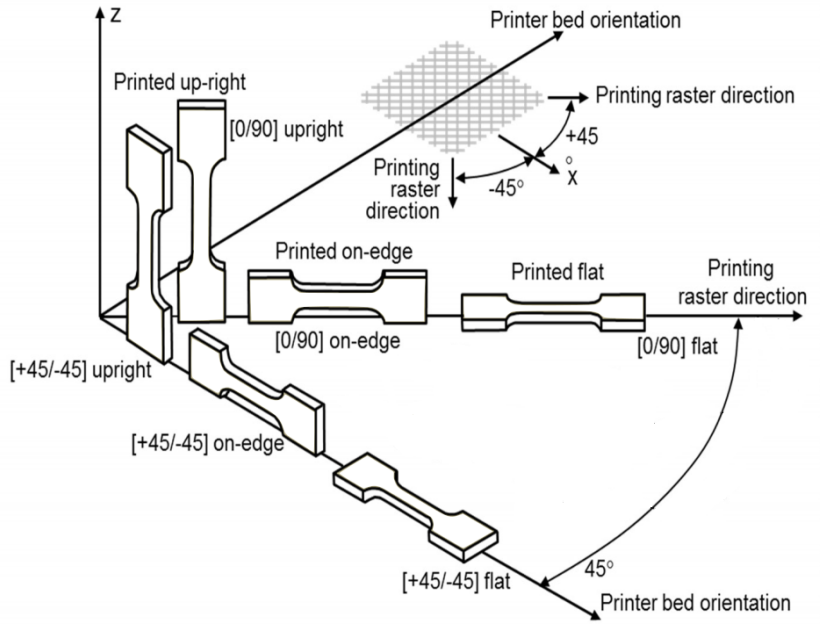


Figure 2.16 – Orientation types [170]

These different orientations are shown in Figure 2.16. This figure shows specific orientation types like flat, on-edge and up-right in different raster direction ($\pm 45°$, $0/90°$).

The bi-objective optimization problem is written as:

Minimize:

$$f_1(\boldsymbol{x}) = \text{Time}(\boldsymbol{x})$$

$$f_2(\boldsymbol{x}) = \text{Material}(\boldsymbol{x})$$

Under the constraints:

$$g_{R_\text{a}}(\boldsymbol{x}) \leq R_{\text{a}\text{Max}} \tag{2.2}$$

$$g_{\text{UTS}}(\boldsymbol{x}) \geq \sigma_{\text{Max}} \tag{2.3}$$

$$\boldsymbol{l_b} \leq \boldsymbol{x} \leq \boldsymbol{u_b}$$

With:

$$\boldsymbol{x} = \{\theta_x, \theta_y, \theta_z, L_t\}$$

$$\boldsymbol{l_b} = \{-180^\circ, 0^\circ, -180^\circ, L_{t\text{Min}}\}$$

$$\boldsymbol{u_b} = \{180^\circ, 180^\circ, 180^\circ, L_{t\text{Max}}\}$$

As shown by mathematical formulation, the first objective is the time that machine requires for fabrication. The second objective is the mass of material that is consumed for manufacturing. The optimal solution for manufacturing will be provided by minimizing these objectives.

The vectors of lower and upper bound of the decision variable components are $\boldsymbol{l_b}$ and $\boldsymbol{u_b}$ which show their minimum and maximum allowable values. Layer thickness value is between $L_{t\text{Min}}$ and $L_{t\text{Min}}$. To consider all possible orientations for product in the space, the angle of $\boldsymbol{x}$ and $\boldsymbol{z}$ are between -180° and 180°, and $\boldsymbol{y}$ is in the range of 0° and 180°. It must be mentioned that rotation along $\boldsymbol{z}$-axis determines the filling angle.

The objective functions are calculated through simulation of additive procedure for each orientation and layer thickness value by the additive simulation software for each technology and machine.

The first constraint (Equation (2.2)) provides a relation between layer thickness and orientation to estimate the surface roughness to satisfy the surface quality of the product.

Equation (2.3) is used to present the mechanical behavior of AM products. Resistance is

formulated with the maximum mechanical stress in the product (σ_{Max}) and Ultimate Tensile Strength (UTS) of the material that depends on the manufacturing parameters (orientation, layer thickness, infill angle, etc.). This constraint shows that the AM product must be more resistant than the desired behavior. The UTS values for different orientations and layer thickness are obtained by analysis of several experiments performed by other researchers like [156, 171, 172, 157, 170]. It must be mentioned that these experiments must be performed in the same experimental conditions including material type, specimen kind, and temperature. Moreover, other manufacturing parameters for fabrication of the specimens must be identical.

Before solving this optimization problem, it is necessary to formulate this bi-objective optimization problem including objectives and constraints.

As shown in Figure 2.14, time and material mass are calculated through simulation of tool-path by AM software and analysis of the G-code file. Roughness is formulated as a roughness model, this model is obtained by geometric analysis of the filament and experimental measurements are used to validate this roughness model. Mechanical behavior of the AM products are analyzed through experimental methodologies, The UTS values are collected through a tensile tester for different values of layer thickness and orientation types. These formulations are the calculation tools for time and material, as well as roughness, and the UTS database provide the preconditions for solving this optimization problem.

Solving Procedure

To solve this bi-objective optimization problem, two methods are used in this thesis:

1. UTS data are obtained by analysis of experimental approaches. Time and material values are calculated through software simulation of printing for these data. Also, roughness values are coming from roughness formulation. These data permit to create a meta-models to provide the models which formulate time and material, roughness, and UTS data.

   In this study, Modefrontier which is a software for process integration and design optimization is utilized. It provides a multi-objective optimization problem and design environment that can be easily integrated with almost any CAE and CAD package. It utilizes a lot of optimization algorithm and tools including response surface modeling tool, MOGA and

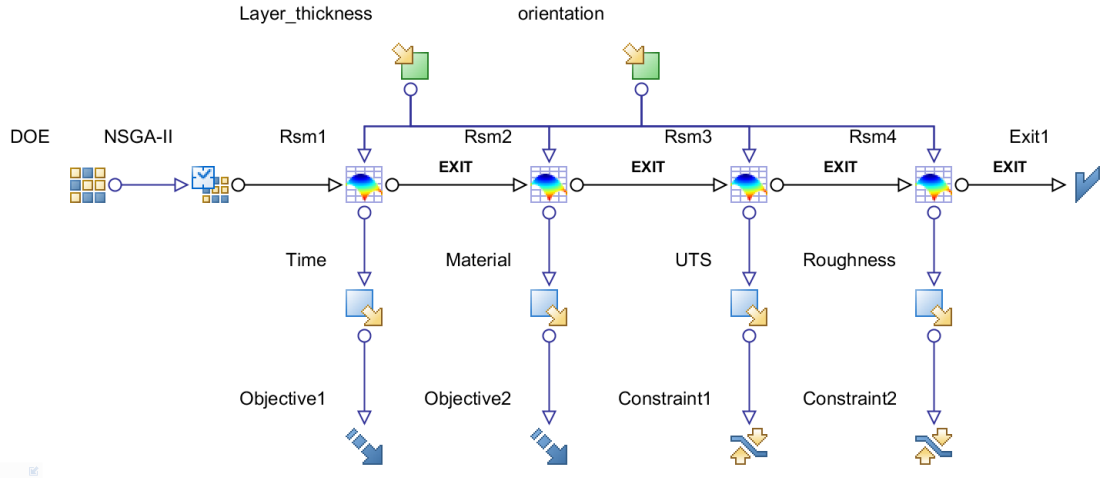


Figure 2.17 – ModeFrontier workflow to solve bi-objective optimization problem

NSGA [135]. The environment of this software is illustrated in Appendix II. Response Surface Methodology (RSM) helps to provide these meta-models by polynomial function.

This software helps us to determine the optimal Pareto of manufacturing parameters (layer thickness, orientation type) by optimization of time and material regarding to product roughness and mechanical properties. A work-flow of this bi-objective optimization problem is shown in Figure 2.17. As shown in this work flow, layer thickness and orientation types are the decision variables of discrete problem. To define DOE, the results of time, material, roughness, and UTS which are required. This DOE is used for meta-modeling and RSM is used to formulate the response of the criteria for different values of layer thickness and orientation types. Moreover, the NSGA-II algorithm is used to find the optimal Pareto.

It seems that the data which are used as DOE are not sufficient to create a meta-model and in the next step of this thesis, it is decided to use another methodology for solving and formulating this bi-objective optimization problem. In the following, this methodology will be described.

2. Execution of Cura as an open source software in MATLAB permits finding the production time and material mass values for all possible orientations in space and all allowable values of layer thickness by simulation of printing procedure as G-code file.

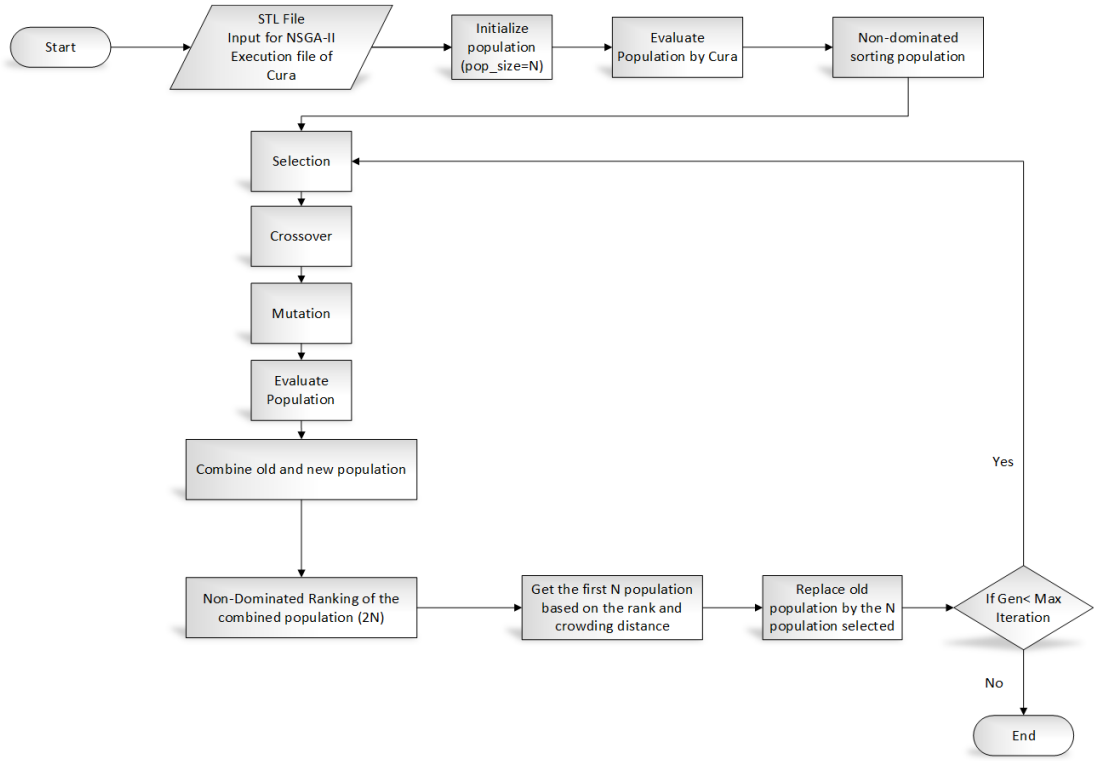


Figure 2.18 – NSGA-II procedure for solving the optimization problem

Not only, this bi-objective optimization problem is a combinational optimization problem and it is categorized as an Non-linear Polynomial problem, NP-hard problem, but also, simulation of AM procedure through AM software and creating the G-code files are time-consuming. Therefore, to find the feasible solutions for this continuous optimization problem in a reasonable time, a meta-heuristic algorithm seems helpful. So, Non-Dominate Sorting Genetic Algorithm-II (NSGA-II) is used to find the optimal solutions for manufacturing.

The essential inputs of this problem are the STL file, execution file of additive software, roughness calculation method, UTS data, and algorithm parameters. By this algorithm, the solutions are presented and improved in some generations as Pareto front. The implementation procedure of this algorithm into the optimization problem is shown in Figure 2.18. Finding the optimal manufacturing parameters permits to provide the essential information for our product model that is explained in the next section.

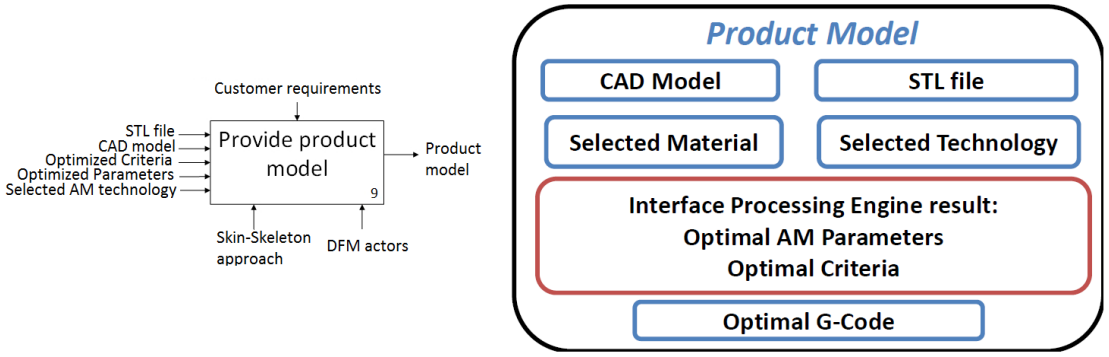


Figure 2.19 – Product model

2.2.5 Product model

Analysis of FBS model, usage model, manufacturing model, and interface processing engine allow providing the product model. This product model is the result of proposed approach that is shown in SADT diagram (Figure 2.19). This product model consists of required information to fabricate the 3D model by AM technology. It contains the selected material and AM technology, manufacturable usage model as CAD model and STL file, the optimal values of manufacturing parameters and criteria, as well as the optimal G-code for fabrication as shown in Figure 3.24.

2.3 DFM-Skin and skeleton approach for AM: Proposition 2:

The second proposition permits for implementing the DFM-skin and skeleton approach for AM. According to this proposition, this proposed approach contains several steps:

1. Functional analysis and providing FBS model.

2. Identification of usage model contains skin and skeleton: According to the first proposition, optimized usage model, including skin and skeleton, is created through topological optimization, but this proposition permits defining the skin and skeleton separately:

   Usage skin: It is defined through topological optimization and it is a surface that material flow on it.

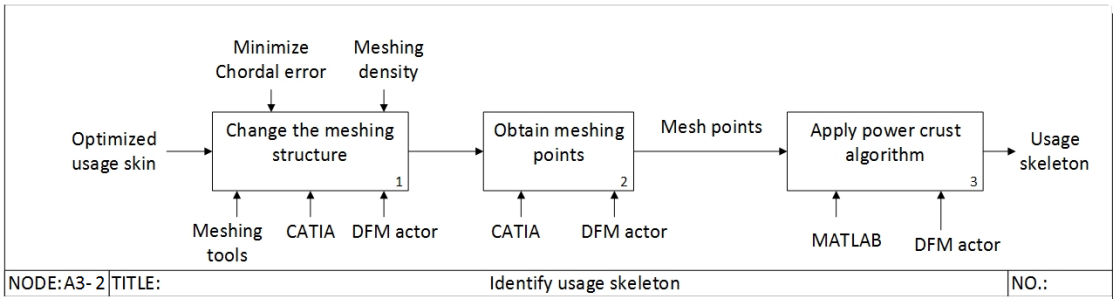


Figure 2.20 – Providing usage skeleton by power crust algorithm

Usage skeleton: Two methods are presented to determine this skeleton as follow:

Power crust algorithm: Power crust algorithm is used to define the skeleton based on the optimized usage skin. This algorithm needs an STL file as input but it must be mentioned that this STL file must be enriched with point numbers through modification in meshing (Figure 2.20).

This usage skeleton provides the approximate medial axis of part as an overview of product and its general schema that can be presented in several possible geometry solutions which satisfies the physical constraints and functional requirements. Power crust is an algorithm which is used to construct surface mesh and approximate medial axis. Power crust takes the points derived from STL file as input. Then, Medial Axis Transform (MAT) as a skeletal shape representation of object is approximated and surface representation is created by inverse transform [173, 33]. The procedure of this algorithm which is shown in Figure 2.21 is described as follow:

- STL file is converted to sample of points as pts format.
- Medial Axis Transform is a skeletal shape representation which is approximated by Voronoi diagram which is a computational geometry concept that represents partition of the given space onto regions, with bounds determined by distances to a specified family of objects.
- Polar balls approximate maximal balls contained in interior or exterior of balls.
- Power diagram is used to divide space into polyhedral cells by inverse transform.

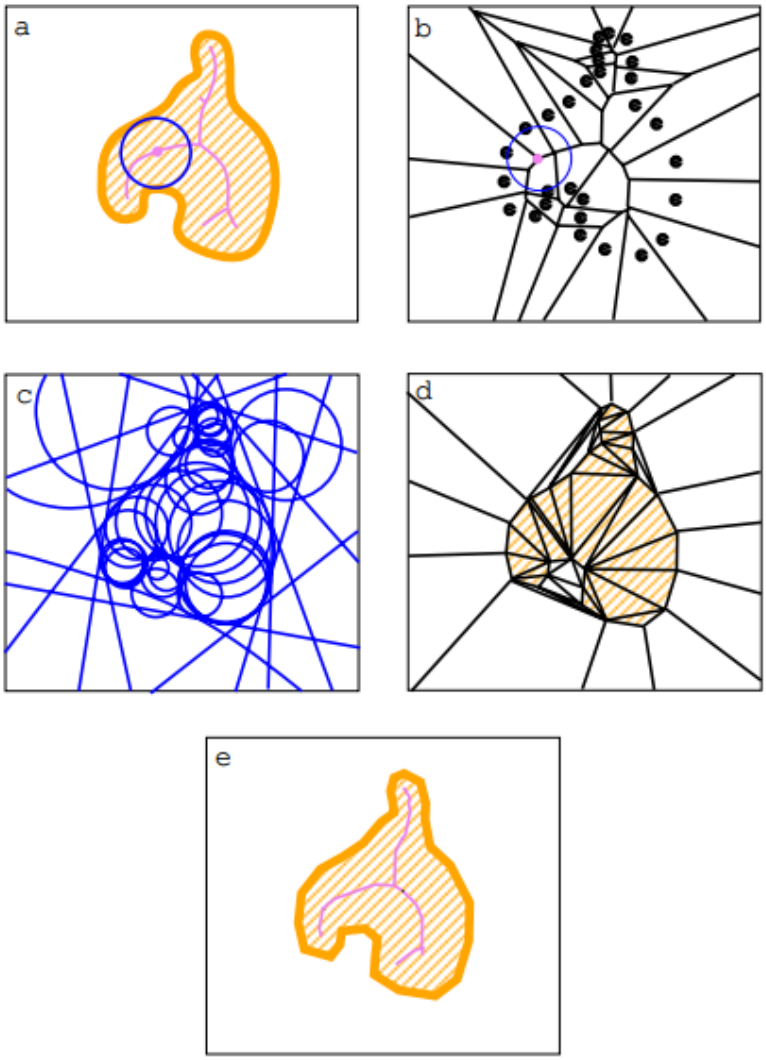


Figure 2.21 – Power Crust algorithm procedure on a two dimensional example (a) An object with its medial axis-(b) The Voronoi diagram-(c) Inner and outer pollar balls-(d) The power diagram cells of the poles-(e) power crust and power shape of its interior solid [173]

- Finally, the subset of two-dimensional polygonal faces of power diagram is power crust [173].

So, the initial forms must be created. Then, the possible morphology of the skeleton is proposed by the designer [33, 30, 3].

Manually: Skeleton is specified according to the special required behavior of the product as its functionality. According to the form obtained by topological optimization, the material flow as the skeleton can be specified easily.

3. Manufacturing model is defined in section 2.2.3, it consists of skin as contours of layer and part orientation as skeleton. According to proposition 2, manufacturing skeleton must be determined based on the usage skeleton. In this proposition, the main objective is considering the AM geometrical constraints, as well as AM unique characteristics such as anisotropic material, non-homogeneous structure of produced part by AM (different infill pattern and density), etc. In this thesis, there is no possibility to create the part orientation and continuing the DFM-skin and skeleton approach.

4. The optimization approach as an interface processing engine will be created by considering other parameters without considering the part orientation as decision variable.

5. Defining the product model based on the results of interface engine and skin-skeleton approach.

2.4 Summary

Generally, the SFM-skin and skeleton approach for AM provides a general and integrated approach for AM to consider usage, design and manufacturing attributes simultaneously. This approach addresses an integrated design methodology as Design For Additive Manufacturing (DFAM). This method allows defining a product model by investigation of many AM attributes, constraints, and criteria. This methodology is developed through a skin-skeleton approach which help us to create the final product model based on the functional requirement. FBS model, usage and manufacturing skin-skeleton models describe the initial information for design and manufacturing, as well as 3D

model simultaneously. As the main contribution of this thesis, a novel interface processing engine is developed to investigate the usage, design, and manufacturing attributes simultaneously to suggest a product model. This black box permits engineers to find the manufacturing parameters by analysis of AM procedure, calculation tools, and optimization model. It contains a multi-criteria decision-making approach that handles a large number of criteria. Thus, a continuous bi-objective optimization problem is presented to minimize manufacturing time and material regarding product roughness while targets a desired mechanical behavior and it prepares an integrated product model with optimization solutions before designing the product as a CAD model. It creates a possibility to redesign a product through comparison of the desired criteria and product specifications. Thus, this methodology is used to find the optimal product model including 3D model, optimal manufacturing parameters, G-code file for fabrication.

In the next chapter, this approach will be implemented into a popular AM technology, Fused Deposition Modeling (FDM), and two case studies are used to show the reliability of this approach for industrial implementation.

3

Application into Fused Deposition Modeling

Outline of the current chapter

3.1 Introduction

Fused Deposition Modeling (FDM), developed by Stratasys in Eden Prairie, Minnesota, is one of the most extensively used Additive Manufacturing (AM) technique which has substantially shortened the product development time and cost. The application has been extended to the various industries as medical ones like fabrication of biomedical implants or prosthesis through investment casting process, use by hobbyists, inventors, and small business owners, etc. [37].

FDM is a layer AM process that uses a thermoplastic filament (ABS, PLA,...) by fused depositing. The layers are fabricated by extrusion of the filament which is extruded by a nozzle. The nozzle contains resistive heaters that keep the plastic at a temperature just above its melting point so that it flows easily through the nozzle and forms the layer. The plastic hardens immediately after flowing from the nozzle and bonds to the layer below. It traces the part's cross sectional geometry layer by layer, then moving up vertically to repeat the process to produce the layers from down to up for finishing the part fabrication [37, 174] as shown in Figure 3.1. The layer thickness and vertical dimensional accuracy are determined by the extruder diameter which is different for each machine. A range of materials is available including ABS, polyamide, polycarbonate, polyethylene, polypropylene, and investment casting wax [40, 174].

Nowadays, the extensive usability of FDM technology and effects of the manufacturing process and especially unique characteristics of AM technologies encourage the researcher to analyze this manufacturing process. The integrated design approach is helpful to analyze the product which is produced by AM technologies from the first step of product life cycle development to final one to define a product model. Therefore, the proposed methodology as an integrated design approach for AM technologies, described in the chapter 2, will be verified through an FDM technology which fabricates two case studies. The study is started by a case study as a bag hook and this

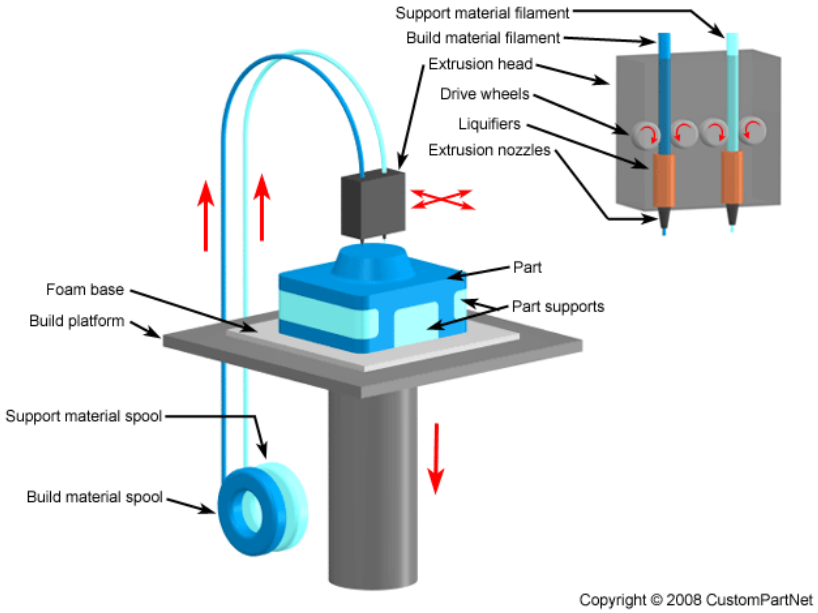


Figure 3.1 – Fused Deposition Modeling [175]

study will be continued to apply in another case study as a wheel spindle which is more complex and useful. This second case study can show the ability of AM techniques in bringing life to the broken parts and re-utilizing the product.

In this chapter, the application of this proposed approach into FDM technology based on two hypotheses through a bag hook will be described in section 3.2 and the second case study will be explained in section 3.4.

3.2 DFM-skin and skeleton approach based on proposition 1 for case study 1: Bag hook

In this research, a bag hook is investigated as case study to verify the proposed approach. The bag hook is an accessory that is used to hang a handbag on a table. It must be slim, light and fits into even the smallest bag. As summarized in Table 3.1, the requirement analysis shows that ABS (Acrylonitrile Butadiene Styrene) is a suitable choice as the raw material for bag hook because of its characteristics like recyclability, availability, and cost. FDM (Fused Deposition

Material	ABS
Technology	FDM
Weight	As light as possible
Functionality	Tolerate 7.5 kg
Initial size	45*90*10 cm

Table 3.1 – Bag hook specifications

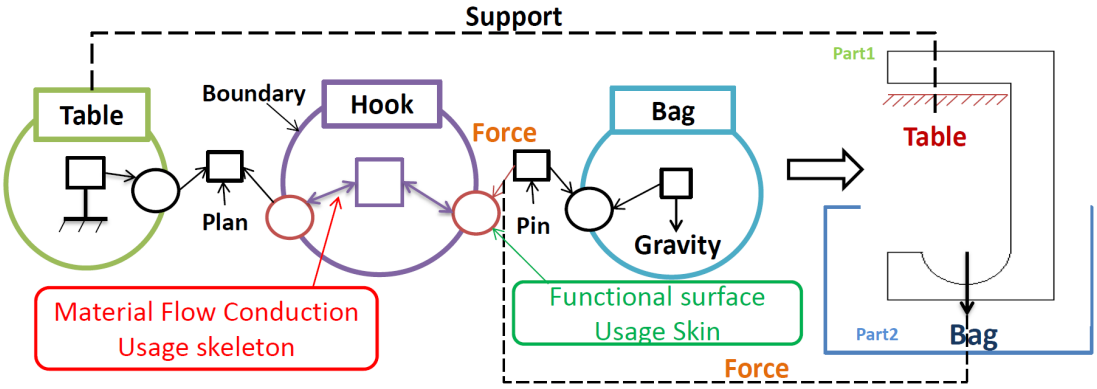


Figure 3.2 – FBS model defined for bag hook

Modeling) as the technologies of AM is chosen to manufacture the product on ABS [34]. The initial dimensions of hook are defined equal to 45*90*10 cm which will be optimized through this proposed approach.

The proposed methodology will be applied to present the optimal solutions of 3D model by using usage model and analysis of manufacturing system as manufacturing model to create an interface processing engine to provide a product model for this bag hook.

3.2.1 Functional analysis for bag hook

The first activity that must be performed in this approach is the functional analysis based on the defined customer requirements as A1 activity in SADT diagram (Figure 2.4). As required product specifications depend on the customer requirements, it is supposed that bag hook must be as light as possible to put in the bag and it can tolerate 7.5 kg as its functionality (Table 3.1). As illustrated in FBS model, bag hook must tolerate the bag weight as its function, the table is considered as support to help it for its function. So, table, hook, and bag are connected together

in this model. Actually, bag weight and gravity create a force which is transmitted to the hook. Hook must contain boundary as skin, as well as internal structure which is shown by arrows as material flow conduction which shows the part skeleton. This hook is hung to the table which plays the role of support in order to maintain the hook and bag with together. There is a surface that connect hook and table, as well as a pin to connect the bag to hook. This model is utilized to identify usage skin and skeleton due to boundary and material flow inside the hook.

The Function-Behavior-Structural (FBS) model (illustrated in Figure 3.2) is used to determine the initial structure according to desired function and behavior of the product. Therefore, this FBS model defines the part functionality which provides the initial volume of the part that can be created by CATIA-V5 (Activity A2) due to FBS model which contains functional surface, the relation between support and material flow conduction, product function as applied force, and mechanical performance. This initial volume must be converted to STL file as input for identification of the usage model. This procedure will be explained in section 3.2.2.

3.2.2 From usage model to 3D model for bag hook

Identification of usage model is the second step that must be performed in this approach. This model is determined based on the desired product characteristics and requirements as defined by FBS model in section 3.2.1. This step is related to the A3 activity in SADT diagram (Figure 2.4) which is identifying usage model:

Usage model identification of bag hook:

The topological optimization is used to optimize initial volume as an innovative form that supports the hook functionality regarding optimizing mass and structure. To apply this optimization into the case study, Inspire [1] as a topological optimization software is chosen and STL file of bag hook is needed as input of this optimization software.

Inspire is an industry's most powerful and easy-to-use generative Design/Topology Optimization software. It provides a rapid simulation solution for design engineers for creating and investigating structurally efficient concepts quickly and easily. The topological optimization procedure is as follows:

[1] https://solidthinking.com/inspire2018.html

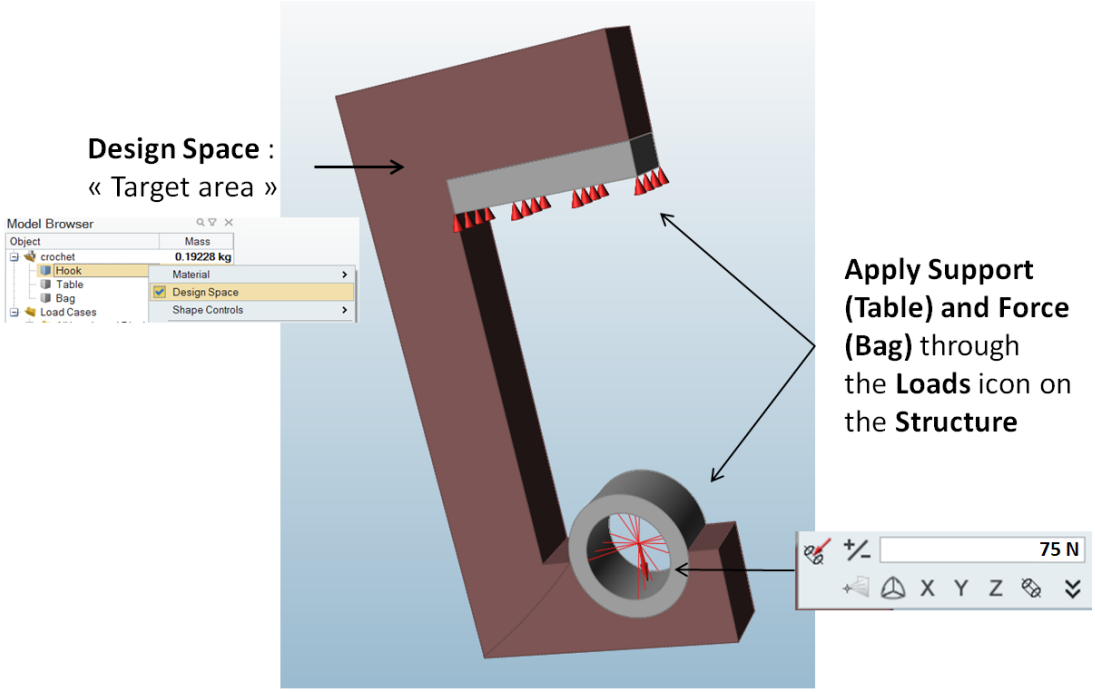


Figure 3.3 – First definition of hook for topological optimization

1. Firstly, the STL file as input is loaded in software which is the design space.

2. Table as support and weight bag as force source must be applied to the design space. This support and load parts are the non-design spaces as shown in Figure 3.3.

3. The material must be chosen for this bag hook. ABS is supposed as raw material for bag hook (Figure 3.5).

4. To optimize this bag hook, some constraints must be defined like stress constraint as safety factor, frequency constraint, and thickness constraint. Inspire analyzes the materials used in the model to determine which has the lowest yield stress then divides by its minimum safety factor to calculate the stress constraint.

   In this optimization, minimum safety factor is considered equal to 1.2 and minimum thickness is determined as 5.4 mm and there is no frequency constraint.

5. Speed of the optimization must be determined between fast and accurate one. To increase the speed of optimization fast option as default value is considered.

6. There are different types of contact between the part as sliding only and sliding with separation. In this optimization, sliding is considered as a type of contact.

7. There is an option to apply gravity force. This option must be active along -Y-axis.

8. Load case is considered as 7.5 kg and the software calculates the pressure applied to the contact surface of hook automatically.

9. The objective of this optimization must be determined. There are several options including maximum stiffness and minimum mass. Minimizing mass produces a part that is as light as possible, this is a good choice when a displacement constraint and stress targets need to be met. Maximizing stiffness creates a part that is as stiff as possible. This is a good starting choice to find out the load paths in the part. Stiffness is considered as objective of optimization to help in the hook functionality. Both objectives need to be combined with constraints and targets to fully define an optimization problem which is presented in next step.

10. Mass target is another parameter of optimization which is presented as total percent of mass. If maximizing stiffness is considered, mass target is set, either as a percentage of the design space or as the total mass for the entire model. This percentage is determined as 30 % in this optimization (default value).

11. The symmetric tool on the structure ribbon is used to apply symmetry planes to a design space (Figure 3.4). Symmetric plans are valid for optimization but not for analysis.

12. All these steps are shown in Figure 3.5 and the final result is obtained through running optimization.

Recognition of this usage model, consists of skin and skeleton, helps us to determine the 3D model of the product which will be described in the next section.

3.2.3 Optimized 3D model

This usage model permits to recognize the skin and skeleton in order to create the product 3D model. According to this usage model, the final 3D models is provided between different possible

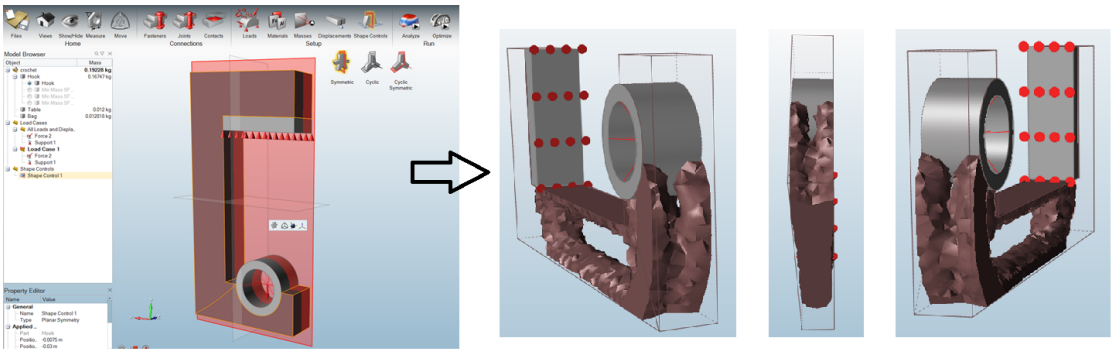


Figure 3.4 – Symmetric optimized bag hook

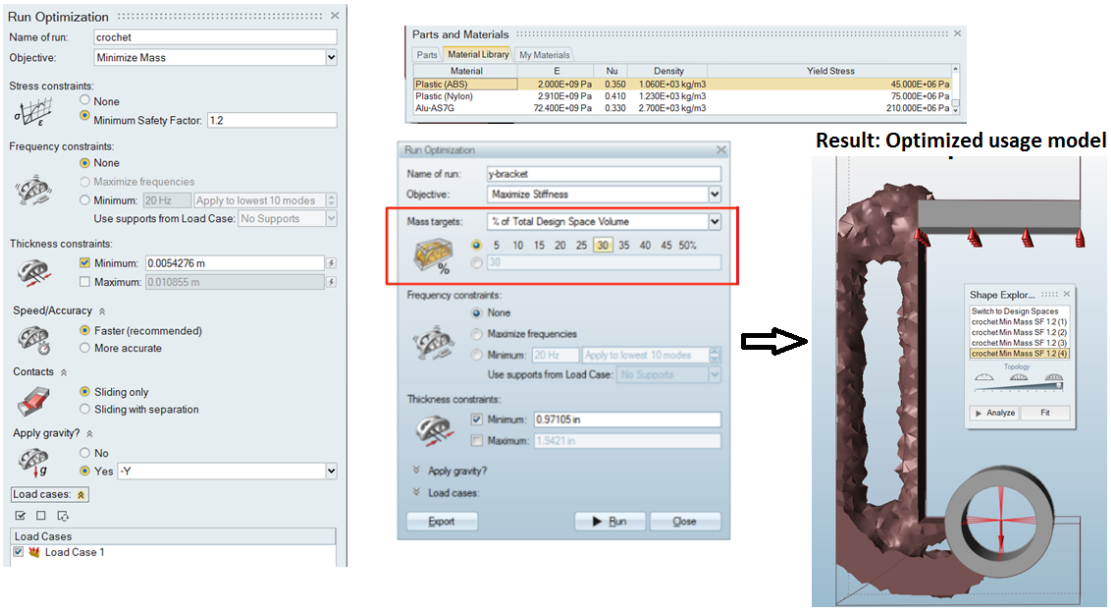


Figure 3.5 – Topological optimization procedure and optimized usage model as result

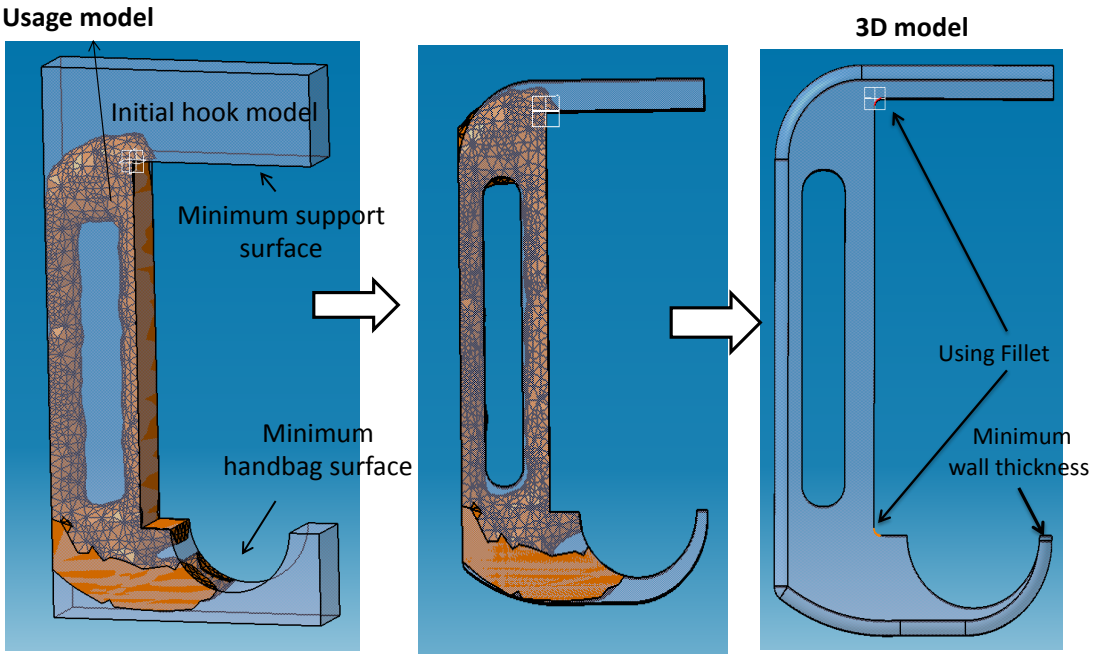


Figure 3.6 – CAD model obtained according to usage model

forms. Actually, this optimized model will be modified as the 3D draft of the product (which will be entitled "3D model" in this thesis). This 3D model is defined according to usage model through 3D modeling in CATIA-V5 as shown in Figure 3.6. Several factors are considered in this definition as follow:

- Functionality
- Minimum required wall thickness
- Using fillet instead of sharp edge to improve product strength.
- Minimizing the surface like the surface which is connected to table and hand bag.

After defining the 3D model, it is necessary to determine the manufacturing model for FDM as process for fabrication of the product. This model will be described in the next section (section 3.2.4).

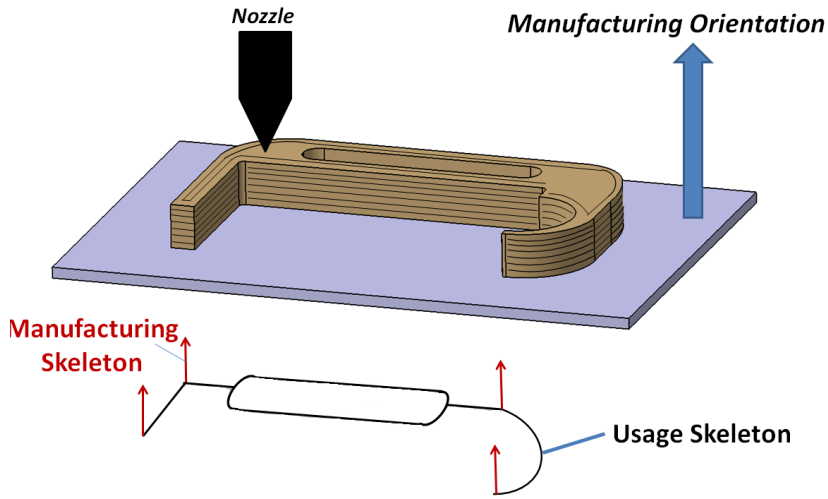


Figure 3.7 – Manufacturing Skin-Skeleton

3.2.4 FDM manufacturing model

In this step, the manufacturing model must be identified for FDM process. In this process, the layer production is started by creating the contours and interior structure. Actually, the produced contours of layers create the manufacturing skin. The interior structure and the path that nozzle crosses for filling the layers are the important parts of manufacturing. Orientation is another significant parameter that determines the tool-path including filling angle and build part direction which is considered as manufacturing skeleton. As shown in Figure 3.7, this model defines layer with its contours and the part orientation which is perpendicular to the build platform.

To fabricate the hook with AM, the CAD model must be converted to STL file as suitable AM format which is shown in Figure 3.8. This STL file is created in high resolution and with many triangles to minimize dimensional inaccuracy and roughness. Identification of manufacturing skin and skeleton permits to identify the manufacturing parameters. These manufacturing parameters must be analyzed according to important criteria and constraints like time, material, UTS, and roughness.

The attributes related to FDM are identified through analysis of technology and its related software like Cura, Slic3r, and Makerbot desktop, which are shown in Appendix II, and several machine types like Makerbot Replicator 2x, Zortrax, and Ultimaker. These attributes come from

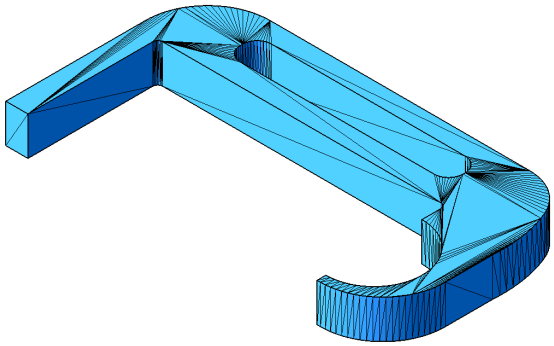


Figure 3.8 – STL file of bag hook

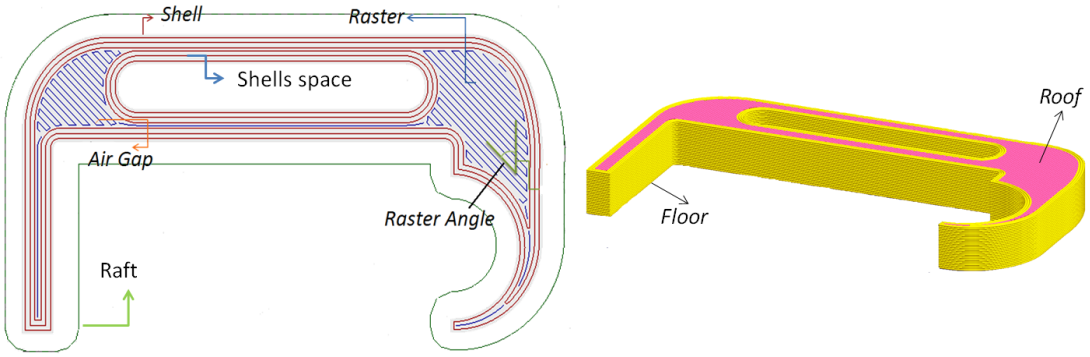


Figure 3.9 – Different parts of produced bag hook

machine settings as manufacturing parameters defined by software.

Analysis of FDM technology illustrates that the manufactured part by FDM consists of different sections of infill structure, roof and floor layers, as well as raft and support parts. This structure is illustrated in Figure 3.9. A comprehensive literature analysis is performed on the studies (131 articles) related to the evaluation of manufacturing parameters and criteria in FDM technology. A summary of this analysis is demonstrated in Table 3.2. This table contains the parameters that affect the product and manufacturing system criteria and constraints. A number is devoted to each parameters which is the number that this parameter is investigated in the studies. This number shows the importance degree of these parameters. The analysis demonstrates that layer thickness and part orientation in build platform are the most significant parameters for manufacturing.

Criteria	Mechanical behavior	Accuracy	Roughness	Build Time	Quality	Cost	Min material
Investigation number	63	33	27	14	9	7	2
Parameters	Orientation/27	Layer thickness/21	Orientation/16	Layer thickness/10	Layer thickness/5	Orientation/7	Orientation/2
	Raster angle/34	Orientation/19	Layer thickness/11	Orientation/9	Toolpath/4	Layer thickness	Shell width
	Air gap/17	Raster width/9	Raster width/9	Raster angle/8	Geomtry/3	Shell width	Layer thickness
	Layer thickness/19	Raster angle/9	Raster angle/8	Raster width/6	Ext. temp/3	Air gap	Raster width
	Raster width/18	Air gap/7	Shell width/3	Infill Density/2	Raster width/2	Raster width	Raster angle
	Ext. temp/6	Travel speed/4	Travel speed/2	Air gap/3	Infill structure/2	Raster angle	
	Plat. temp/4	Infill structure/3	Air gap/2	Shell width/5	Print speed/2	Geometry	
	Infill Density/4	Plat.Temp/3	Infill Density/2	Shell number/2	Orientation/2	Pre-processing	
	Bead width/3	Dimension/3	Radio/2	Infill structure/2	Travel speed	Process	
	Infill structure/6	Print speed/2	Infill structure	Travel speed	shrinkage rate	Post-processing	
	Shell number/3	STL/2	Shell number	Part location	Raster angle		
	Color/2	Ext. Temp/2	Tip Deimension	Ext. Temp	Plat. temp		
	Material type	Shell width/3	Road width	Plat. Temp	part palacement		
	Scan speed	Geometry/2	STL	Part Dimension	part dimension		
	Part location	Infill Density	Inclination	Materila type	Tip dimension		
	Machine	Shell number		STL	Road width		
	Cooling fan speed	Cooling fan speed		Print speed	Scan speed		
	Shell width	Part location			Radio		
	Part dimension	Part placement			Infill Density		
	Strain rate	Deposition angle			Shell number		
	Deposition Density	Road width					

Table 3.2 – Parameters and criteria derived from literature analysis for FDM (131 articles)

The important attributes, criteria, and constraints related to FDM technology are defined comprehensively as follow, some of these attributes and criteria as part volume, part build direction, layer thickness, print speed, and part interor structure are common between all AM technologies.

- **Part volume**: It is restricted due to machine capacity. The suitable machine must be chosen due to the part volume.
- **Part build orientation**: Orientation is the inclination of the part in a build platform due to $\boldsymbol{x}$, $\boldsymbol{y}$ and $\boldsymbol{y}$ axis. $\boldsymbol{x}$ and $\boldsymbol{y}$ axis are parallel to build platform and $\boldsymbol{z}$-axis is considered along with the part build direction [176].
- **Layer thickness**: For each machine, the defined range for layer thickness is different. These values are restricted by the nozzle diameter. It affects the criteria like production time and material, roughness, and mechanical behavior of AM parts.
- **Print speed**: Printing at high speed reduces the production time but it has a negative influence on the product quality but this influence deponds on the machine type.
- **Print temperature:** Print temperature must be determined due to the material and machine characteristics. It affects the surface quality, as well as the dimensional accuracy of the produced product by FDM.
- **Shell structure:** Shell or wall is a parameter related to manufacturing that produces the contours as the manufacturing skin. According to the obtained results by other researchers [177], the wall thickness must be at least twice the layer thickness to avoid walls which are subject to do buckling and enhance the product strength. Thus, shell is created two times (number of shells=2) in the manufacturing setting that not only, it satisfies the buckles constraint, but also, it satisfies product resistance. Moreover, it must be mentioned that it is defined as minimum value regarding time and material constraints. Owing to increasing shell number, time and material consummation will be increased.
- **Raft structure:** Raft structure is one part of printing as a surface that is printed as the first layer below the desired 3D model. This structure permits to have a better bottom

surface and it creates a larger adhesion area to keep the object stable during printing. Also, it reduces the possibility of deforming [178].

- **Infill structure:** Infill structure and density are the parameters related to the interior structure of AM parts. There are various patterns including linear, hexagonal, moroccan star, catfill, sharkfill, diamond, etc. According to the research performed by [179] various patterns provide the different levels of mechanical resistance. It is concluded that rectilinear pattern in a 100 % infill shows the highest tensile strength. Then, the honeycomb pattern under the same density creates a better tensile strength, although the difference between the patterns is less than 5 %. The change into the infill density determines mainly the tensile strength and stiffness, especially between 20 % and 50 % [179].

- **Support structure:** The complex geometries or the curved surfaces needed to be maintained with a support material [37]. There are some attributes that must be determined to define support structure like support density, threshold angle for support, and its layer thickness and dimension.

These attributes create different levels of criteria and constraints which are described as follow:

- **Production time:** Manufacturing parameters affect the manufacturing time. For example, time is increased by reducing layer thickness and it is proved by AM simulation software. Also, print speed affects the manufacturing time.

- **Material mass:** Fabrication by different manufacturing parameter values modifies the required amount of mass for fabrication. The most important parameters which have influence on the required material mass for production are layer thickness, part orientation, infill density and pattern, support density and pattern, and raft structure.

- **Strength:** Mechanical behavior of the AM products are not like a product that is produced by the traditional manufacturing process because of the material processing, layer-by-layer production, and filling structure of additive parts. In this study, linear is considered as infill pattern to enhance the product resistance. Layer thickness values affect the different levels of resistance for product [168]. Filament direction must be perpendicular to load direction in order to improve the strength of the product [33, 180]. Moreover, It is better to avoid

sharp edge and use fillets in the product structure due to tool path and infill structure to improve the product strength [33].

- **Dimensional inaccuracy:** Deviation for AM can be derived from conversion of3D model into STL file, as well as manufacturing system. However, it is supposed that STL conversion is performed in the high level of quality through increasing the numbers of triangles in order to reduce the deviation. So, this deviation is ignored in this study. Temperature difference as thermal stress and strain can produce inaccuracy between the produced product and 3D model [33]. Temperature is another important factor in the deviation that increasing extrusion and platform temperature decrease the deviation amount. Moreover, fabrication in the low level of layer thickness can reduce the deviation. Part orientation can be considered as deposition angle which affects the dimensional accuracy of the produced products [127].
- **Roughness:** Roughness is a criterion to investigate the surface quality of the product. The staircase effect creates the rough surface for AM due to layer thickness value and orientation type through deposition angle. In the same orientation, increasing layer thickness reduces the roughness as surface quality.

After recognition of usage and manufacturing model by skin and skeleton approach, the required information for design and manufacturing are provided, but it is essential to find the best manufacturing parameter values for fabricating the 3D model (derived from FBS and usage model). An interface processing engine is developed to investigate this information, attributes, parameters, and criteria concurrently. So, the interface processing engine is applied to the bag hook in the following (section 3.2.5).

3.2.5 Interface processing engine for bag hook to fabricate by FDM:

the interface processing engine plays an important role in this proposed methodology. The status of interface processing engine is depicted in Figure 3.10 which illustrates the DFM-Skin and Skeleton approach for the selected technology (FDM). According to this approach, FBS, usage and manufacturing model contain essential information to provide the interface processing engine to find the optimal final product model. This figure shows that the manufacturing model contains some attributes related to skin and skeleton that must be determined before fabrication. Layer

thickness as an attribute related to skin and part orientation for skeleton are the significant factors for fabrication. Usage skin attributes specifies design features like product dimensions and material type and skeleton attributes are material flow and its direction. Also, product model will be constituted through integration of FBS and usage model to find the CAD model, as well as the desired values of parameters and criteria that come from the interface processing engine results. This engine contains calculation and optimization tools to determine the manufacturing parameters. Actually, this engine shows the relationships between the parameters related to usage and manufacturing model attributes as shown in Table 3.3. This table contains usage skin and skeleton attributes and manufacturing skin and skeleton attributes. Also, the product criteria and constraints are mentioned as usage attributes. These attributes are related to each other and they determine the product and manufacturing criteria and constraints. For example, this table determines that material mass depends on manufacturing attributes as like layer thickness and number, prototype dimensions, infill density and air gap, raster density and pattern, roof and floor structure, raft structure, support structure, shell structure, and nozzle diameter. Printing and travel speed are also manufacturing attributes that determine the production time. Manufacturing system temperature is also dependent to the material properties. It is worth noting that there are relationships between the usage attributes together, as well as manufacturing attributes. For instance, material properties like young modulus affect the part strength.

To provide an interface processing engine for bag hook which is produced by FDM, the hypotheses are investigated:

Initial fixed parameters for interface processing engine of bag hook

To provide the calculation tools inside this engine, some initial hypotheses are considered to define a final product model through crossing from design stage to manufacturing.

- The MakerBot Replicator 2X is selected as the desired machine to fabricate the part. The platform dimension of this machine is 246 mm×152 mm×155 mm that supports the case study dimensions. This machine is an experimental 3D printer which makes three-dimensional objects solid by melting filament. The STL file is translated by the MakerBot software. Then, this machines starts its work by heating the filament and squeeze it out

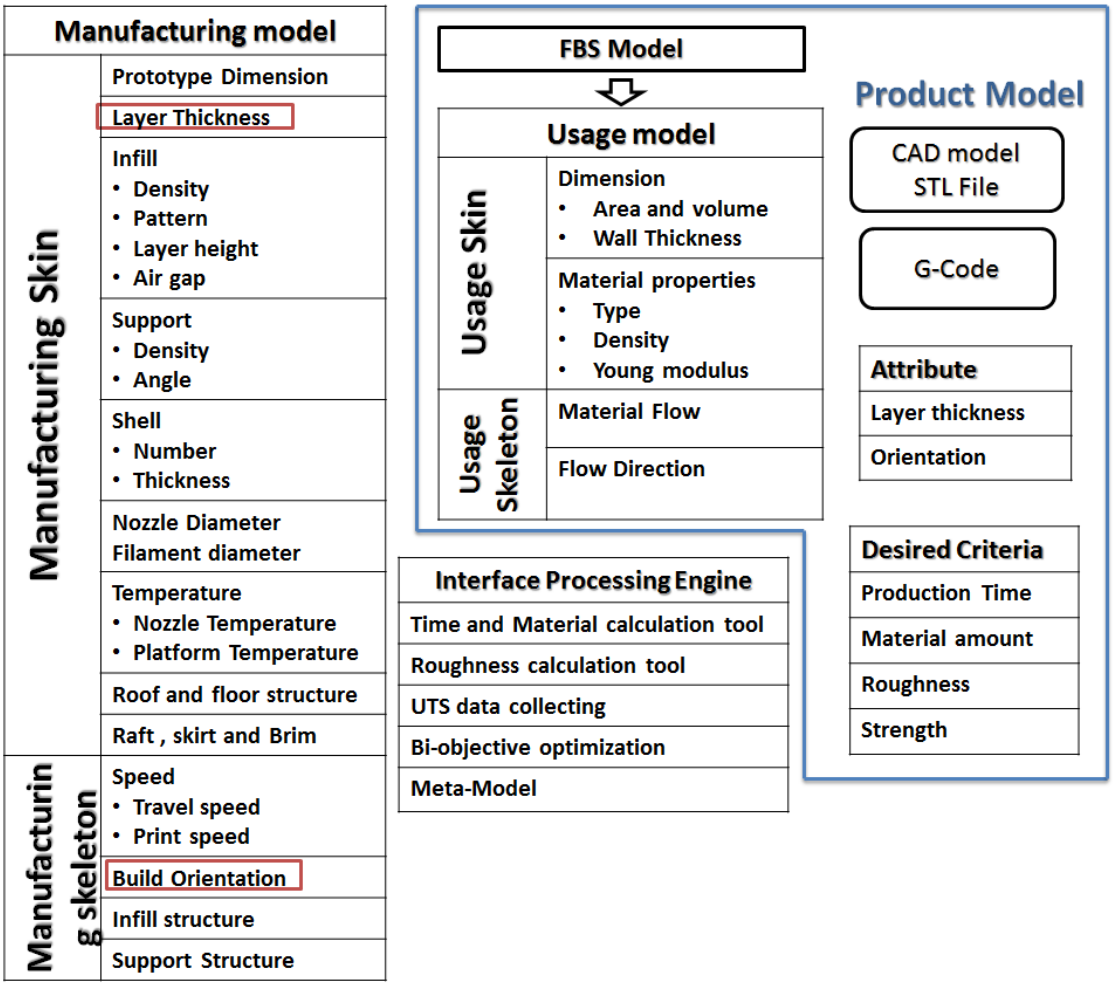


Figure 3.10 – DFM-Skin and Skeleton approach for FDM

Usage model attributes		Manufacturing model attributes																	
		Manufacturing skin attributes										Manufacturing skeleton attributes							
		Layer thickness	Prototype dimension	Layer numbers	Infill density-air gap	Raster Width	Raster angle	Roof & Floor structure	Shell structure	Raft structure	Support density	Nozzle diameter	build orientation	travel speed	print speed	Infill structure	Support structure	Plateform temperature	print temperature
Usage Skin attributes	Part Dimensions	*	*	*						*	*								
	Material Mass	*	*	*	*	*	*	*	*	*	*	*	*			*	*		
	Material properties														*			*	*
	wall thickness	*		*					*			*							
	Part strength	*	*	*	*	*	*	*	*				*			*			
	Surface roughness	*											*						*
	Accuracy	*											*						*
	Time	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		
	Cost	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		
Usage skeleton attributes	Material Flow				*		*	*	*	*	*					*	*		

Table 3.3 – Relation between usage and manufacturing attributes

through a nozzle onto the heated platform in order to build solid object layer by layer as FDM.

- As the interior structure, infill structure is selected as the linear pattern and part is fabricated in full density (100 %) to create more resistant structure.
- Nozzle diameter is 0.4 mm which permits to print the part by the layer thickness between 0.1 mm and 0.4 mm that corresponds to the minimum and maximum values of layer thickness in the defined optimization problem.
- The extruder and platform temperature are considered due to ABS characteristics as 230 °C and 110 °C respectively.
- The number of shell is considered equal to two that supports wall structure of the part (shell number=2).
- Part orientation can be defined in three angles of θ_x, θ_y, and θ_z. These elements are the angles between related axis and product normal. This orientation shows the build direction and filling angle of the interior structure.
- Support structure is enabled in setting to create the desired structure for product. Support is created in 20 % density and for the angles greater than 68° as its default values. The other parameters are also defined as the default values for the machine settings.
- Raft is enabled by its predefined parameters settings.

FDM criteria

The required information for interface processing engine is collected by calculation tools for the considered criteria. These calculation tools are used in performing A7 activity as providing interface processing engine as the activities in SADT diagram (Figure 2.4 and 2.14). These criteria and how they are calculated are described in the following:

Manufacturing time and material mass: Manufacturing time and material mass calculation are described as a sub-activity of A71 and A72 in Figure 2.14. These activities are generation of G-code files and calculation of production time and material mass based on these files.

Production time and material mass are calculated through Cura 2.5 simulation by MATLAB for different layer thickness and orientation. Cura is a slicing software which processes 3D model into 3D printing structure for Ultimaker and other G-code based 3D printers.

Since Cura is an open source software, the soures codes which are JSON files as the data format in javaScript are modified due to the print settings and desired machine. In this study, the characteristics of MakerBot replicator 2x are defined for Cura like machine specifications in machine definition as its related JSON file. Also, the settings which are the default values for working with MakerBot are defined in the Cura sthece code.

MATLAB is used to automate and execute Cura to find different G-code files for the decision variables values (layer thickness and orientation). Each orientation is created by rotation matrix in 3D space as mesh rotation matrix in Cura as presented in Equation (3.1). Cura provides different G-code files for each value of layers thickness and orientation.

$$R_x = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_x & -\sin\theta_x \\ 0 & \sin\theta_x & \cos\theta_x \end{bmatrix} \quad R_y = \begin{bmatrix} \cos\theta_y & 0 & \sin\theta_y \\ 0 & 1 & 0 \\ -\sin\theta_y & 0 & \cos\theta_y \end{bmatrix} \quad R_z = \begin{bmatrix} \cos\theta_z & -\sin\theta_z & 0 \\ \sin\theta_z & \cos\theta_z & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$R = R_x \times R_y \times R_z \tag{3.1}$$

Each G-code is a tool-path as coordinate points that the nozzle must cross, as well as the amount of extruded material (used filament) which are shown as the letter E in G-code file (Figure B.2 and B.1 in Appendix II). These E values are calculated through Equation (3.2). This equation is based on the reality that the volume of extruded material coming from the nozzle is equal to the volume of extrusion path crossed by the nozzle. So, the E value is dependent on the distance between coordinates (L), extrusion width (e), layer thickness (L_t) and filament diameter (d). In this case, d as filament diameter is 1.75 mm and extrusion width (e) for Cura is considered equal to nozzle diameter value (0.4 mm). The material mass is calculated due to this E value and the volume of extruded material and material density ($\rho_{\mathrm{ABS}} = 1.04\,\mathrm{g/cm^3}$) (Equation (3.3)).

The manufacturing time is calculated according to the distance between the coordinates and speed as shown by the letter F in G-code for all parts. This manufacturing time is mentioned as elapsed time in the G-code files. It must be mentioned that there are other movements like

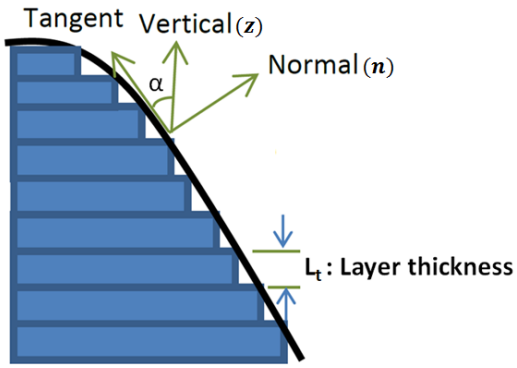


Figure 3.11 – Roughness parameters [182]

retraction, travel, and their speeds that affect the E values and manufacturing time.

$$E = \frac{4L.e.L_t}{\pi d^2} \tag{3.2}$$

$$M = \rho_{\text{ABS}} \pi \frac{d^2}{4} E \tag{3.3}$$

Surface roughness of part fabricated by FDM: Different researchers [48, 164, 181] presented several models for roughness estimation. Vahabli et al. [49] estimated the roughness (R_a in µm) through hybrid methodology based on geometrical model of the filament and analysis of staircase effect. This model is verified through comparison of the existed models in the literature and experimental data. In this formulation (Equation (3.4)), α is defined as the angle between the tangent vector of parts and vertical direction (Figure 3.11). In this formulation, $W = 0.2$, $R_1 = 0.045$ as the radius of the fillet in the FDM systems, $R_2 = 0.01$ as radius of the corner, are the fixed dimensionless parameters in roughness calculation for FDM that are illustrated in Figure 3.12. Figure 3.13 shows the roughness function that different values of deposition angle and layer thickness create the different levels of surface quality through roughness value.

To analyze the roughness in the interface processing engine according to these relations as A83 activity (calculate roughness), a code including these relations as roughness which is the function of layer thickness and orientation is written in MATLAB. The written algorithm is summarized as follow:

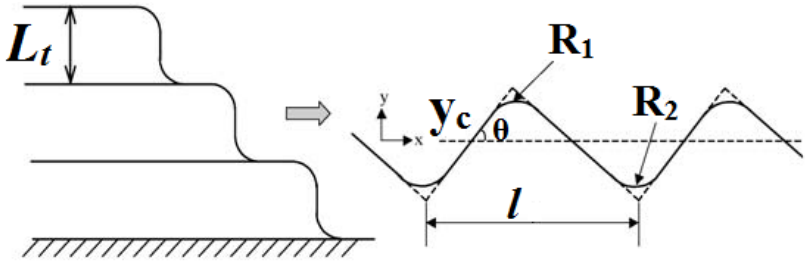


Figure 3.12 – R_1 and R_2 [164]

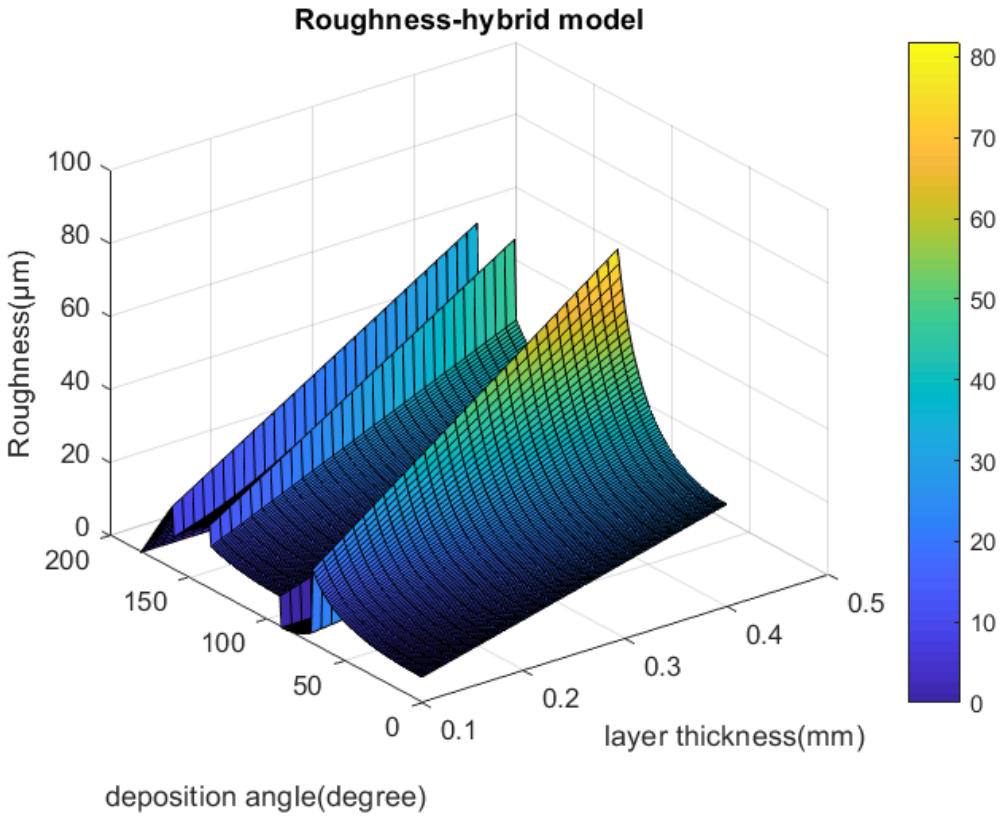


Figure 3.13 – Roughness values for different deposition angles and resolution

$$R_{\mathrm{a}}(\alpha, L_t) = \begin{cases} 70\dfrac{L_t}{\cos(\alpha)} & 0 \le \alpha \le 70^\circ \\ 1000 L_t \sin\left(\frac{90^\circ-\alpha}{4}\right)\tan(90^\circ-\alpha) & 70^\circ < \alpha \le 90^\circ \\ 70\dfrac{L_t}{\cos(\alpha-90^\circ)}(1+W) & 90^\circ < \alpha \le 135^\circ \\ 1000\frac{L_t}{4} - \frac{(R_1^2+R_2^2)(1-\frac{\pi}{4})\sin(90^\circ-\alpha)}{1000 L_t} + \ldots & \\ \frac{\left((R_1^2-R_2^2)(1-\frac{\pi}{4})\right)^2}{(1000L_t)^3}\frac{\sin^2(90^\circ-\alpha)}{\cos(90^\circ-\alpha)} & 135^\circ < \alpha < 160^\circ \\ 1000\frac{L_t}{2}\cos(90^\circ-\alpha) & 160^\circ \le \alpha \le 180^\circ \end{cases} \tag{3.4}$$

- The normal ($\boldsymbol{n}$) of each triangle j (T_{j}) of STL file ($\boldsymbol{n}_{\boldsymbol{T}_{\mathrm{j}}}$) is obtained for different orientations through normal mesh computation for each facet of a triangular mesh.

- The orientations are created due to the same rotation matrix (R) and normal and tangent vector are rotated along the rotation angles (θ_x, θ_y, θ_z). This rotation matrix is calculated through Equation (3.5).

  Orientation along the rotation angles rotates the normal vector of each facet of STL model, as well as deposition angle which changes the value of roughness for each triangle facet (T_{j}).

$$R_x = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_x & -\sin\theta_x \\ 0 & \sin\theta_x & \cos\theta_x \end{bmatrix} \; R_y = \begin{bmatrix} \cos\theta_y & 0 & \sin\theta_y \\ 0 & 1 & 0 \\ -\sin\theta_y & 0 & \cos\theta_y \end{bmatrix} \; R_z = \begin{bmatrix} \cos\theta_z & -\sin\theta_z & 0 \\ \sin\theta_z & \cos\theta_z & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$R = R_x \times R_y \times R_z \tag{3.5}$$

- $\alpha_{T_{\mathrm{j}}}$ as the angle between the tangent vector of part and the vertical direction $\boldsymbol{z}$ is calculated through the vector algebra for each orientation (Equation (3.6)).

$$\alpha_{T_{\mathrm{j}}} = 90^\circ - \arccos\frac{\boldsymbol{n}_{\boldsymbol{T}_{\mathrm{j}}}.\boldsymbol{z}}{|\boldsymbol{n}_{\boldsymbol{T}_{\mathrm{j}}}|.|\boldsymbol{z}|} \tag{3.6}$$

- For each value of $\alpha_{T_{\mathrm{j}}}$ and layer thickness, the roughness value is calculated due to the presented equations (Equation (3.4)) for each triangle.

- The maximum value of roughness for triangles is selected as the maximum roughness of the product surface for each orientation and layer thickness.

Deviation of the products fabricated by FDM: Deviation of the fabricated part is important when the parts need to be assembled for required functionality. These mechanical parts must have high dimensional accuracies in order not to have loose connections between the connecting parts. Corresponding dimensions may have clearance, transition and interference fit tolerances which are standardized by ISO System of Limits and Fits depending on the assembly function [183]. Obtainable desired accuracy for AM and especially FDM technology is a critical drawback which inhibits AM utilization. A lot of parameters affect the accuracy of the product as material withdrawal and process parameters like layer thickness and orientation. There are only a few indications, relating the dimensional deviations that exist, and they are conflicting each other, not allowing a reliable prediction. However, Boschetto et al. 2014 [127] developed a geometrical model of the filament [126], dependent upon the deposition angle and layer thickness, in order to predict the obtainable part dimensions. In this study, physical aspects related to material characteristics and unexpected effects are ignored. The proposed method employs the findings of a previous study in which they developed a deterministic model able to predict the part dimensional deviation from the given shape as a function of layer thickness and deposition angle [113].
Filament profile is described by a sequence of circumference arcs characterized by a radius r and spaced by f. According to this geometry, a new model is developed to predict the deviation from the nominal value. A schematic of the filament section, for a generic and 90° deposition angles, is shown in Figure 3.14. The semicircle Ω illustrates the filament in vertical wall configuration. In this figure, f is the spacing and r is the radius that corresponds to the layer thickness L_t. The height of this profile as $L_t/2$ represents the nominal value. The semicircle Σ is related to an inclined surface. The modification of the deposition angle α determines r and f increments: the height h of the profile increases by a Δh value, which corresponds to the dimensional deviation [127]. The filament height of a surface inclined of α angle is as follows (Equation (3.7)):

$$h(\alpha, L_t) = r(\alpha, L_t) - \sqrt{r(\alpha, L_t)^2 - (\frac{f(\alpha, L_t)}{2})^2} \tag{3.7}$$

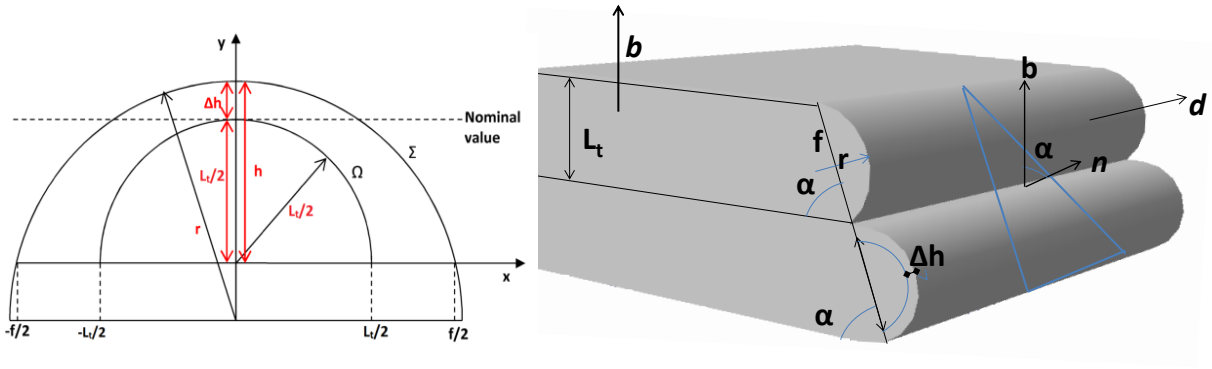


Figure 3.14 – (a) Schematic of filament section (b) Deposited filament parameters [127]

The deviation from nominal value, as the deviation of the fabricated product rather than 3D model, is stated as follows (Equation (3.8)):

$$\Delta h(\alpha, L_t) = h(\alpha, L_t) - \frac{L_t}{2} = r(\alpha, L_t) - \sqrt{r(\alpha, L_t)^2 - \left(\frac{f(\alpha, L_t)}{2}\right)^2} - \frac{L_t}{2} \tag{3.8}$$

The experiments are performed for two angles (α) of 30° and 90° and two different values of layer thickness have been employed: 0.254 and 0.331 mm. The results of these experiments which are measured by a profilometer show that the acceptable results compared to the results generated from the predicted model. Figure 3.15 demonstrates the value of dimensional deviation for different values of layer thickness and deposition angle. This deviation value is modified between -0.1 and 0.5 mm for the values of layer thickness between 0.1 and 0.4 mm and deposition angle in the range of 0 and 180°.

$$\Delta h(\alpha, L_t) = 2.21(L_t - 0.168)\cos^2(\alpha) \tag{3.9}$$

To calculate the deviation of the produced product than its 3D model, the starting model needs the STL format as input. The STL file consists of an unordered list of triangular facets which represent the object skin. This formulation (Equation (3.10)) can be applied for each triangle of

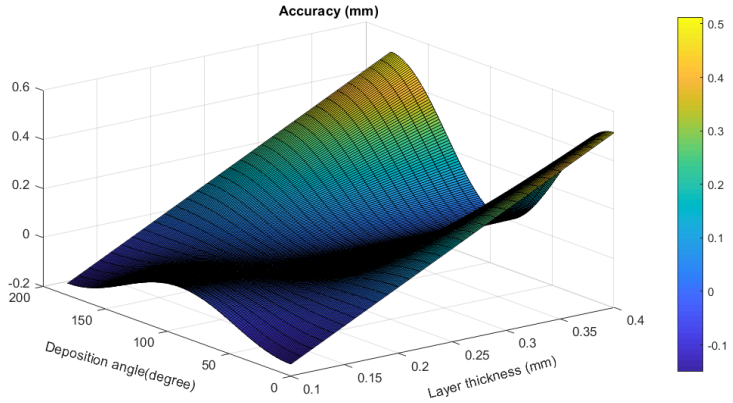


Figure 3.15 – Accuracy function [181]

STL file to calculate the deviation of each facet (T_j) and it is presented as Equation (3.10):

$$\Delta h_{T_j}(\alpha_{T_j}, L_t) = 2.21(L_t - 0.168)\cos^2(\alpha_{T_j}) \tag{3.10}$$

Each triangle T_j is composed by a triplet of the vertices (V_1, V_2, V_3) and each vertex is shared by several triangles. The normal of the triangle ($\boldsymbol{n_{T_j}}$) can be calculated by the following normalized vector product (Equation (3.11)).

$$\boldsymbol{n_{T_j}} = \frac{\boldsymbol{V_{1j}V_{2j}} \times \boldsymbol{V_{2j}V_{3j}}}{|\boldsymbol{V_{1j}V_{2j}} \times \boldsymbol{V_{2j}V_{3j}}|} \tag{3.11}$$

where

$$\alpha_{T_j} = \arccos \frac{\boldsymbol{n_{T_j}}.\boldsymbol{b}}{|\boldsymbol{n_{T_j}}|.|\boldsymbol{b}|} \tag{3.12}$$

In this formulation, α_{T_j} is the deposition angle as the angle between normal vector of each triangle $\boldsymbol{n_{T_j}}$ and stratification direction $\boldsymbol{b}$ as shown in Figure 3.16.

Orientation along the rotation angles (θ_x, θ_y, θ_z) as shown in Figure 3.17 changes the normal vector of each facet of the STL model, as well as deposition angle which changes the value of deviation for each triangle facet. The rotation matrix is defined as Equation (3.5) which is used also for roughness calculation.

Therefore, the deviation for the STL file of bag hook which is orientated can be calculated for

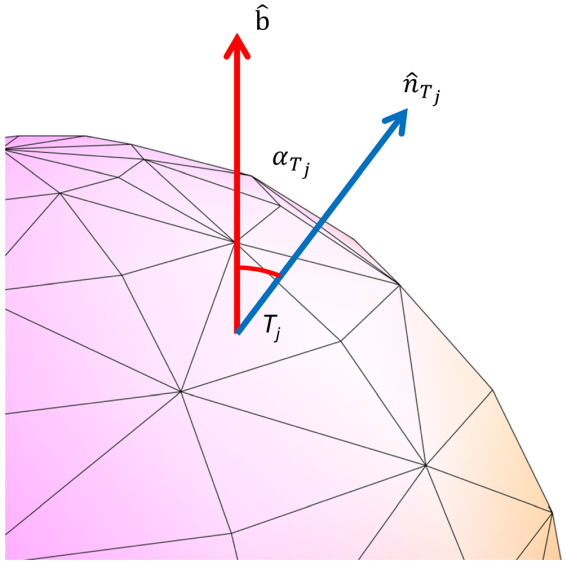


Figure 3.16 – Deposition angle for the triangle [184]

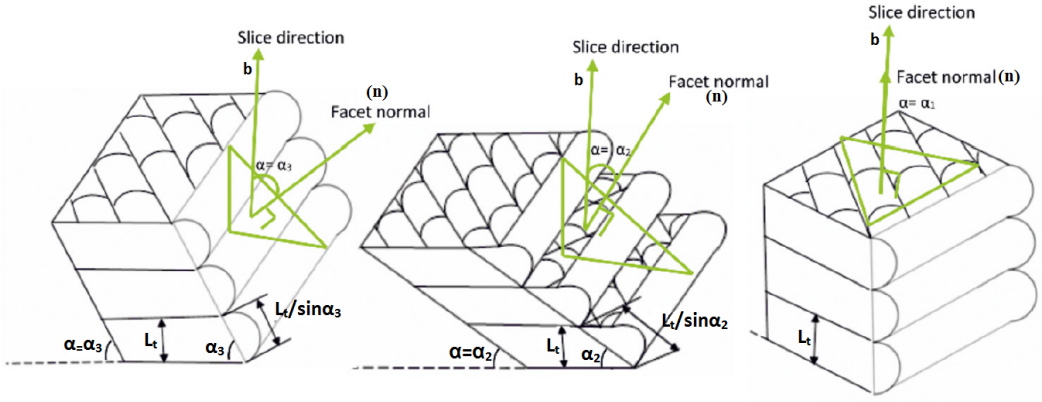


Figure 3.17 – Oriented facet of triangles STL of a FDM product [185]

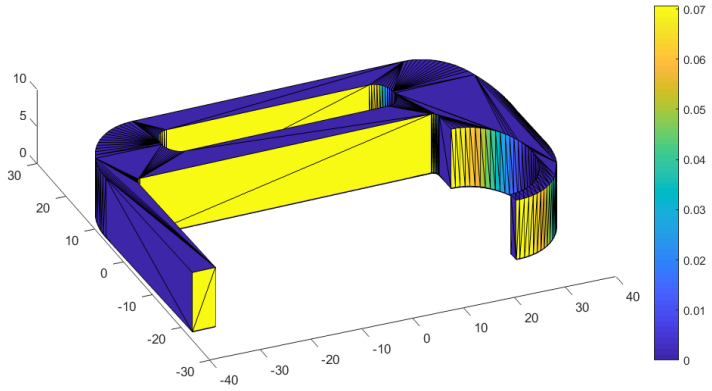


Figure 3.18 – Hook facet deviation

different layer thickness. Figure 3.18 illustrates the value of deviation for the hook as orientated by θ_x =90°, θ_y =0°, θ_z =45° with the layer thickness of (L_t =0.2 mm).

Mechanical behavior of the product fabricated by FDM: As shown by mathematical formulation, there is a relation between layer thickness, orientation, and Ultimate Tensile Strength (UTS). Several experiments performed by some researchers [156, 171, 157, 170, 186] with the same experimental conditions are analyzed to obtain these parameters values for ABS specimens fabricated by FDM. So, tensile test specimens were made using ABS-M30 and characterized according to ASTM D638-03 [187] "Standard Test Method for Tensile Properties of Plastics" in the different orientations and values of layer thickness. The Instron as a materials testing hardware is used to obtain the desired data for each specimen.

Orientation types and the data consist of the UTS values for some values of layer thickness (L_t in mm) in special types of orientation including flat, up-right, and on-edge for filling angle of ±45° and 0/90° for a standard specimen are shown in Table 3.4. These UTS values are compared together in Figure 3.19. This figure shows that the FDM parts do not have the same mechanical behavior in each orientation types. Also, no rule can not be found to estimate the UTS values. Therefore, it is necessary to complete the study on this criteria by experimental approaches.

Bi-objective optimization problem: Until now, a bi-objective optimization problem was presented mathematically and calculation tools were provided to formulate time, material mass,

Orientation	Flat ±45°	Flat 0/90°	On edge ±45°	On edge 0/90°	Up right ±45°	Up right 0/90°
θ_x	0°	0°	0°	0°	90°	90°
θ_y	0°	0°	90°	90°	0°	0°
θ_z	0°	45°	0°	45°	0°	45°
L_t [mm]	UTS values [MPa] for different orientation					
0.1	32.8	30	31.9	33.5	30.7	30.9
0.13	27.8	30	29.6	25.7	29.11	30
0.2	27.5	-	-	-	-	-
0.25	27.3	32.7	25.4	29	-	-
0.33	28.94	-	-	31.64	-	24.72
0.35	20.22	27.35	-	22.7	-	-

Table 3.4 – Orientation types and its UTS data for different layer thickness

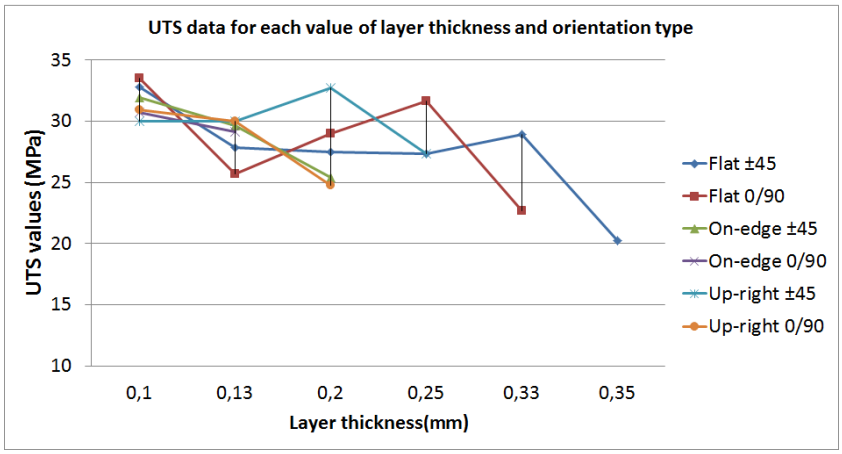


Figure 3.19 – UTS data for different values of layer thickness and orientation derived from literature

Nozzle Temperature	230 °C
Platform Temperature	110 °C
Nozzle Diameter	0.4 mm
Infill	100 % - linear
Shell number	2
Travel speed	130 mm s^{-1}
Infill speed	90 mm s^{-1}
Outline speed	40 mm s^{-1}
Floor-Roof speed	90 mm s^{-1}
Support	(20 %) 0.2 mm
Support Angle	68°
Retraction speed	25 mm s^{-1}

Table 3.5 – Bi-objective optimization problem parameters

and roughness, as well as the data for considering mechanical behavior of the parts were collected. So, it is necessary to find the best manufacturing parameters including layer thickness and orientation via optimization in order to fabricate the product.

This required information and calculation tools provide the preconditions for creating a bi-objective optimization problem and solving it. As mentioned in section 2.2.4, this problem is used to find the optimal manufacturing parameters by optimization of time and material by considering UTS and roughness as the constraint functions to fabricate the bag hook by FDM.

The fixed parameters of production must be defined in Cura source code file which are considered as the parameters of optimization problem. a summary of these parameters are presented in Table 3.5.

The value of 20 µm is assumed as the maximum desired roughness. The maximum obtained value of roughness for each triangle is considered as the desired value of roughness for each layer thickness and orientation.

Figure 3.20 illustrates the bag hook dimensions that permit to estimate the maximum stress σ_{Max} in the hook. Based on beam theory and knowing the applied force F, this stress can be easily estimate by Equation (3.13), where $M_f = Fa$ is the bending moment, I the second moment of the cross section $(b \times h)$.

$$\sigma_{\text{Max}} = \frac{M_f}{I}\frac{h}{2} \longrightarrow \sigma_{\text{Max}} = \frac{12Fa}{bh^3}\frac{h}{2} = \frac{6Fa}{bh^2} \tag{3.13}$$

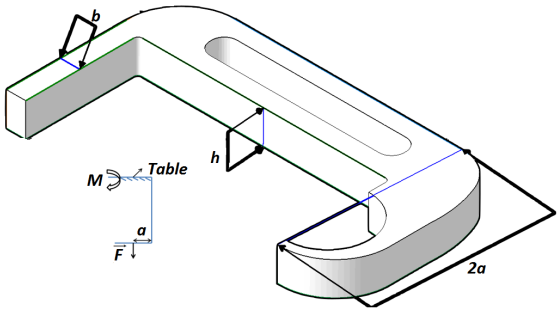


Figure 3.20 – Bag hook structure and function

In this application, with the real dimensions of the bag hook, $h = 8\,\text{mm}$, $b = 4.6\,\text{mm}$, $a = 20.9\,\text{mm}$ and $\boldsymbol{F_{T2}} = 58.9\,\text{N}$, the maximum stress value is $\sigma_{\text{Max}} = 25\,\text{MPa}$.

In this thesis, two methods are considered to solve this bi-objective optimization problem including meta-modeling by Modefrontier, as well as providing continuous and discrete optimization problem:

- **Meta-modeling by ModeFrontier:** As shown in Table 3.4, the UTS values exist for some values of layer thickness and orientation types. The material mass and time are calculated for these values by printing simulation through Makerbot replicator 2x. Roughness is also calculated through its formulation by coding in MATLAB.

  This data is gathered together as input for meta-modeling in Modefrontier. Layer thickness and orientation types are decision variables. In Design Of Experiment (DOE), 20 experiments are created in a random sequence. It fills randomly, with a uniform distribution, the design space. RSM, by considering polynomial functions, is used to provide the meta-model by formulation of the criteria based on the layer thickness values and orientation types. NSGA-II is used to solve this optimization problem to obtain a feasible solution in a reasonable time. The parameters for this algorithm are summarized in Table 3.6 and finally the optimal solution is obtained as shown in Figure 3.22:

  As the data, which are the inputs for the meta-modeling, is not sufficient to provide a continuous optimization problem and have a reliable solution, Cura is used to provide a continuous bi-objective optimization problem which will be described as follow:

- **Continuous and discrete bi-objective optimization problem:** As the data for investigation the UTS constraint function is not sufficient, this optimization is performed for two types of optimization problems as the continuous and discrete problems. Ignoring the UTS constraint function permits to define a continuous bi-objective optimization problem for AM.

  - **Continuous bi-objective optimization problem:** The continuous bi-objective optimization problem is used to optimize time and material regarding roughness as a constraint function. Layer thickness and orientation angles (θ_x, θ_y and θ_z) are the decision variables.

    To solve this problem, the essential inputs for NSGA-II algorithm are STL file, execution file of Cura, and algorithm parameters. In this algorithm, the parents are selected from the first random population by binary tournament selection based on the rank and crowding distance. This selection is based on their fitness values that reflect the quality of an individual. Then, the off-springs are produced by genetic operators including crossover and mutation. A single point crossover technique and polynomial mutation with given probabilities are adopted to generate the new solutions. The rank of an individual is generally determined by its Pareto dominance in the present populations. NSGA-II algorithm is completed in 50 generations (iteration number=50) to find the Pareto front as the solutions.

    The decision variables including layer thickness, θ_x, θ_y, and θ_z are assumed as the genes of the chromosomes. This kind of character string makes it possible to generate the feasible chromosomes in the continuous problem space. The chromosomes are evaluated by genetic operators. Firstly, the initial solutions are created randomly and considered as parents. Then, non-dominated sorting strategy is used to rank these parents. Crossover and mutation as genetic operators are used to generate different populations. Finally, crowding distance strategy is used to find the optimal solutions as Pareto front.

    The data which is collected for UTS constraint function is not sufficient to analyze this problem as a continuous optimization problem. This data consists of the UTS

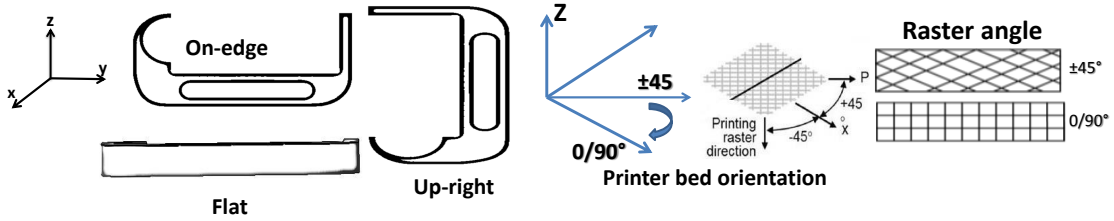


Figure 3.21 – Defined orientation for bag hook in discrete problem

values for some values of layer thickness in specific types of orientation including flat, upright, and on-edge for filling angle of ±45° and 0/90° for a standard specimen. To investigate UTS constraint function, the discrete optimization problem is extracted from continuous space for specific kinds of orientation and specific values of layer thickness which are described in the next section.

– **Discrete bi-objective optimization problem:** The discrete optimization problem is a part of the continuous optimization problem. The discrete problem space is extracted from the continuous space. Layer thickness as the first decision variable is defined between 0.1 mm and 0.4 mm. The orientations include three main orientations of flat, on-edge and up-right. Also, rotation around the z-axis provides different filling angles. The rotation angle is ±45° to convert default infill structure from ±45° to 0/90°. These orientation types are illustrated for the bag hook in Figure 3.21 with different raster angle. Moreover, the maximum roughness is determined to be 20 µm.

  The discrete solutions are extracted from the continuous space due to the angle values for the special types of orientation. Also, UTS constraint function and σ_{Max} are specified for the problem to provide the feasible discrete problem space. Non-dominated sorting strategy and crowding distance strategy are implemented to find the optimal Pareto.

In the next section, the results related to NSGA-II are presented and discussed.

Run Number	1
Population numbers	1000
Iteration numbers	100
Crossover Index	20
Mutation Index	20
Crossover Probability	0.9
Mutation Probability	1

Table 3.6 – NSGA-II defined parameters in Modefrontier

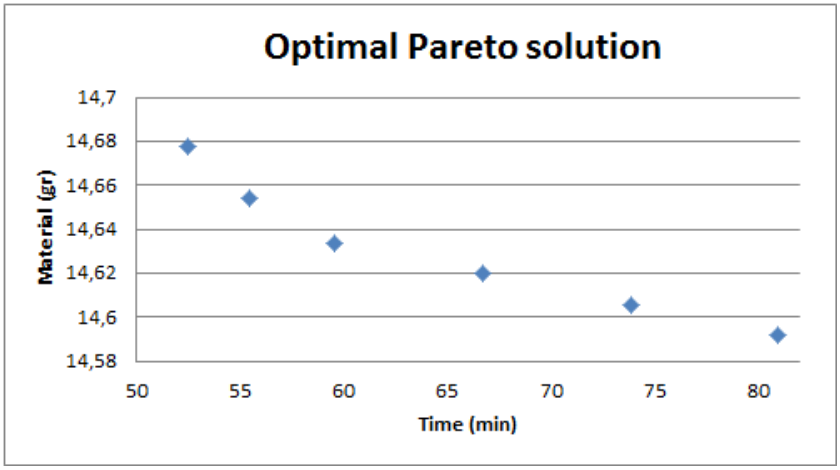


Figure 3.22 – Result obtained by Modefrontier

Final results and discussions for bag hook

1. Firstly, Modefrontier is used to solve the optimization problem through meta-modeling. The defined parameters for NSGA-II algorithm are summarized in Table 3.6. This algorithm provides the optimal solutions as Pareto front which is shown in Figure 3.22.

2. To obtain the results for a continuous and discrete optimization problem, a computer with 3.2 GHz Intel(R) Xeon(R) processor and 12 GB RAM is used to solve this problem. Total run time for this algorithm is 9 hours and 13 minutes. The genetic operators and their criteria are defined in Table 3.7.

   The obtained Pareto solutions for continuous and discrete optimization problem are presented in Figure 3.23. This figure illustrates all the feasible solutions as the continuous solutions by stars. The feasible solutions for discrete problem as squares are extracted from the feasible

Run Number	2
Population numbers	100
Iteration numbers	50
Crossover index	20
Mutation index	10
Mutation Probability	0.25

Table 3.7 – NSGA-II defined parameters

populations. NSGA-II provides the Pareto front as the optimal solutions for continuous and discrete optimization problem which are shown by stars and circles respectively. These 14 optimal solutions for the continuous problem are numbered and the solutions for discrete optimization problem have been named alphabetically. These optimal solutions are described in Table 3.8 and 3.9.

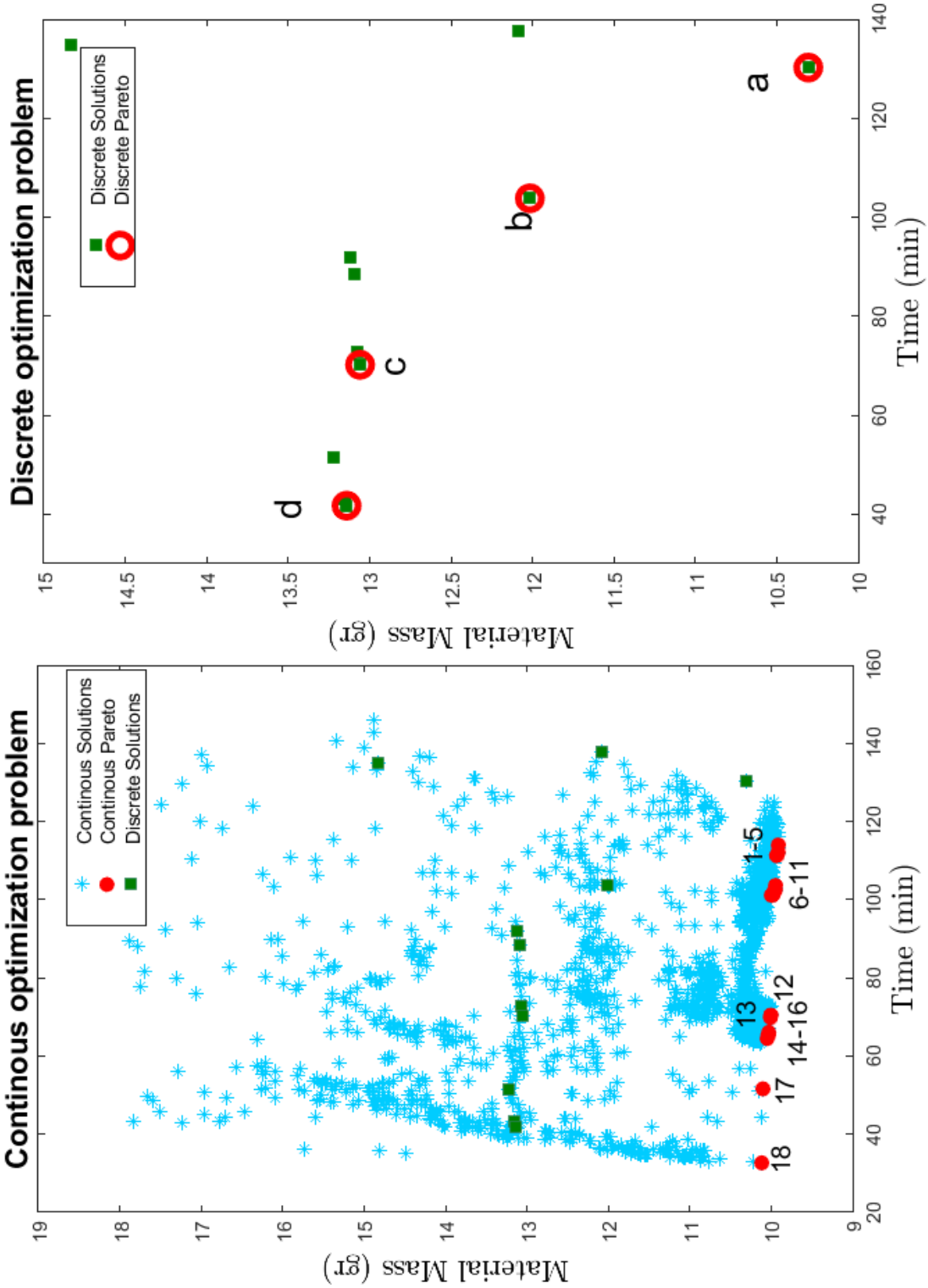


Figure 3.23 – Optimal solutions obtained by NSGA-II for bi-objective optimization problem for bag hook

According to the obtained results, it is finding that:

- Fabrication in different orientations and resolutions (different values of layer thickness) affects the material mass and manufacturing time.
- For the continuous optimization problem, optimal values of time are varied between 33.66 and 113.99 min and optimal mass is changed in the range between 9.91 and 10.12 g. These ranges for the discrete problem are not the same as the continuous problem. The fabrication in flat, on-edge and up-right positions causes more changes in the time and material consumption. The range of time is comprised between 41.73 and 103.82 min and mass is between 10.31 and 13.14 g. In continuous case, mass varied by 2 % and time is varied by a factor of 2.38 (238 %) and for discrete, the mass variation is 20 % and this factor for time is 1.48 (148 %). Therefore, the variation of mass and time are more important for the defined orientations of the discrete problem rather than continuous possible orientations.
- There is an antagonism between mass and time as the main principle of the multi-objective optimization problems. The maximum mass is related to the solution with minimum time and conversely, the maximum time is for the minimum mass.
- The difference in time and mass are imposed because of the layer construction, raft, and support structure. Layer thickness values affect the number of layers to produce the product due to its volume (product height for the considered orientation). Since the number of layers is decreased by increasing layer thickness, it needs less time for manufacturing of a product. So, the trade-off between these parameters illustrates the required material and time for fabrication. In the same orientation, increasing layer thickness decreases the manufacturing time. Support and raft mass are dependent on the product geometry and its orientation in build platform.
- The results for continuous optimization problem demonstrates that its optimal solutions do not consist of flat, on-edge, and up-right orientations as they require more mass of material and time rather than other orientation types.
- Among defined orientation types for the discrete problem, the up-right position is more time consuming than others. This orientation uses more material for support

Sol.	L_t [mm]	θ_x [°]	θ_y [°]	θ_z [°]	Time [min]	Material [g]	R_a [µm]
1	0.11	132.89	125.75	−87.31	113.99	9.91	19.53
2	0.11	133.12	125.44	−87.31	112.08	9.91	19.80
3	0.11	133.25	125.55	−87.19	112.00	9.92	19.74
4	0.11	133.22	125.88	−87.64	111.31	9.93	19.79
5	0.11	133.05	125.90	−87.65	111.26	9.94	19.87
6	0.12	141.90	125.38	−88.20	103.08	9.95	18.51
7	0.12	141.93	125.41	−88.21	101.37	9.98	18.50
8	0.12	141.96	125.42	−88.24	101.14	9.98	18.59
9	0.12	141.99	125.42	−88.25	101.12	9.99	18.48
10	0.12	141.90	125.37	−88.20	102.25	9.96	18.56
11	0.12	141.92	125.41	−88.21	101.91	9.97	18.54
12	0.18	40.00	147.91	−25.01	70.45	10.00	19.69
13	0.18	39.04	148.03	−24.95	69.81	10.01	19.06
14	0.19	44.33	169.90	−45.05	66.06	10.03	19.60
15	0.2	143.36	150.35	−88.75	65.56	10.03	19.91
16	0.2	143.34	151.53	−88.75	64.48	10.05	19.76
17	0.26	140.40	156.61	−73.35	51.60	10.10	19.60
18	0.28	−179.84	0.26	−4.48	33.66	10.12	19.56

Table 3.8 – Optimal solutions for continuous bi-objective optimization problem

Sol.	L_t [mm]	Orientation	Time [min]	Material [g]	UTS [MPa]	R_a [µm]
a	0.1	On-edge ±45°	103.82	12.01	31.90	19.04
b	0.1	On-edge 0/90°	130.24	10.31	33.50	19.04
c	0.13	Flat 0/90°	70.18	13.05	30.00	9.10
d	0.25	Flat 0/90°	41.73	13.14	32.70	17.50

Table 3.9 – Optimal solutions for discrete bi-objective optimization problem

construction. So, fabrication in this position is not optimal. Fabrication in the flat and on-edge direction require less time and material.

- The third and fourth solutions (solution c and d) are related to the flat position that needs less time but more material, as the construction of raft structure for the hook in flat orientation consumes more amount of material.

- As mentioned, fabrication in different orientations makes the differences in material mass by creating support and raft structures, and layer thickness modification changes the numbers of layers for production that modify the material mass. So, orientation types impose more difference in material mass than layer thickness value.

- From the comparison of solution a and b, it can be concluded that fabrication in raster angle $\pm 45°$ is faster than $0/90°$ but it consumes more material.

- Roughness is changed based on the resolution and orientation types. AM layer by layer production imposes a staircase error which is the origin of a large value of surface roughness. Producing with the thicker layer (low resolution) increases the roughness values and the surface quality is decreased. Besides, orientation has an influence on the surface quality due to the angle between tangent vector of parts and vertical direction for each orientation. Roughness value is independent of raster (filling) angle, as the top and bottom layers of AM parts are filled as the default setting ($\pm 45°$). The best surface quality of product among these solutions is provided by fabrication in the flat for resolution of 0.13 mm.

- Different layer thickness affects the mechanical behavior of the product. Fabrication in on-edge position with filling angle $0/90°$ and the resolution of $L_t = 0.1$ mm creates the highest mechanical strength. Fabrication in filling angle $0/90°$ produces the more resistant product rather than $\pm 45°$.

Both results, meta-modeling in Mode frontier and continuous bi-objective optimization problem, illustrate that the material mass are not varied in a large interval while the production time is varied in a wide range for the optimal solutions.

3.2.6 Final bag hook product model

Since the meta-modeling with insufficient data is not reliable, the results that are obtained through continuous bi-objective optimization problem are used to define the product model as A9 activity (Figure 2.4).

The product model is created through the information collecting based on the skin-skeleton model and interface processing engine results. This product model consists of FBS model, usage model, 3D model, optimal parameters and criteria, and optimal G-code file which illustrates manufacturing tool-paths (see Figure 3.24).

The results obtained from interface processing engine permit to find the optimal solutions for manufacturing. Pareto front as the non-dominated solutions are the different compromises of manufacturing parameters which are optimal and the producer should select between these solutions. All the solutions of the Pareto front are optimal but to find the best one between these optimal solutions, other criteria must be analyzed. In this study, mechanical behavior is a factor that must be investigated. According to the defined product specification, the bag hook must tolerate until 7.5 kg that creates the stress of 31.34 MPa. As solution c does not satisfy the constraint related to the UTS value, fabrication through this solution requires redesign of the product.

There are other criteria which could be analyzed to find the best compromise for production, as cost which consists of the expenses imposed to the manufacturer during production and the material price. Also, batch production and fabrication on the same machine simultaneously are others important factors that affect the manufacturers in their solution.

In this study, it is decided to fabricate through solution d as one of the solutions of the discrete optimization problem with considering the mechanical behavior of the hook, and it is faster than other solutions and provides a better surface quality rather than solution a and b. the bag hook is fabricated with a layer thickness of $L_t = 0.25$ mm in the flat orientation by raster angle $0/90°$. This fabrication takes 41.73 min by consuming 13.14 g of ABS as material. The manufactured product roughness is 17.5 µm with the UTS value of 32.7 MPa. It is fabricated by using the MakerBot Replicator 2x and the manufactured product is shown in Figure 3.24.

In the rest of this chapter, the proposed methodology will developed through second proposi-

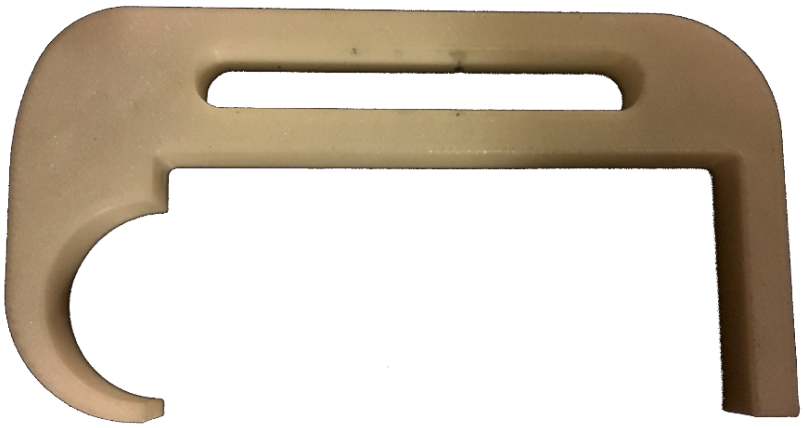


Figure 3.24 – Final product fabricated by AM

tion.

3.3 DFM-skin and skeleton approach based on proposition 2 for case study 1: Bag hook

As described in the introduction of this chapter, two propositions are provided to create the DFM-skin and skeleton approach for FDM technology. In this section, proposition 2 is assumed to help in implication of the proposed approach for defining a bag hook which will be fabricated by FDM. This approach contains several steps:

- Functional analysis and providing FBS model based on the product specifications and customer requirements which is the same step of the approach based on proposition 1. This FBS model helps to identify usage model.

- In this step, the usage model must be determined based on the product features and initial structure coming from FBS model. This usage model consists of usage skin and skeleton:

  - **Usage skin identification:** The usage skin is the surface of the product which material as skeleton circulates on it. Topological optimization is used to determine this usage skin.

  - **Usage skeleton identification:** There are two methods to obtain usage skeleton:

    1. **Power crust algorithm:** It is applied into STL file of bag hook and obtained result is shown in Figure 3.25. The obtained result of determining usage skeleton is dependent to the meshing of the STL file. The numbers of points in STL file must be sufficient to define the skeleton. Also, the hook does not have a complex structure and the skeleton can be determined easily as follow:

    2. **Manually:** If the geometry of the product is simple, usage skeleton as material flow can be identified manually (Figure 3.25).

- Manufacturing model as defined in section 2.2.3, consists of skin as contours of layer and part orientation as skeleton. In second proposition, the manufacturing skeleton must be determined based on the usage skeleton. In this thesis, there is no possibility to create the part orientation as manufacturing skeleton based on the usage skeleton and continuing the

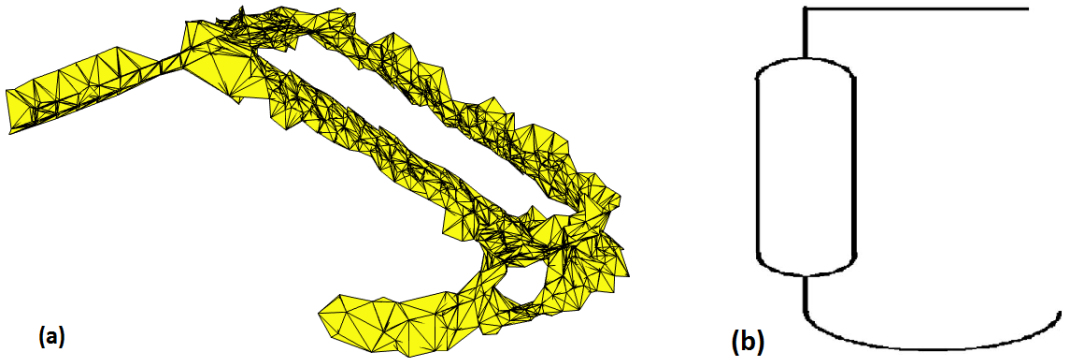


Figure 3.25 – (a) Usage Skeleton by power crust algorithm (b) Usage skeleton as material flow (manually)

DFM-skin and skeleton approach based on this proposition. Also, the 3D model of the product must be defined by comparison of usage and manufacturing skin and skeleton.

Therefore, the proposed approach will be developed based on the first proposition in order to define the product model. According to this proposition, the part orientation is determined through an optimization approach regarding the criteria of manufacturing system and product features.

In the following, the proposed approach will be applied to another case study in order to utilize AM capability to reuse a product that has a broken part.

3.4 DFM-skin and skeleton approach under proposition 1 for case study 2: Wheel spindle

Another characteristic that encourages manufacturers to use AM as a new technique for production is bringing life into the products that are broken in some parts. This technique bring the opportunity to reuse the products by " Re-manufacturing" the broken part.

In this study, a child car is considered that it is broken in the spindle of front wheel through a shock as shown in Figure 3.26. Therefore, it is supposed that this shock creates a force against wall and it causes the spindle to break.

To produce this spindle for re-utilizing the car, as well as enhancing the product quality and

Figure 3.26 – Broken spindle as problem statement in the second case study

its performance, DFM skin and skeleton approach as the proposed methodology in this thesis will be used.

Firstly, as essential input for this approach and all the product development cycle for design and manufacturing, the product specifications must be prepared according to the customer requirements. For this purpose, firstly the dimensions and functionality of the product are investigated. Figure 3.27 illustrates the car dimensions and functionality. As shown in this figure, two forces of $\boldsymbol{F_F}$ and $\boldsymbol{F_B}$ are the forces that are applied to the front and back wheels. Also, $\boldsymbol{G}$ is a force that is created due to the child weight. It is supposed that child creates the force equal to $G = m \times g$ as $m = 20\,\text{kg}$. To calculate the applied force, the statistic analysis is performed in the following:

Statistic analysis: This spindle is broken while the child had an shock with the wall. This shock imposes a force to the wheel and spindle which breaks the spindle. Therefore, the force is applied to wheel for shocked situation against wall. This force is shown in Figure 3.28. It is supposed that $\boldsymbol{G}$ is applied along the longitudinal axis. Therefore, these forces can be calculated

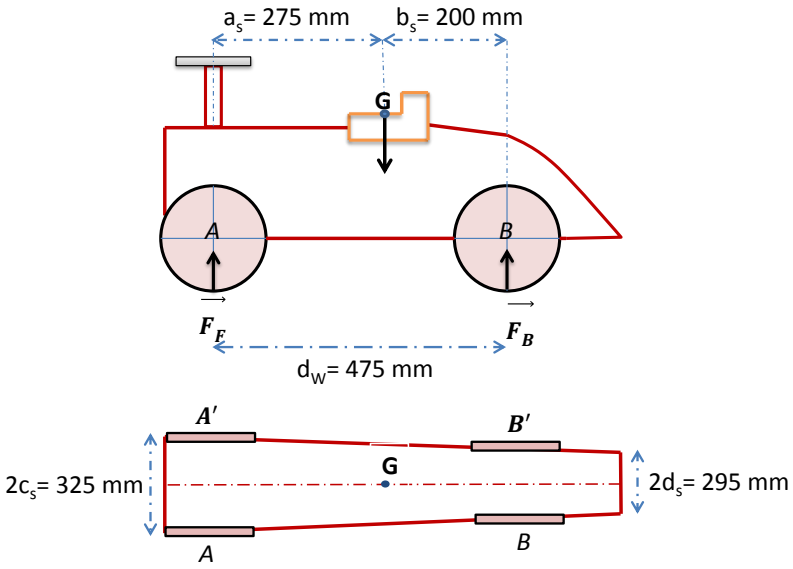


Figure 3.27 – Vehicle dimensions and functionality

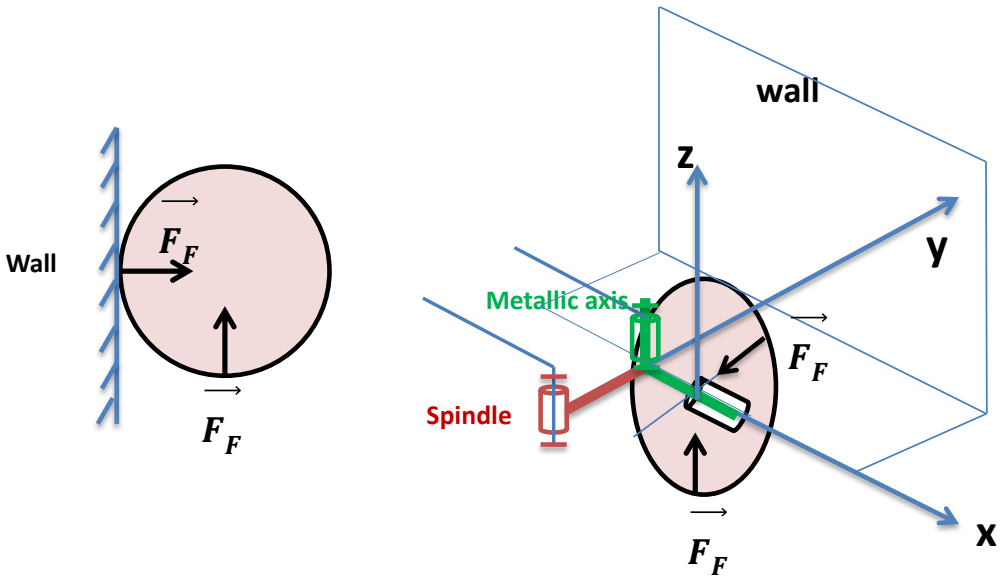


Figure 3.28 – The force applied to wheels

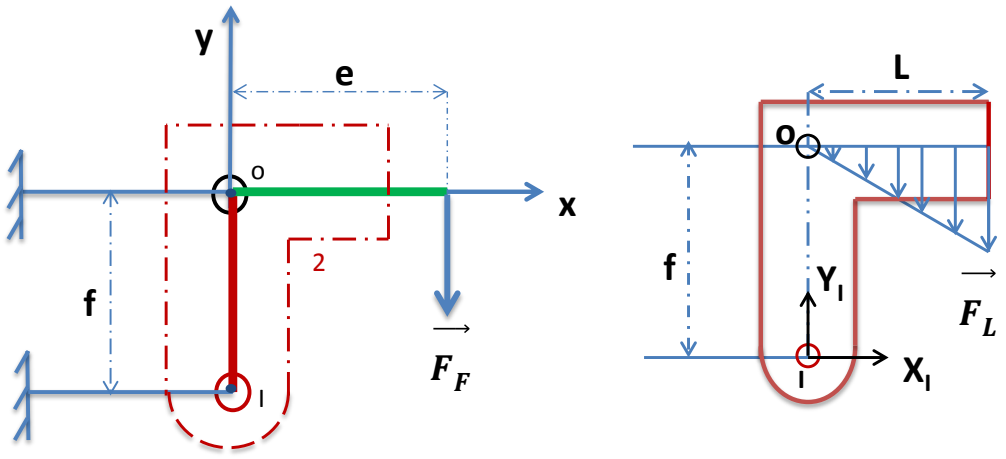


Figure 3.29 – The force applied to spindle

as follow:

$$2\boldsymbol{F_F} + 2\boldsymbol{F_B} - \boldsymbol{G} = 0 \tag{3.14}$$

$$2a\boldsymbol{F_F} - 2b\boldsymbol{F_B} - \boldsymbol{G} = 0 \tag{3.15}$$

According these equations, $\boldsymbol{F_F}$ and $\boldsymbol{F_B}$ are obtained through Equation(3.16) and(3.17):

$$\boldsymbol{F_F} = \frac{a_s \boldsymbol{G}}{2(a_s + b_s)} \tag{3.16}$$

$$\boldsymbol{F_B} = \frac{b_s \boldsymbol{G}}{2(a_s + b_s)} \tag{3.17}$$

Figure 3.27 depicts the car dimensions, $b_s = 200\,\text{mm}$ and $a_s = 275\,\text{mm}$, as $b_s \leq a_s$, it can be determined that the force which is applied to the back wheel is bigger than front one ($\mid F_F \mid \leq \mid F_B \mid$). According to these equations, the back and front force are $F_F = 56.79\,\text{N}$ and $F_B = 41.30\,\text{N}$.

To avoid breaking again the spindle when child has an accident, the statistic analysis is also performed to produce a stronger spindle. This force is transfered to the wheel axis and spindle as a distributed force ($\boldsymbol{F_L}$). The spindle dimensions are measured as $e = 43.42\,\text{mm}$, $f = 39.8\,\text{mm}$, $L = 33.6\,\text{mm}$, these values are shown in Figure 3.29.

This triangular distributed force ($\boldsymbol{F_L}$) applied on the spindle along L is calculated as equation:

$$\boldsymbol{F_L} = -\frac{6e\boldsymbol{F_F} - 2L\boldsymbol{F_F}}{L^2} \quad (\frac{\mathrm{N}}{\mathrm{m}}) \tag{3.18}$$

This triangular distributed force applied along L is equal to $F_L = -7072.1\,\mathrm{Nm}^{-1}$ and total force which is applied to the spindle is computed through Equation (3.19) and $F_{T2} = -118.81\,\mathrm{N}$.

$$\boldsymbol{F_{T2}} = \frac{\boldsymbol{F_L}L}{2} \tag{3.19}$$

The forces of $\boldsymbol{X_I}$ and $\boldsymbol{Y_I}$ which is applied to the pivot section can also be calculated through Equation (3.20) and (3.21). Therefore, This forces are equal to $X_I = 45.05\,\mathrm{N}$ and $Y_I = 41.30\,\mathrm{N}$.

$$\boldsymbol{X_I} = \frac{e}{f}\boldsymbol{F_F} \tag{3.20}$$

$$\boldsymbol{X_I} = \boldsymbol{F_F} \tag{3.21}$$

The proposed methodology, DFM-Skin and Skeleton approach for AM, is used to define a product model for this spindle which contains the functional analysis as the FBS model, usage model, manufacturing model, and interface processing engine.

3.4.1 Functional analysis for wheel spindle

As mentioned before, two types of force are imposed to the axis and spindle which are derived from the child weight and the force which is imposed at the time of shock which are shown in Figure 3.30. As illustrated in this figure, the spindle is in connection with axis and steering tie rod directly. There is a complete linkage as housing between axis and spindle. The force created through shock situation is applied directly to the axis and it is transformed to spindle. The axis is the support for this spindle. The steering tie rod is in connection with spindle via a pivot as linkage. The car body tolerates the force imposed by child weight. As mentioned before, this model depicts the shock situation, so, the force which is applied from the wall is also shown. the wheels create the force that is transformed to the axis. These wheels are in connection with ground. So, this FBS model permits to determine the product functionality and recognize usage

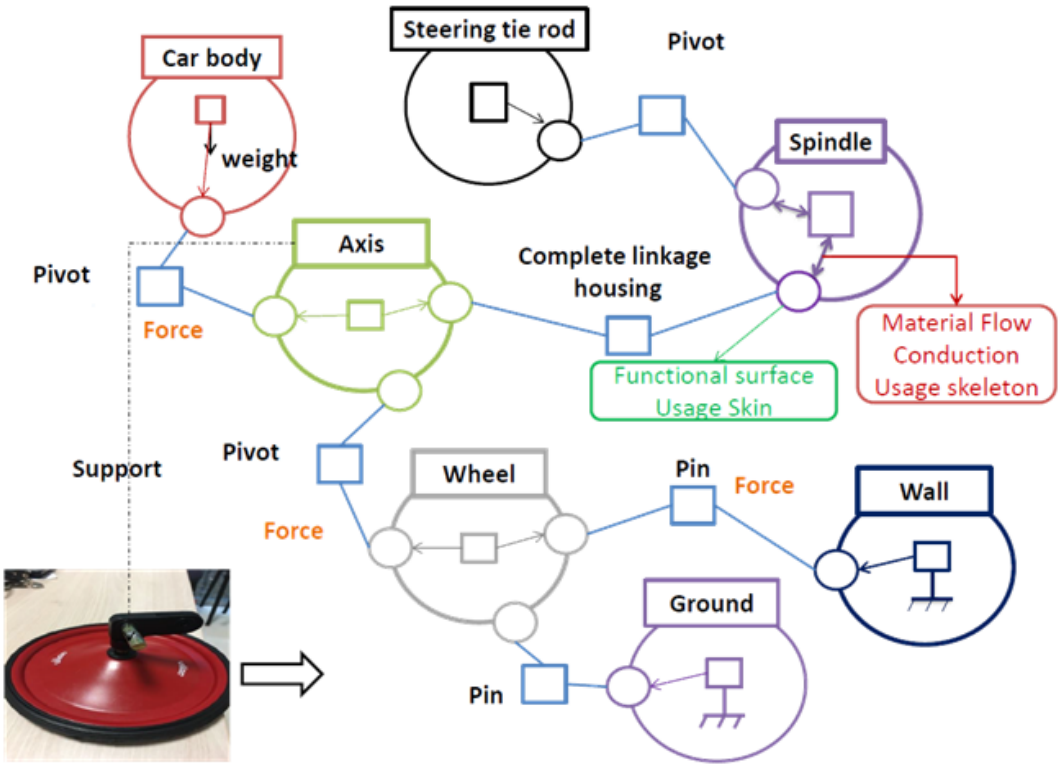


Figure 3.30 – FBS model for wheel spindle

model in the following. The initial part volume is created in CATIA based on this FBS model and the initial broken part. This initial volume is shown in Figure 3.31.

3.4.2 From usage model to 3D model for wheel spindle

In this section, the usage model and consequently 3D model will be provided in the following:

1. As mentioned, the initial model is created in CATIA which is derived from the initial form of the current product is the input for topological optimization.

2. The 3D model is converted to STL file.

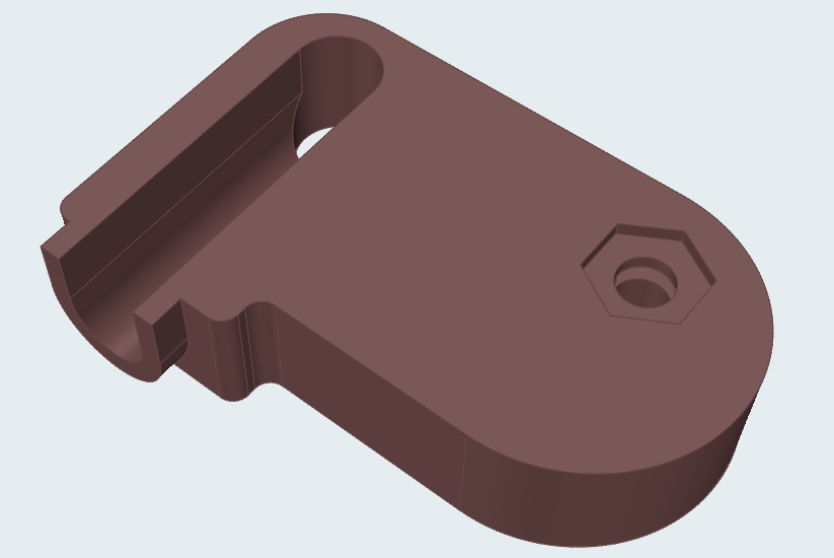


Figure 3.31 – Initial spindle volume

3. This STL file is loaded in Inspire to provide an optimal structure through topological optimization.

4. ABS is selected as material for this spindle.

5. The axes as non-design spaces are prepared in Inspire.

6. The product functionality is determined as applied force to these axes. The support as bearing surface is fixed in this structure. These forces are calculated before in section 3.4.

7. An analysis is performed to determine the mechanical behavior of the product.

8. The optimization with objective of maximizing the stiffness is performed and optimized usage model is provided. In this optimization, a minimum safety factor is 1.2 and minimum thickness is considered equal to 5.4 mm. For optimization, the fast option is used to increase the optimization speed. Also, a mass target of 30% is selected which shows the percentage of total mass for the entire model.

9. Smoothing is applied to the optimized usage model.

This smoothed usage model is converted to the STEP file and it is loaded in CATIA. The initial

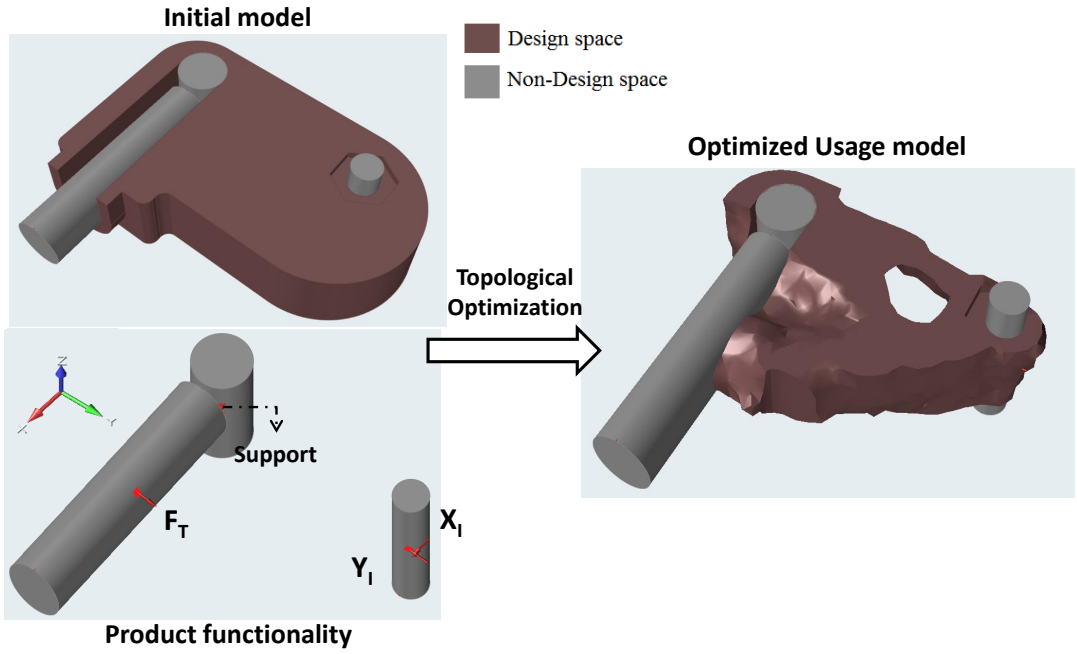


Figure 3.32 – Usage model for spindle coming from topological optimization

3D model is modified based on this optimized usage model as shown in Figure 3.33. This 3D model is obtained based on the product functionality. As it is necessary to add functional parts of the product to the 3D model like axis surface contact (a) and groove for this spindle (b), the 3D model is modified based on these functionalities (Figure 3.34).

3.4.3 FDM manufacturing model

Since AM is used to fabricate the spindle, 3D model of the product must be converted to the STL file as the standard format for AM technologies. As mentioned in chapter 2 and due to AM layer construction manner, nozzle starts the layer production from the contours of layers which are considered as manufacturing skin, then, interior structure is created that can be determined by manufacturing skeleton as part orientation which are shown in Figure 3.36. The same manufacturing parameters also exist for production with FDM technology which allow defining the interface processing engine.

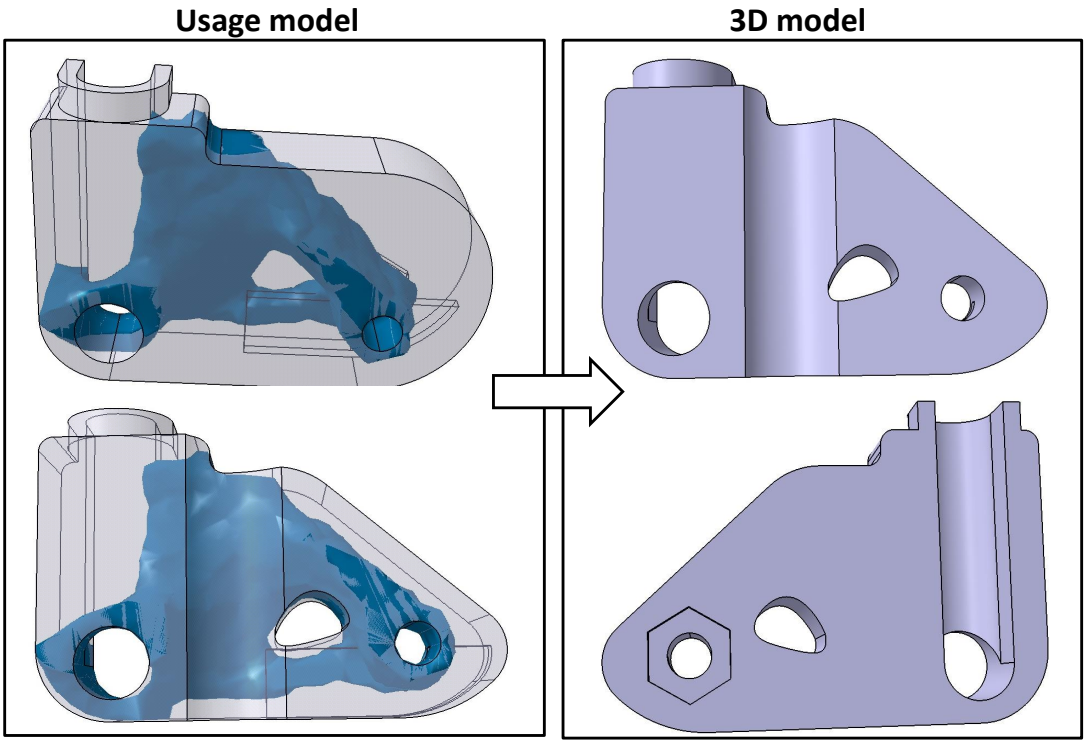


Figure 3.33 – 3D model of spindle

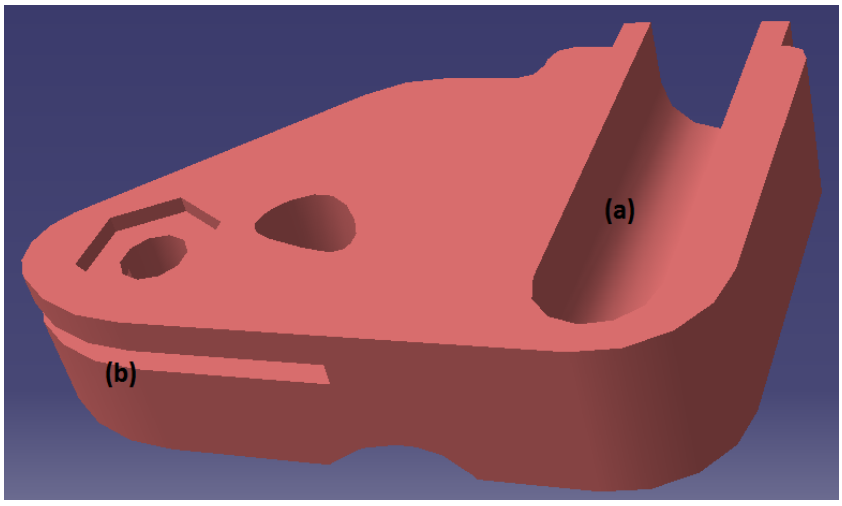


Figure 3.34 – Spindle functional parts

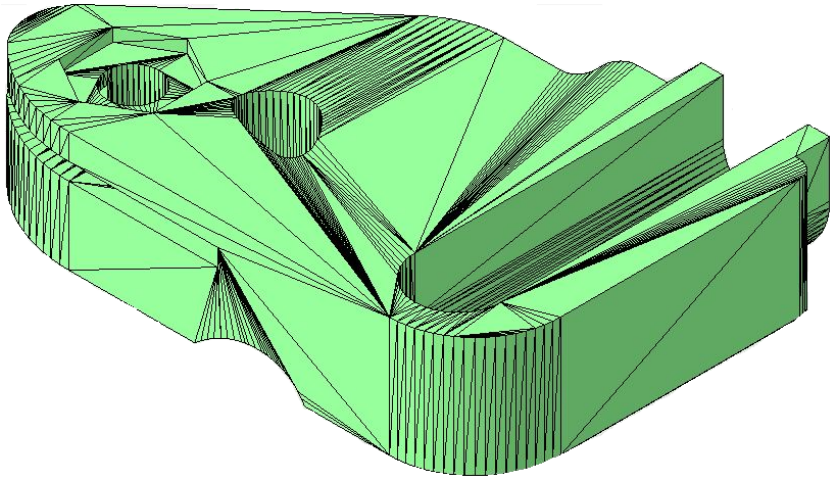


Figure 3.35 – Spindle STL file

3.4.4 Interface Processing Engine of wheel spindle

As described in section 2.2.4 of chapter 2, this interface processing engine is an interface between usage and manufacturing model which helps to provide the product model based on the optimization of the manufacturing parameters regarding the desired criteria and constraints.

For this purpose, the bi-objective optimization problem is solved through utilization of NSGA-II algorithm. The input file of this algorithm is the STL file of the 3D model.

Moreover, it is necessary to determine the minimum value of σ_{Max} for the wheel spindle. For this purpose, a Finite Element Analysis (FEA) is performed on this case study. To perform this analysis, firstly, Octree Tetrahedron Mesher is used to create a 3D mesh. ABS as a new material is added to the material library of CATIA and its characteristics during printing is considered as desired characteristics. These characteristics are presented in Appendix II. The calculated force ($\boldsymbol{F_{T2}}$) must be imposed to the axis. The steel axis is created to define the product functionality. Two rigid virtual parts are also provided in order to apply pivots (Figure 3.37).

The FEA result is demonstrated in Figure 3.38. This analysis shows that the axis tolerates the imposed force and it can tolerate until 17.5 MPa, and the spindle as case study tolerates the 5.24 MPa. These values are less than the tensile stress at yield of the material ($\sigma_{\text{yield(ABS)}} = 39\,\text{MPa}, \sigma_{\text{yield(Steel)}=250\,\text{MPa}}$), but it is necessary to consider the effects of the decision variables (layer thickness and orientation) on the AM product model.

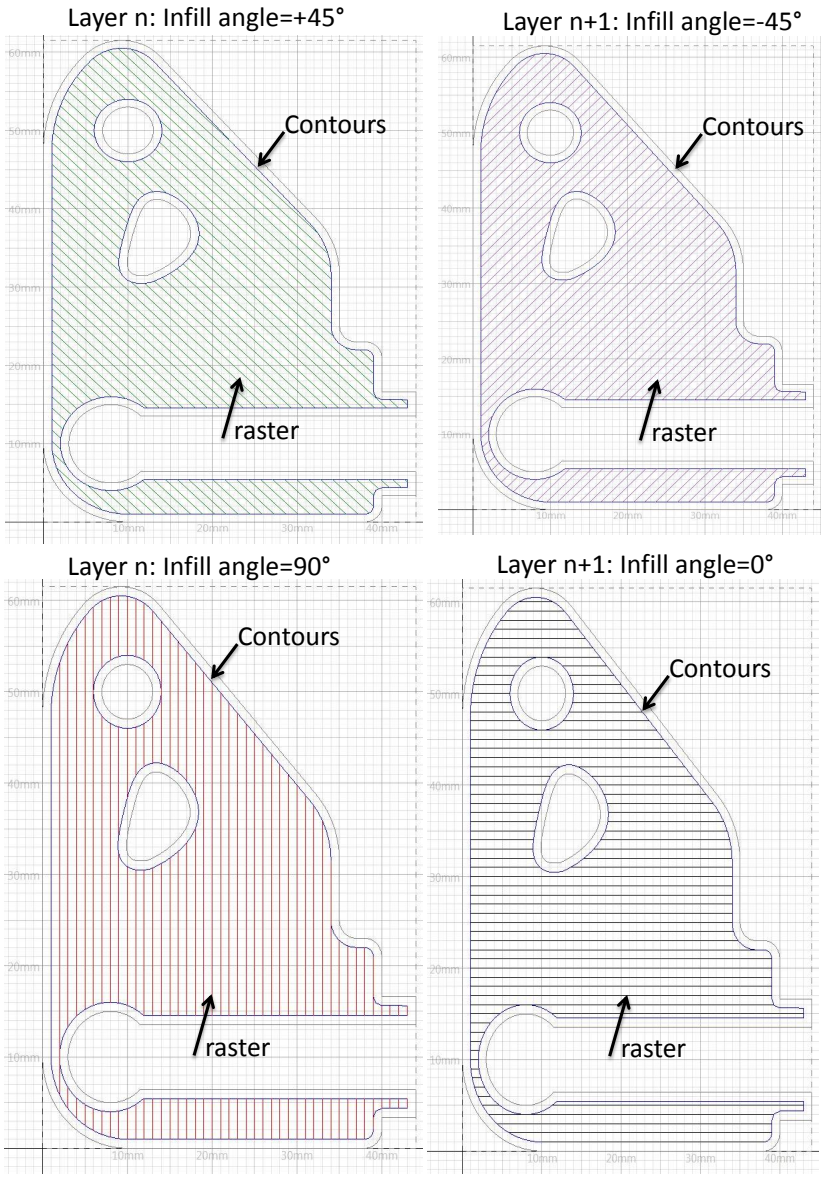


Figure 3.36 – Manufacturing model and spindle structure in different raster (infill) direction

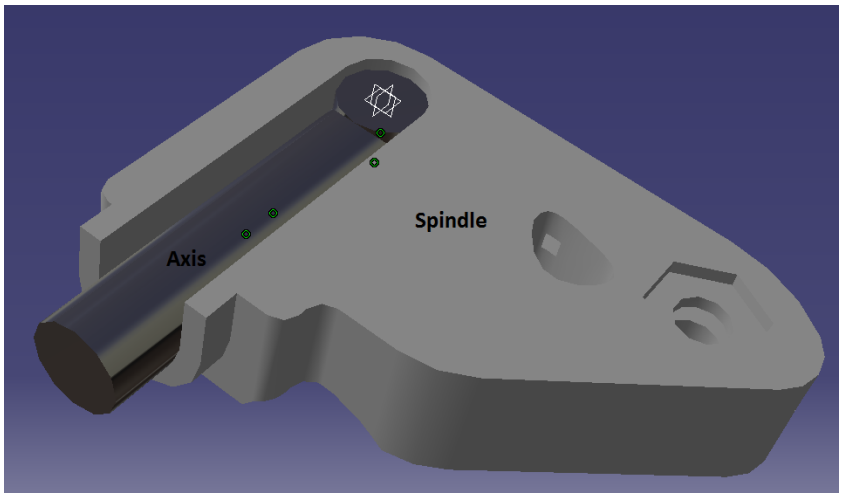


Figure 3.37 – The initial model for Finite Element Analysis

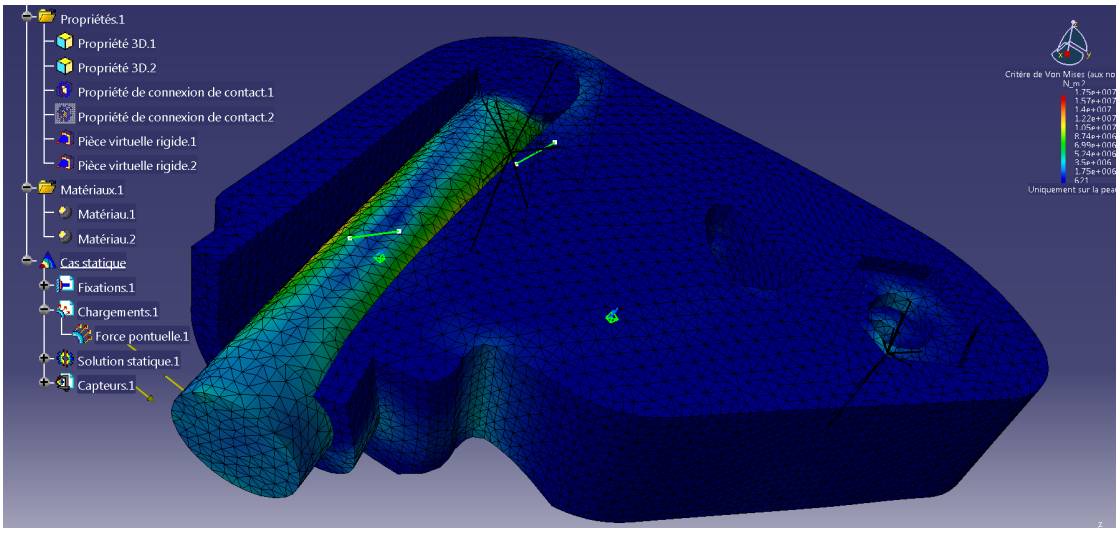


Figure 3.38 – Finite Element Analysis of new wheel spindle

Like the first case study, the optimization problem is performed in two types of continuous and discrete problems. Firstly, the continuous one is solved and the discrete space is extracted from this continuous space. The obtained results of this optimization problem including optimal manufacturing parameters as Pareto front are described in section 2.

Results

To obtain Pareto front for continuous and discrete optimization problem, NSGA-II algorithm is used. The same parameters are considered and total run time is 8 hours 33 min. The obtained Pareto are shown in Figure 3.39. This figure illustrates all the feasible solutions for continuous and discrete problem as stars and squares. The optimal Pareto for continuous and discrete one are also shown by squares. The 26 solutions of continuous problem as its Pareto front are illustrated in circles. The Pareto front for discrete is shown alphabetically. All these solutions are presented in Table 3.10 and 3.11:

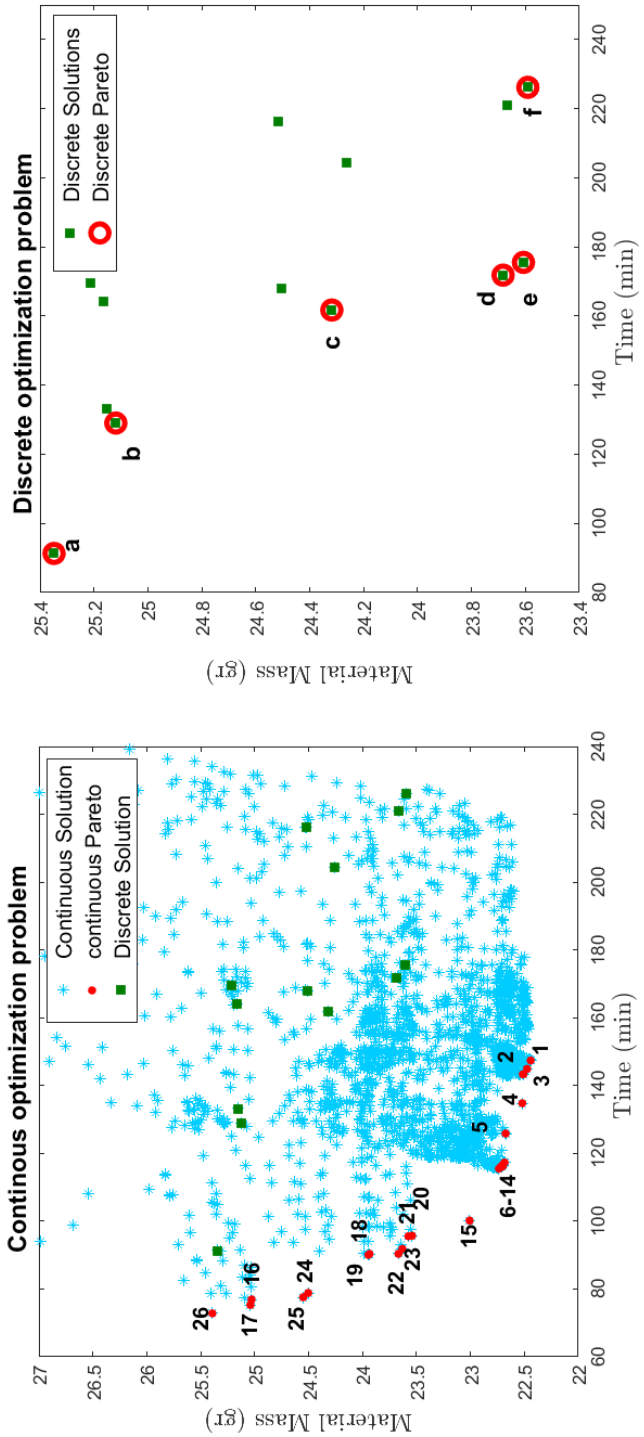


Figure 3.39 – Optimal solutions obtained by NSGA-II for wheel spindle

According to these obtained results:

- Manufacturing criteria and constraints are variable due to layer thickness and orientation angles.
- For continuous case, the optimal values for time are between 72.8 min and 147.38 min, and mass values are in the range of 22.44 g and 25.39 g, while this range is different for discrete problem. Time values are varied between 91.31 min and 226.17 min and mass values are in the range of 23.59 g and 25.35 g. For continuous case, mass varied 13% and this factor for time is 1.02 (102%). In the discrete problem, mass and time factor are 7.4% and 1.47 (147%). Therefore, variation of time and mass for discrete problem are more important rather than the continuous one.
- Like the Pareto front obtained for the bag hook, there is an antagonism between mass and material as the main principle of multi-objective optimization problem. Solution with minimum time consume maximum material.
- The continuous solutions (solution 16 and 17) are produced in a flat orientation. Solution 18 is related to up-right orientation with infill angle of 90°.
- Solution a and b are fabrication in flat orientation which is more faster than other solutions but it consumes more material to create the raft and initial structure of product.
- On-edge orientation consumes less material but fabrication in this orientation is longer than others.
- Solution e and f show that increasing layer thickness in the same orientation reduces the fabrication time but mass depends on nozzle feature.
- This results shows that product roughness is dependent to the layer thickness and deposition angle which is determined by the orientation angles. The best surface roughness can be produced by solution f which is fabrication in high resolution ($L_t = 0.1$ mm).
- According to the FEA analysis and UTS values for discrete solutions, all the solutions can satisfy the mechanical behavior of the product.

Sol.	L_t [mm]	θ_x [°]	θ_y [°]	θ_z [°]	Time [min]	Material [g]	R_a [µm]
1	0.14	−47.89	143.60	−176.54	147.38	22.44	19.02
2	0.15	−48.33	142.78	−176.54	144.93	22.47	19.77
3	0.16	−140.29	38.06	−113.90	143.32	22.51	18.65
4	0.17	−140.29	38.06	−113.90	134.78	22.52	19.82
5	0.18	162.42	45.05	−19.12	125.84	22.67	19.73
6	0.19	175.93	45.22	−31.41	116.04	22.71	19.94
7	0.19	176.45	45.24	−31.44	116.00	22.72	19.94
8	0.19	176.43	45.24	−31.43	115.98	22.72	19.94
9	0.19	179.35	45.04	−31.26	116.06	22.71	19.85
10	0.19	175.69	45.04	−31.24	116.32	22.69	19.91
11	0.19	175.61	45.06	−31.24	117.29	22.68	19.92
12	0.19	175.68	45.04	−31.25	116.51	22.70	19.91
13	0.19	175.66	45.05	−31.24	116.76	22.70	19.92
14	0.2	178.43	44.92	−30.93	115.48	22.74	19.87
15	0.23	156.25	40.51	83.70	100.18	23.00	25.92
16	0.24	0.00	0.00	−180.00	76.92	25.03	48.64
17	0.24	0.00	0.00	45.00	75.29	25.04	48.64
18	0.24	90.00	0.00	90.00	90.35	23.94	49.07
19	0.24	90.00	90.00	90.00	90.06	23.95	48.64
20	0.25	148.80	41.49	53.64	95.73	23.54	26.86
21	0.25	149.05	41.31	54.43	95.55	23.57	26.82
22	0.26	−170.60	144.50	24.87	90.38	23.67	31.33
23	0.26	179.97	60.54	−13.48	91.84	23.63	37.66
24	0.31	−34.59	143.31	60.90	78.84	24.51	36.39
25	0.32	−34.35	144.33	64.60	77.57	24.55	37.98
26	0.34	−151.86	40.98	−149.95	72.80	25.39	36.13

Table 3.10 – Pareto front for wheel spindle for continous optimization problem

Sol.	L_t [mm]	Orientation	Time [min]	Material [g]	UTS [MPa]	R_a [µm]
a	0.2	Flat ±45°	91.31	25.35	32.80	40.53
b	0.13	Flat 0/90°	129.04	25.12	30.00	26.35
c	0.13	Up-right ±45°	161.74	24.32	29.11	26.58
d	0.13	Up-right 0/90°	171.83	23.68	30.00	26.58
e	0.13	On-edge 0/90°	175.52	23.61	26.35	25.70
f	0.1	On-edge 0/90°	226.17	23.59	33.35	20.27

Table 3.11 – Pareto front for wheel spindle for discrete optimization problem

The obtained results for these two case studies show that the product features and its manufacturing criteria and constraints depend on product geometry. There is no optimal solution which is common for all products and product geometry plays an important role to find the best solution for fabrication. It is not possible to define a rule for these criteria that can be applied for all products. Therefore, this interface processing engine helps to find the best manufacturing parameters for all 3D model and consequently, preparing the final product model.

3.4.5 Final spindle product model

The results obtained from optimization permit to define the best manufacturing parameters. As mentioned before, Pareto front as non-dominated solutions are the different compromises for production and the producer must select between these solutions. Considering other criteria like cost which includes the costs of production and material price, as well as considering the other criteria like, batch production, can help to select between these parameters.

In this thesis, it is decided to select between the fast solution of a and b of discrete solutions to consider the product mechanical behavior. Solution a is faster than b but its surface is rougher. Fabrication through solution b is fast and it has a good surface quality. Therefore, this wheel spindle is fabricated with a layer thickness of $L_t = 0.13\,\text{mm}$ in flat orientation with infill angle of 0/90°. This fabrication takes 129.04 min and 25.12 g of ABS is consumed. Makerbot Replicator is used to fabricate this spindle and the manufactured product is shown as Figure 3.40.

Figure 3.40 – Produced wheel spindle by FDM

3.5 DFM-skin and skeleton approach based on proposition 2 for case study 2: Wheel spindle

As described, two proposition are provided to develop the DFM-skin and skeleton approach for FDM technology. In this section, proposition 2 is assumed to help in implication of the proposed approach for defining the spindle which will be fabricated by FDM. This approach contains several steps:

- Functional analysis and providing the FBS model based on the product specifications and customer requirements which is the same step of the approach in proposition 1. This FBS model helps to identify the usage model.

- In this step, the usage model must be determined based on the product features and initial structure coming from the FBS model. This usage model consists of usage skin and skeleton:

  - **Usage skin identification:** Topological optimization is performed to determine usage skin.

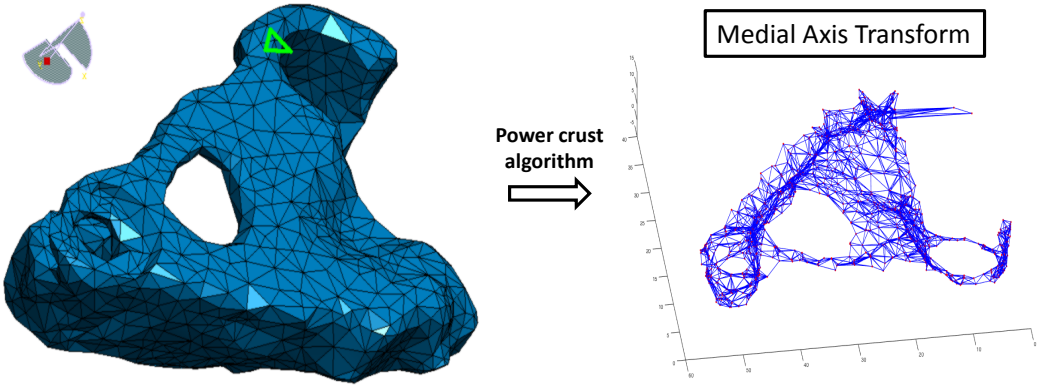


Figure 3.41 – Usage Skeleton of wheel spindle by power crust algorithm

– **Usage skeleton identification:** Power crust algorithm is applied into STL file of wheel spindle. This STL file is reinforced in meshing. This reinforcement add the triangles and consequently their points which can define the medial axis as the output of power crust algorithm. This obtained result as manufacturing skeleton is shown in Figure 3.41.

- Manufacturing model as defined in section 2.2.3, consists of skin as contours of layer and part orientation as skeleton. In proposition 2, manufacturing skeleton must be determined based on the usage skeleton. In this thesis, there is no possibility to create the part orientation and continue the DFM-skin and skeleton approach. Moreover, the 3D model must be prepared by comparison of usage and manufacturing skin and skeleton.

  Therefore, the proposed approach developed based on proposition 1 is used to define a product model. In this proposition, the part orientation is determined through optimization approach regarding the criteria and constraints of the manufacturing system and product features.

In the next section, a summary of this chapter will be presented.

3.6 Summary

In this chapter, the proposed methodology is implemented into Fused deposition Modeling and two case studies are considered to verify this methodology. The proposed methodology helps designer to provide the 3D model by using FBS and usage model. The manufacturing model is proposed for Fused Deposition Modeling (FDM) as a common and useful technology of AM. After identification of the 3D model and manufacturing model, the 3D model is converted into a STL file. Interface processing engine is developed to determine the optimal manufacturing parameters for all 3D models regarding the desired criteria and constraints like time, material mass, roughness, and mechanical properties of the produced product by FDM.

Therefore, this skin-skeleton approach helps to determine an optimized 3D model due to the functional requirements, as well as to find the manufacturing parameters by optimization of manufacturing criteria like time and material mass regarding mechanical behavior of product and its surface quality. There are two limits in this approach. Firstly, it is not capable of analysis different diversity of the products, so, the approach must be further developed to provide and compare these possible solutions. Mechanical behavior of the AM products is not still clear which is the second limit of this approach. Interface processing engine as the main contribution of this thesis permits to optimize the manufacturing process and find the best manufacturing parameters for production of all 3D models through its optimization problems and calculation tools.

Validation of the DFM-skin and skeleton into the case studies illustrates the efficiency of this approach for all the 3D model and AM technologies.

4 Conclusions

Outline of the current chapter

Finally in this chapter, a summary of this thesis will be described and the contribution is highlighted. A brief conclusion is presented in this chapter, then perspectives is discussed to help other researchers to continue this work.

This thesis presented a methodology to master and define the AM products in the product life cycle. This thesis aims to provide a DFM approach for AM to investigate concurrently different attributes, constraints, and criteria of design and manufacturing in the product definition level. The Integrated Design approach used to create a final optimal product model based on the product specifications.

For this purpose, firstly a complete study of Additive Manufacturing (AM) and its technologies have been performed. The benefits and disadvantages of this new technology were described in chapter 1. To improve the fabrication through this technology, Concurrent Engineering and Integrated Design and their application in product life cycle management is helpful. Concurrent engineering and integrated design, as well as DFM approach were described respectively in

section 1.3 and 1.4. Skin-skeleton approach as a methodology to implement DFM for different manufacturing processes were presented in section 1.4.3. Different studies have been investigated to analyze the approaches as Design For AM (DFAM) in section 1.6. According to DFM definition, these proposed approaches were categorized into four categories of functional DFAM, manufacturability DFAM, material and process selection, as well as a combinational approach. Analysis of these approaches illustrated that there is no integrated and complete approach that considers manufacturing constraints of AM in the design stage. Also, it is necessary to develop a combinational approach by considering functional analysis and manufacturability analysis by focusing on verification, quantification, and optimization of the manufacturing process and manufactured products. For this purpose, an integrated methodology of Design For Manufacturing for AM due to Concurrent Engineering was presented in chapter 2. This method allows for considering of all attributes, constraints, and criteria of AM as soon as possible in the product definition. This methodology is used to create the final product model based on the functional requirements through Function-Behavior-Structure (FBS) model, skin-skeleton model and onterface processing engine. The first step of product life cycle management is requirement engineering and FBS model helps to analyze the product behavior and function, as well as to provide the initial volume of the product. The skin-skeleton model was defined in two types of usage and manufacturing models which depict initial information for design and manufacturing simultaneously. The usage is related to product specifications and analysis of this model allow providing a draft of the product. Also, manufacturing one contains the essential information for manufacturing. A novel interface processing engine has been developed in section 2.2.4 to consider the usage, design, and manufacturing attributes simultaneously in the product definition as an integrated approach of Design For Manufacturing. It is like a decision-maker tool for a user which find the manufacturing parameters (layer thickness, orientation, infill pattern). It consists of calculation and optimization tools to analyze the AM procedure, it handles a large number of criteria and constraints related to AM like time, material, roughness, and mechanical behavior in order to propose an integrated product model with optimization solutions before designing the product as a CAD model and it creates a possibility to redesign a product through comparison of the desired criteria and product specifications. Therefore, this methodology was used to find the optimal product model as presented in section 2.2.5 including 3D model, optimal manufacturing

parameters, G-code file, and all important issues of the product manufacturing.
Chapter 3 was devoted to the validation of the proposed methodology into two case studies. This chapter illustrated that this methodology can be applied to all products which will be fabricated by AM technologies.

4.1 Conclusions

Overall, this thesis provided a methodology to define a product by optimization of the 3D model, and manufacturing parameters for fabrication. The main conclusion that can be mentioned for this thesis is as follows:

- This thesis presented a DFAM approach in the product definition level.
- This thesis focused on quantification and optimization of manufacturability by considering significant AM criteria and constraints together.
- AM and product features were modeled simultaneously by skin-skeleton model.
- A manufacturing model for Additive Manufacturing was presented by analysis of the technologies and related software.
- A novel interface processing engine as a decision-making tool for designer and manufacturer was presented. This engine contains a bi-objective optimization problem which optimizes layer thickness and orientation angles by minimizing production time and material mass regarding the surface quality of FDM product and mechanical behavior of the material.

In the following, the next step of the research will be presented as perspectives and future works to help other researchers to continue their researches in this domain.

4.2 Perspectives and future works

This thesis provided a product model through an integrated design and a multi-objective optimization approach. The improvements in this methodology can be performed regarding the following aspects as short-term and long-term perspectives:

4.2.1 Short-term perspectives

- **User-friendly software:** Interface processing engine can be presented as a software which can be used to find optimal manufacturing parameters for all STL files.

- **Developing DFM-skin and skeleton approach due to Proposition 2:** According to the second proposition assumed in this thesis, the manufacturing skeleton must be determined based on the usage skeleton. In this study, usage skeleton was found through the power crust algorithm, but it is necessary to complete the approach by determining the manufacturing skeleton (part orientation). It must be mentioned that power crust-algorithm is dependent on the meshing of the STL file. The numbers of point in STL file must be sufficient to define the skeleton. This approach must be continued, but until now, no possible solution for continuing this approach is found. Moreover, the 3D model must be created through comparison of usage and manufacturing skin and skeleton.

- **Evaluation of different possible geometries:** Usage model prepared the preconditions to define a 3D model. This possible forms can be obtained by analysis of usage skin and skeleton.

- **Mechanical properties of AM parts:** As AM produces the products layer by layer as a non-homogeneous structure, the study on mechanical behavior of the AM products is different with other products fabricated by classic manufacturing processes. Experimental approach can be a method to construct a meta-model to formulate the mechanical behavior regarding manufacturing parameters

- **Dimensional accuracy:** Translation from STL file to CAD model and layer by layer production create the deviation between 3D model and manufactured one. This criteria must be considered as a constraint in this multi-objective optimization problem. In this thesis, this constraint was analyzed but no reliable formulation is found that investigates both physical and geometrical aspects which create the dimensional deviation.

- **Another AM technology:** This DFM-skin and skeleton approach can be applied to another AM technology like SLM, SLS, etc.

4.2.2 long-term perspectives

- **Developing DFM-skin and skeleton approach due to proposition 2:** It is necessary to consider the geometrical constraints related to AM technologies to define 3D model of the product. Also, AM unique characteristics such as anisotropic material, non-homogeneous structure of produced part by AM (different infill pattern and density), etc. must be considered in developing this proposed approach.

- **Enhancing the topological optimization results:** In this study, inspire as topological optimization software is used but, there is some limits in this application in defining the product functionality, as it is not possible to determine the functional parts that must be fixed during optimization. Also, it is not possible to create the different types of force in order to provide an analysis and optimization near product real function.

- **Hybrid manufacturing:** Development in this methodology can be performed by considering hybrid manufacturing of AM with other traditional processes in order to utilize all advantages of the manufacturing technologies simultaneously.

- **Mechanical properties of AM parts:** It is useful for analysis of the mechanical behavior of AM parts by finding a method to create the structure of AM parts in a 3D format can help to analyze their mechanical properties through Finite Element Analysis.

- **Applicable to all AM technologies:** The presented usage, manufacturing, and interface processing engine must be applied to all AM technologies.

- **Material and process selection:** This approach must be completed to help the producer from the first step of material and technology selections regarding product specifications.

Part II

French version

French Summary

Outline of the current chapter

Introduction

De nos jours, la fabrication additive (FA ou Additive Manufacturing en anglais) fait évoluer le monde de la fabrication par ses avantages et sa capacité à produire des formes complexes. Une technologie de FA met en forme une pièce couche par couche en utilisant des matériaux spécifiques [37]. Ces caractéristiques uniques induisent de nouveaux critères de conception et de fabrication mais introduisent des limites d'utilisation dans l'industrie. Donc, il est essentiel d'intégrer dès que

possible les contraintes et les attributs de fabrication au sein de la phase de conception.

Ainsi, l'ingénierie simultanée est une méthodologie indispensable pour considérer les attributs de conception et de fabrication dans le cycle de gestion du produit afin d'aider les concepteurs et les fabricants à trouver un modèle de produit intégré. Cette méthode englobe toutes les activités d'analyse fonctionnelle et d'ingénierie des exigences, de conception et de fabrication pendant la phase de définition du produit en utilisant l'approche de conception pour la fabrication (ou DFM pour Design For Manufacturing en anglais) pour évaluer la fabricabilité du produit. Le DFM repose sur des activités de sélection des matériaux et des processus, ainsi que l'évaluation de la fabricabilité à trois niveaux de vérification, de quantification et d'optimisation [3].

La conception et la fabrication du produit par FA sont très différentes de celles des procédés de fabrication traditionnels et créent de nouveaux problèmes et de nouvelles problématiques dans leur mise en œuvre industrielle. Le lien entre la conception et la fabrication est peu formalisé et est encore difficile à systématiser en FA due à la nouveauté des pratiques et des applications. Ainsi, ce travail de thèse propose de définir une méthodologie pour considérer tous ces aspects simultanément.

Problématique et objectifs de l'étude :

Pour aborder ce champ d'étude, nous commençons par quelques questions :

- Comment intégrer l'étape de fabrication et ses contraintes dans l'étape de conception pour améliorer le modèle de produit en termes de coût, de temps et de qualité ?
- Comment modéliser et optimiser le produit pour répondre aux exigences du client ?
- Quels attributs et critères de FA influencent le processus de développement du produit ?
- Quels paramètres technologiques ont des effets significatifs sur les attributs et les critères de FA et comment trouver les meilleurs paramètres de fabrication ?
- Comment intégrer toutes les étapes du processus de conception et de fabrication dans une approche générale ?

Il est nécessaire de présenter une approche intégrée et complète traitant la plupart des attributs, capacités, critères, et contraintes simultanément pour fournir un processus interopérable dans la

gestion du cycle de vie du produit. L'intégration de la conception et de la fabrication liées à la FA peut faciliter sa mise en œuvre. Il est prévu de considérer le processus de fabrication au début de la définition du produit comme une approche de conception intégrée. Le modèle de produit est complété par un modèle 3D, des informations de fabrication et des attributs définis grâce à l'approche DFM. Dans ce but, il est nécessaire de fournir une approche générale pour formaliser la prise en compte des contraintes d'usage et de fabrication lors de la définition du produit. Pour atteindre ce but, il est primordial de trouver une méthodologie pour une approche de conception intégrée dédiée à la FA. L'approche DFM a été appliquée aux processus de fabrication traditionnels par l'approche peau et squelette dans plusieurs études [3, 4]. Dans cette étude, cette approche peau-squelette semble utile pour modéliser la première définition du produit et du processus de fabrication. Ce modèle sera complété par un moteur de résolution qui est une interface qui traite des informations provenant simultanément du domaine de la conception et du domaine de la fabrication qui sont interdépendants. L'étude analyse les technologies de FA et identifie les paramètres et critères pour trouver le ou les modèles de produit optimisé.

Dans le contexte de l'ingénierie simultanée et de la fabrication additive, cette thèse est motivée par la proposition d'une nouvelle approche de conception intégrée dédiée aux solutions reposant sur l'utilisation de la fabrication additive. Ainsi, il est nécessaire de fournir une approche générale pour formuler et prendre en compte simultanément les contraintes d'usage et de fabrication lors de la définition du produit.

Cette thèse est organisée comme suit :

Organisation du mémoire

Le manuscrit est structuré en quatre chapitres. Le premier chapitre présente les principales technologies, méthodes et approches telles que la fabrication additive, l'ingénierie simultanée et la conception intégrée. Une analyse de la littérature présente les recherches existantes dans ce domaine. Le deuxième chapitre décrit la méthodologie proposée en tant qu'approche DFM-peau et squelette pour la fabrication additive grâce à une approche d'optimisation multi-objectif. Dans le chapitre 3, l'approche proposée est appliquée à travers deux études de cas qui utilisent l'impression 3D par dépôt de fil chaud (ou FDM pour Fused Deposition Modeling en anglais).

Enfin, ce manuscrit se termine sur une conclusion et des perspectives.

Conception intégrée et fabrication additive : état de l'art

La Fabrication Additive (FA) évolue dans un monde où l'industrie a des attentes très fortes sur ce nouveau principe de fabrication. On parle souvent de quatrième révolution industrielle à propos des technologies de FA. Le principe de la FA repose sur une fabrication couche par couche avec des matériaux très différents qui aboutit une structure anisotrope très différente d'une technologie à une autre ([37]). Le comportement physique d'une pièce se rapproche d'une pièce composite. Il est donc essentiel d'étudier dès que possible les contraintes et les attributs de fabrication pendant la phase de définition du produit afin de concevoir des composants fiabilités [54, 33]. À cette fin, l'ingénierie concurrente est une méthodologie utile pour considérer simultanément des attributs d'usage, de conception et de fabrication afin d'aider les concepteurs et les fabricants de définir un modèle de produit maitrisé.

La Figure II.1 montre différentes configurations du processus de conception. Selon cette figure, la simultanéité est démontrée par le chevauchement des étapes du processus de conception et d'intégration à travers l'implication des acteurs professionnels et des parties prenantes. Les parties a et b de cette figure sont respectivement liées à la conception systématique et à la conception intégrée. Dans la partie c, l'approche de conception intégrée est présentée en fonction du travail de notre équipe de recherche (ICD-LASMIS). Ce dernier met l'accent sur l'intervention de différents métiers d'expertise dans la définition du produit. Cette approche est connue sous le nom de Design For X (DFX) où X représente les différentes activités de fabrication, d'assemblage, de la qualité, ou de coût.

La conception pour la fabrication (ou DFM pour Design For Manufacturing en anglais) est l'un des concepts qui aide le concepteur et le fabricant à étudier les contraintes et les attributs du processus de fabrication dans la phase de conception [33]. Enfin, il fournit un modèle de produit par l'analyse fonctionnelle, la conception et la fabrication de produit en même temps [33]. La DFM repose sur certaines activités de sélection des matériaux et des processus, et l'évaluation de la fabricabilité à trois niveaux de vérification, de quantification et d'optimisation (Figure II.2) [3].

Selon cette définition, l'approche de conception intégrée existante pour la FA (ou DFAM pour

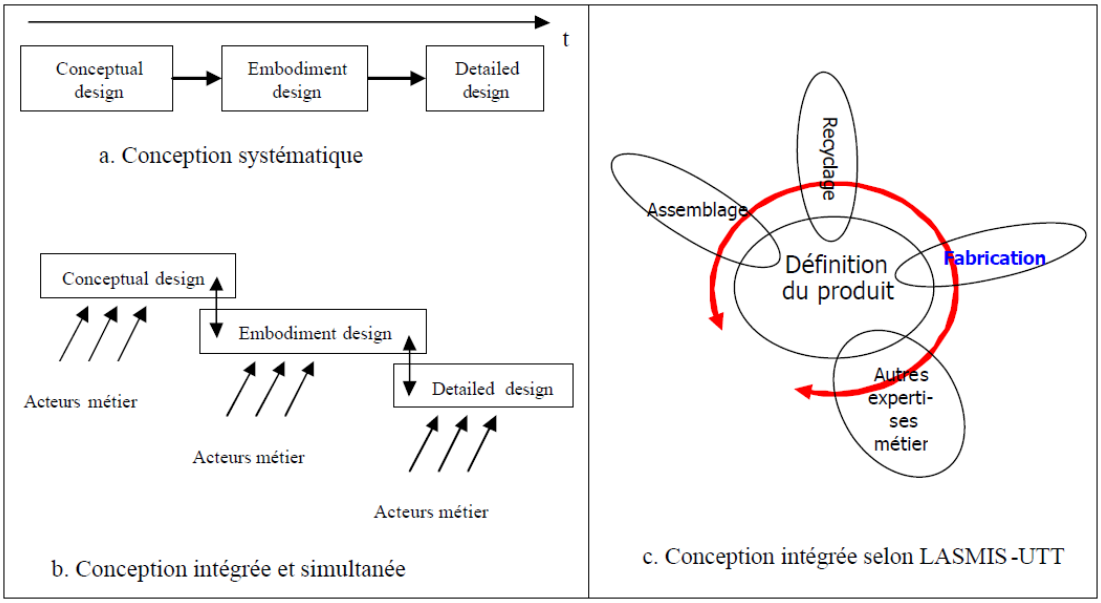


FIGURE II.1 – Présentation du processus de conception, a. Conception systématique, b. Conception intégrée et simultanée, c. Conception intégrée selon LASMIS-UTT.

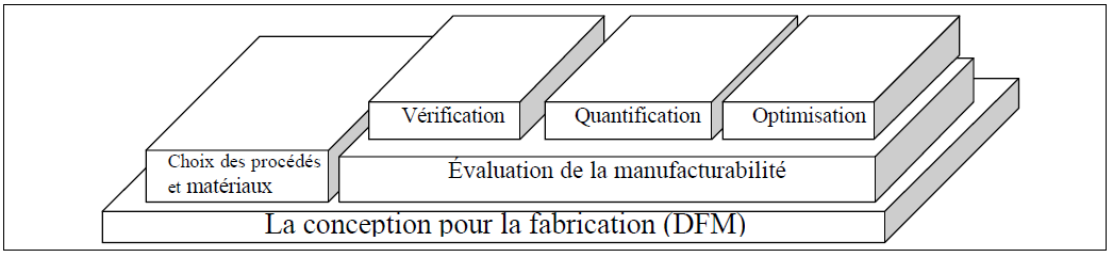


FIGURE II.2 – Définition schématique de la conception pour la fabrication (DFM) [12]

Design For Additive Manufacturing) sont analysées et catégorisées comme suit :

1. **Approche de sélection des matériaux et des processus :** L'importance du type de matériau sur la spécification du produit et les technologies de FA encouragent les chercheurs à fournir une approche DFAM dans le contexte de sélection des matériaux et des processus.

2. **DFAM fonctionnel :** Les capacités de la FA ont inspiré de nombreux chercheurs à optimiser les performances de conception et de fabrication tout en minimisant les poids des pièces fabriquées. Cette catégorie est basée sur l'analyse fonctionnelle du produit et les exigences du client. L'optimisation topologique (TO) [80] est utilisée pour satisfaire les exigences de conception, y compris le comportement mécanique, la fonctionnalité, la masse, la structure, le temps et le coût. La structure en treillis [110, 77]), l'analyse de modèles CAO [36, 104], la consolidation de pièces [36] et la conception basée sur les fonctions sont également utilisées dans les solutions DFAM.

3. **DFAM fabricabilité :** La fabricabilité doit être évaluée dans l'approche DFM. Certaines études [80, 52, 97, 102, 71, 105, 94, 88, 91, 96, 188, 189] ont discuté de l'analyse utilisée au niveau de la vérification comme les règles de conception AM. Des études existent sur le niveau de quantification des critères et contraintes de fabrication, coût [111, 51], de précision dimensionnelle [146, 147, 127], de rugosité [48, 49, 113], et de comportement mécanique des produits [156, 171, 157, 170, 186, 172] mais ces aspects doivent être étudiés dans des approches DFM comme le décrit [113].

   Pour compléter ce processus DFM collaboratif, il est nécessaire de passer du niveau de quantification et d'atteindre le niveau d'optimisation. L'optimisation dans les approches combinatoires [79, 115] seront expliquées dans la section suivante mais elle présente des solutions intéressantes pour traiter de nombreux attributs afin de proposer une ou des solutions optimales.

   Ces méthodologies d'optimisation sont utilisées pour évaluer la fabricabilité de la fabrication additive (FA) au niveau d'optimisation dans différentes études. Une approche DFAM pour le métal est développée par [115] qui consiste en une estimation des coûts et une optimisation de l'orientation des pièces. L'orientation des pièces, l'optimisation fonctionnelle et l'optimisation de la trajectoire dans l'approche DFAM sont analysées par Ponche et al.

DFAM fonctionnel	DFAM fabricabilité	Sélection des matériaux et des processus	Approche combinée
Rosen 2007a [70]	Burton 2005 [71]	D'antonio et al. 2015 [72]	Yim 2007 [73]
Rosen 2007b [74]	Bernard 2008 [75]	Thompson et al. 2016 [46]	Ponche et al. 2012 [76]
Chu et al. 2008 [77]	Thomas, 2009 [52]	Salonitis and Zarban, 2015 [78]	Ponche et al. 2014 [79]
Vayre et al. 2012 [80]	Kerbrat el. 2011 [81]	Zamen et al. 2017 [82]	Zhang et al. 2014 [83]
Arisoy et al. 2015 [84]	Doubrovski et al. 2011 [85]	Zamen et al. 2018 [86]	Tang et al. 2014 [87]
Yang et al. 2015 [36]	Seepersad et al. 2012 [88]		Hallgren et al. 2016 [89]
Jiang et al. 2017 [90]	Seepersad et al. 2014 [91]		Klahn et al. 2014 [92]
Vogiatzis et al. 2017 [93]	Wegner and Witt, 2012 [94]		Klahn et al. 2015[95]
Pradel et al. 2017 [96]	Adam and Zimmer 2014 [97]		Primo et al. 2017 [98]
Leary et al. 2014 [99]	Boyard et al. 2013 [100]		Kumke et al. 2016 [69]
Rodrigue and Rivette, 2010[101]	Kranz et al. 2015 [102]		Salonitis, 2016 [103]
Ariadi et al. 2012 [104]	Bin et al. 2012 [105]		Emmelmann et al. 2011 [106]
Walton et al. 2017[107]	Ko et al. 2015 [108]		Hague et al. 2003 [109]
Tao 2016 [110]	Atzeni and Salmi 2012 [111]		Hague et al. 2004 [112]
	Boschetto and Bottini 2016 [113]		Dhokia et al. 2017 [114]
	Barclift et al. 2017 [115]		Zhang et al. 2016 [116]
			Zhang et al. 2016 [117]
			Essink et al. 2017 [118]
			Vo et al. 2017 [119]

TABLEAU 4.1 – Classification d'approche DFAM

2014 [79].

Ainsi, une méthode d'optimisation est présentée par [99] pour trouver l'orientation de construction optimale en évaluant le temps de fabrication et la masse des composants.

4. **Approche combinée :** Certaines études ont combiné des approches fonctionnelles et fabricabilité. Ces approches fournissent des solutions de conception grâce aux principes de FA, objectifs de conception, capacités de processus de fabrication et optimisation structurelle [78], optimisation topologique [79, 78, 76, 98, 84, 89], et la structure réticulaire [110, 98, 84, 89, 87, 190, 191], ainsi que l'analyse des critères comme le poids [87, 106], force et déplacements [98], temps et coût [115, 89, 99], qualité de surface [79], optimisation de l'outil de fabrication [79, 115, 76].

   Depuis plusieurs années, de grands efforts ont été consacrés à l'étude des paramètres de FA comme l'optimisation du chemin d'outil [142, 143], l'optimisation de remplissage [144], la rugosité de surface [145, 49], la précision dimensionnelle [146, 147], le temps [148, 149] et la maitrise des coûts [51]. Selon ces études, les paramètres importants sont l'orientation de la pièce à fabriquer, l'épaisseur des couches, les motifs de remplissage et la densité, la température de l'enceinte de fabrication, les propriétés du matériau et des paramètres comme le diamètre de la buse et la vitesse de déplacement.

Toutes les approches DFAM sont classées dans le tableau suivant (Tableau 4.1). Cette classification

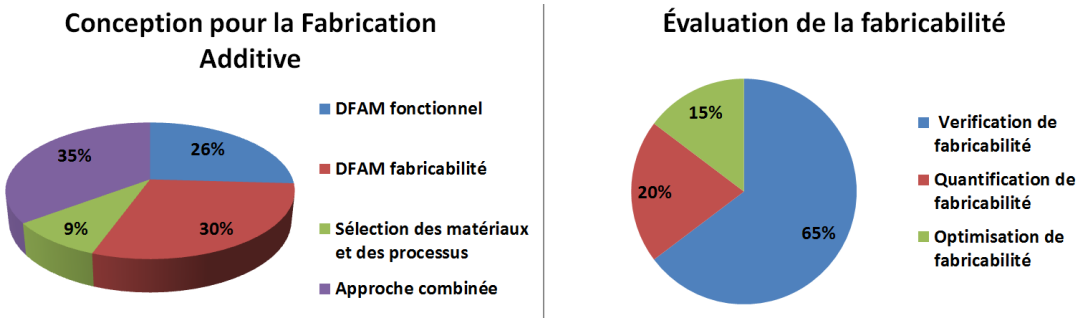


FIGURE II.3 – Analyse statistique des approches DFAM

nous permet de fournir une analyse statistique des recherches effectuées, comme indiqué sur la figure II.3. Il est représenté que la plupart des études sont liées DFAM combinatoire (35 %) qui combine fonctionnalité et analyse de fabricabilité. 30 % des recherches sont consacrées à la DFAM de fabricabilité qui est les études qui ont effectué une analyse de fabricabilité sans considérer l'analyse fonctionnelle. Ces études se concentrent sur la vérification (70%) et l'étude sur les niveaux de quantification et d'optimisation manque encore de 20% et 10% de toutes les approches DFAM de manufacturable et DFAM combinatoire. DFAM fonctionnelle est une autre approche significative pour DFAM qui comprend 26% des recherches. Le bilan de cette recherche bibliographique nous indique qu'il est primordial de maitriser les critères et les paramètres de la FA dans les approches DFAM pour vérifier, quantifier et optimiser la fabricabilité en tant qu'approche DFM. Selon cette analyse, les critères les plus importants à analyser, quantifier et optimiser sont le temps et la masse du matériau, le coût du système de production, la rugosité de surface comme facteur de qualité de surface, la précision dimensionnelle et le comportement mécanique des pièces. Ces critères et contraintes seront analysés dans cette étude à travers une approche décisionnelle multicritères. De plus, notre approche est la combinaison de DFAM fonctionnelle et manufacturable en considérant les critères et les attributs de FA pour fournir une approche intégrée qui englobe toutes les étapes du cycle de vie du produit.

Toutes les études utilisent le DFM pour analyser le modèle 3D et la conception initiale, mais le processus de définition du produit est situé plus en amont et pourrait contenir plus d'informations utiles au concepteur. Ainsi, il est nécessaire de fournir une méthodologie pour optimiser le modèle de produit par l'optimisation du modèle 3D, ainsi que de quantifier et d'optimiser les paramètres

de fabrication. Le processus de conception et de fabrication de FA sont assez différentes par rapport aux processus classiques. Contrairement aux discours entourant la FA, les concepteurs ne sont pas libres de concevoir les produits avec toutes les géométries. De nombreuses analyses et investigations doivent être prises en compte dans la conception des produits pour les processus de FA. Par conséquent, il crée un problème majeur pour la mise en œuvre industrielle de la FA. Il est crucial d'intégrer les attributs d'usage, de conception et de fabrication dans la définition du produit pour prendre en compte les exigences d'un système complexe.

L'objectif principal est de proposer une approche pour aider le concepteur et le fabricant afin de présenter une solution optimale pour la production avec FA en gérant simultanément la conception et la fabrication comme une approche intégrée de DFM pour FA. Par conséquent, cette thèse se concentre sur la définition d'une méthodologie de conception intégrée pour la fabrication additive au niveau du processus de définition du produit afin de trouver un modèle de produit optimal en considérant tous les attributs et contraintes de la première étape de conception à la fabrication.

Plusieurs tâches doivent être effectuées pour faire correspondre graduellement les exigences du client au modèle de produit final dans le processus de développement du produit. Le produit doit être conçu en raison des contraintes de fabrication. Cette intégration dans la définition du produit est réalisée à partir d'un sous-modèle représentant une conception commune et une modélisation de fabrication sous la forme d'une approche peau et squelette. Cette approche peau et squelette permet de modéliser simultanément les processus de conception et de fabrication pour créer un modèle de produit. Cette approche définit le produit désiré comme un ensemble de peau d'usage et de squelette qui est un sous-ensemble du produit et également un squelette de fabrication, ainsi que sa peau.

Par conséquent, la méthodologie proposée sera décrite dans la section suivant (section II) comme une approche de conception intégrée pour la FA par l'approche DFM-peau et squelette.

L'approche DFM-peau et squelette pour FA : Méthodologie proposée

Dans le processus de développement du produit, plusieurs tâches doivent être effectuées pour faire correspondre graduellement les exigences du client au modèle de produit final. Le produit est conçu en fonction des contraintes liées à l'ensemble du cycle de vie du produit (matériaux, analyse structurelle, recyclage, etc.). Par conséquent, l'ingénierie simultanée peut aider à considérer et analyser les contraintes de fabrication dans le développement du produit. L'importance de considérer les contraintes et les attributs de fabrication dans la définition du produit apporte des restrictions pour les intégrer dans l'approche de conception pour la fabrication (DFM). Cette intégration dans la définition du produit est réalisée à partir d'un sous-modèle représentant une modélisation de conception et de fabrication commune [30].

Pour développer cette approche pour les technologies AM, les fonctionnalités doivent être adaptées aux caractéristiques et attributs de FA. Deux proposition sont supposées orienter cette approche. Ces propositions sont différentes en termes de détermination du squelette de fabrication.

- **Proposition 1 :** Pour implémenter l'approche peau et squelette, les modèles d'usage incluant peau et squelette sont obtenus par optimisation topologique. Ensuite, une représentation intermédiaire du modèle 3D est obtenue. Enfin, le modèle de produit correspond à l'évolution de ce modèle d'utilisation obtenu en ce qui concerne les résultats du modèle de fabrication et du moteur de traitement d'interface. Dans cette méthode, la peau de fabrication correspond aux contours des couches et le squelette de fabrication en tant qu'orientation des pièces est déterminée par le biais d'une stratégie d'optimisation dans le moteur de traitement d'interface (voir Figure **??**).

- **Proposition 2 :** Selon cette proposition (Figure **??**), l'enveloppe d'utilisation est obtenue par optimisation topologique, puis le squelette est obtenu par l'algorithme de Power Crust basé sur ce modèle d'usage optimisée. Par conséquent, une représentation intermédiaire du modèle 3D est obtenue. Enfin, le modèle de produit correspond à l'évolution de ce modèle d'usage obtenu en fonction du modèle de fabrication et des résultats du moteur de traitement d'interface. Dans cette méthode, la peau de fabrication correspond aux contours

des couches et le squelette de fabrication en tant qu'orientation des pièces est déterminée en fonction du squelette d'utilisation obtenu par l'optimisation topologique et l'algorithme de la croûte de puissance. Il convient de mentionner que l'objectif principal de cette proposition est de prendre en compte les contraintes géométriques imposées par AM, ainsi que les caractéristiques uniques de l'AM, telles que le matériau anisotrope et la structure non homogène de l'intérieur du produit (structure de remplissage différente).

Premièrement, la proposition 1 est considérée comme mettant en œuvre l'approche DFM-peau et squelette pour la fabrication additive. Ensuite, la proposition 2 nous permet de définir notre approche proposée. Dans ce qui suit, l'approche due à la proposition 1 est décrite.

DFM-peau et squelette pour FA basé sur la proposition 1 :

L'approche peau et squelette permet de modéliser le produit et le processus de fabrication de l'analyse fonctionnelle à l'étape de production. Généralement, les peaux doivent décrire les surfaces fonctionnelles du produit et le squelette montre la trajectoire du flux.

La solution requise pour le modèle de produit n'est pas totalement déterminée par la conception et elle est contrainte par le modèle de fabrication, ainsi que par la modélisation d'interface issue de la conception et de la fabrication. Plusieurs solutions de conception sont alors disponibles. Des ensembles spécifiques d'attributs sont associés à la peau, tels que la forme, la tolérance, la rugosité et la direction du matériau qui dépend du formulaire. Les attributs du squelette sont les suivants : forme de section initiale, forme de section finale, variation de section, et fibre neutre (ligne, courbe, plaque, etc.). Un attribut supplémentaire définit la direction du flux de matériau pour la fabrication des squelettes. Selon ce concept simple, la définition finale du produit sera fournie et analysée en fonction de la sélection du procédé de fabrication. En effet, le modèle 3D final d'un produit (fabriqué à partir de peaux de fabrication) est construit en balayant ou en déformant la section du squelette sur la trajectoire du squelette. Le modèle initial décrit avec la peau et le squelette "d'usage" doit être comparé à celui de "fabrication".

L'approche DFM-peaux et squelettes pour FA consiste en un modèle FBS (Function-Behavior-Structure) pour l'analyse fonctionnelle, le modèle d'usage, le modèle de fabrication et le moteur de traitement de l'information dérivés du modèle d'interface.

Modèle FBS

Nous supposons dans la suite du manuscrit que le cahier des charges est déjà défini. Le cahier des charges comprend la performance mécanique, la taille et la forme, le poids, les aspects esthétiques et la fonctionnalité du produit. Modèle FBS qui est développé par Gero et al. [152] est considéré comme fournissant une analyse fonctionnelle ; par conséquent, la forme initiale et la structure du produit qui satisfait sa fonction et son comportement seront présentées. Ainsi, il aide à identifier le modèle d'usage, y compris la peau et le squelette par son espace de conception initiale.

Les objets de conception sont conceptualisés en tant que fonction (F), comportement (B ou Behavior en anglais) et structure (S) en tant que modèle FBS. Selon le modèle FBS, la conception d'un produit implique une série d'étapes élémentaires incluant la transformation de la fonction de produit désirée en son comportement attendu et le comportement attendu dans une structure [152].

Modèle d'usage

Le modèle d'usage est utilisé pour faire une présentation simplifiée du produit qui consiste en une peau d'usage et un squelette. La peau d'usage est définie comme une surface fonctionnelle dans laquelle circule un flux énergétique. Il prend en charge les attributs géométriques et les spécifications de conception. Le squelette d'usage est un flux énergétique qui peut être mécanique, électrique, magnétique, etc. qui circule dans le produit. Il est spécifié en fonction du ou des comportement(s) spécifique(s) requis du produit. Ainsi, les formes initiales doivent être déterminées. Ensuite, la morphologie possible du squelette est proposée par le concepteur [33, 30, 3].

Le modèle d'usage est dérivé des spécifications du produit, des attributs et du modèle FBS. L'optimisation topologique est sélectionnée pour obtenir un modèle d'usage.

Cette méthode d'optimisation permet de répondre aux exigences de conception comme le comportement mécanique et la fonctionnalité, en plus d'optimiser la masse, la structure, le temps et le coût [120]. Donc, le modèle d'usage est déterminé par l'optimisation topologique de la fonction du produit par l'optimisation de la masse et de la structure.

Après optimisation de la structure initiale, le modèle d'usage optimisé doit être converti en modèle 3D. Ce modèle d'usage optimisé est modifié dans CATIA-V5 en fonction des besoins du

client et des fonctionnalités du produit, ainsi que des contraintes et capacités de FA. Il est à noter que le produit peut être présenté dans une grande diversité et le concepteur peut choisir entre ces modèles possibles.

Jusqu'à présent, une partie du modèle de produit en tant qu'ébauche 3D est déterminé, mais il est nécessaire de définir le processus et ses paramètres pour la production avec les technologies de FA. En conséquence, un modèle de fabrication sera prévu pour recueillir les informations essentielles pour la fabrication. Le modèle de fabrication sera expliqué dans la section suivante.

Modèle de fabrication

Le modèle de fabrication contient des informations de sélection de processus de fabrication. Cette information contient le type de processus et ses paramètres associés. Du point de vue de la fabrication, les processus de fabrication peuvent être réalisés en raison des formes et des qualités de surface que le processus peut effectuer [33, 30, 3].

Il est supposé que le produit doit être fabriqué par les technologies de FA. La Fabrication additive produit couche par couche les produits complexes basés sur le modèle CAO. Ce modèle 3D doit être converti en fichier STL (Standard Tessellation Language) en format standard et approprié pour la FA qui se compose de petits triangles [37]. Cette conversion doit être effectuée en haute résolution pour réduire les écarts entre le modèle CAO initial et le modèle discrétisé STL.
Ensuite, le tranchage est réalisé avec un logiciel spécifique compatible avec la machine et sa technologie. Le modèle de fabrication doit être identifié par le concept de peau-squelette qui est constitué de la peau et du squelette de fabrication :

Peau de fabrication La peau de fabrication est la surface qui est produite durant cette étape. Les caractéristiques de la peau sont créées à partir de squelettes de fabrication par une opération de balayage. Du fait de la stratégie de FA en tant que production couche par couche, les produits fabriqués par FA sont constitués d'accumulations de couches. La buse commence la production de la couche à partir des contours des couches qui sont considérées comme la peau de fabrication, puis une structure intérieure est créée qui peut être déterminée par le squelette de fabrication comme décrit dans ce qui suit.

Squelette de fabrication : Le squelette est la trajectoire d'écoulement et chaque processus de fabrication est supposé basé sur le flux de matière.

Le chemin d'outil de fabrication montre comment un produit est construit pendant la fabrication. L'orientation de la pièce et la structure de remplissage sont les paramètres qui déterminent le trajet d'outil de fabrication additive. Dans cette thèse, le squelette de fabrication est spécifié comme l'orientation du produit dans la plate-forme de construction de la machine. On suppose que l'orientation est définie comme un axe qui est perpendiculaire à la plate-forme de construction. L'orientation est présentée à travers les angles entre la partie et les axes $\boldsymbol{x}$, $\boldsymbol{y}$ et $\boldsymbol{z}$. Il convient de mentionner que l'orientation le long de l'axe $\boldsymbol{z}$ crée les différents motifs de remplissage à différent angles.

Cette stratégie de découpage et le chemin de la machine-outil sont définis comme des fichiers de G-code pour les machines. Ce fichier G-code est un langage machine qui définit le chemin de l'outil de fabrication et les paramètres. En fait, il s'agit d'un langage commun de planification de contrôle numérique qui est spécifié par les instructions sur l'endroit où se déplacer, la vitesse de mouvement et le chemin de mouvement. Il est développé pour guider les machines-outils informatisées et décrire les instructions sur les chemins d'outils à suivre pour la FA [153].

L'identification du modèle de fabrication nous aide à reconnaître les paramètres de fabrication et les critères significatifs :

Les paramètres de fabrication : L'identification des paramètres de fabrication est réalisée par trois activités d'analyse des technologies de FA, l'analyse des logiciels et des machines de FA, ainsi que l'analyse de la littérature.

Différentes technologies de FA sont analysées en fonction de leur processus. Ainsi, divers logiciels de découpage comme Cura, Slic3r et MakerBot. De plus, l'analyse d'autres recherches [49, 156, 48, 126, 127, 157] nous aide à trouver les paramètres de fabrication. Ces études permettent de déterminer les paramètres de fabrication.

Pour trouver les paramètres significatifs qui affectent les critères et contraintes importants, une analyse approfondie de la littérature est effectuée sur plusieurs études. Cette analyse nous aide également à reconnaître les critères de FA et les paramètres qui affectent ces critères. Le tableau 4.2 montre les critères et contraintes, et les paramètres qui sont évalués, ainsi que le

nombre de fois qui sont étudiés dans ces recherches. Ces chiffres présentent le degré d'importance des paramètres sur les critères souhaités.

Criteria	Mechanical behavior	Accuracy	Roughness	Build Time	Quality	Cost	Material
Parameters	Material/3	Geometry/2	Orientation/3	Orientation/5	Orientation/4	Part dimension/3	Orientation
	Infill structure/2	Print speed//2	Layer thickness	Geometry/3	Geometry	Technology/3	Part dimension
	Part dimension	Orientation	Part dimension	Layer thickness/2	Part dimension	Orientation/3	Geometry
	infill density	Layer thickness	Material	Part Dimension/2	Material	Material/2	Machine
	Orientation	Extruder temperatui	Machine	Infill Density/2	Machine	Machine/2	Tehnology
	Machine	Machine	Technology	Toolpath/2	Technology	Infill density	Layer thickness
	Technology	Part dimension		Print speed/2		Geometry/2	
		Scan speed		Technology		Print speed	
				Cooling fan speed		Production volume	
						Part placement	

Tableau 4.2 – Paramètres et critères de FA et leur degré d'importance dérivé de l'analyse de la littérature (30 articles)

L'épaisseur de la couche et l'orientation de la pièce sont les paramètres les plus importants entre ces paramètres de fabrication et ces deux paramètres sont communs à toutes les technologies de FA. Ces paramètres ont des effets importants sur les critères et contraintes du système de fabrication décrits ci-dessous :

Les critères et contraintes de fabrication : De nos jours dans ce monde industriel, le temps et la masse de matériau sont importants pour tous les systèmes de fabrication en tant que facteurs qui déterminent le coût du système de fabrication. Ainsi, le comportement mécanique, la qualité de surface et la précision dimensionnelle sont identifiés comme étant les principaux problèmes pour les secteurs industriels. Les caractéristiques telles que la production couche par couche et la structure intérieure des produits créent la différence entre les produits réalisé par FA et les autres produits qui sont fabriqués selon des méthodes de fabrication classiques. Ces critères sont impressionnés par les paramètres de fabrication, sur quoi les caractéristiques du modèle de produit final seront modifiées. Dans ce qui suit, ces critères et contraintes sont expliqués de manière exhaustive :

- **Temps de fabrication et masse de matériau :** Le temps de fabrication et la masse de matériau sont les premiers critères à analyser pour tous les systèmes de production. Pour FA, ces critères sont impressionnés directement en modifiant les paramètres de fabrication. Leurs tendances de modification peuvent être simulées grâce à un logiciel additif spécial pour chaque machine et technologie. Ces logiciels simulent le parcours de l'outil avant de lancer l'impression en fonction de la géométrie du produit, de l'orientation de la construction et des paramètres de fabrication. Il créée le fichier G-code qui contient le temps requis et la quantité de matériau extrudé pour estimer le temps écoulé et la masse de matériau pour l'impression.

- **Qualité de surface :** En conséquence de la fabrication en couches, la finition de surface des pièces de FA est excessivement rugueuse. Puisque cette qualité de surface a une influence sur les propriétés fonctionnelles du matériau, y compris le comportement mécanique, les propriétés optiques et le comportement de frottement, le contrôle de surface des produits est nécessaire [49, 162].

Pour étudier la qualité de la surface, la rugosité peut être analysée. Comme décrit dans ASME B46.1 [163], "R_a (rugosité) est la moyenne arithmétique des valeurs absolues des écarts de hauteur de profil par rapport à la ligne moyenne, enregistrés dans la longueur d'évaluation. R_a est la moyenne d'un ensemble de mesures individuelles de surfaces pics et vallées."

Dans le processus de AM, une faible rugosité de surface peut être créée par la tessellation du modèle CAO original (conversion du modèle CAO au fichier STL) qui est connue sous le nom d'erreur d'accord et la procédure de découpage utilisée pendant le processus de construction crée l'effet escalier par le dépôt de couche et il impressionne la rugosité de surface [49, 165]. Dans cette recherche, il est supposé que la conversion STL est effectuée en haute qualité avec de grands nombres du triangle et son effet est ignoré.

- **Comportement mécanique :** Les différents types de remplissage et les valeurs d'épaisseur de couche créent les différents niveaux de résistance du produit [168]. Aussi, il existe d'autres paramètres de fabrication tels que l'entrefer, la largeur de trame, le nombre et la largeur de la coque, l'angle de trame et l'orientation de la pièce qui affectent le comportement mécanique du produit. Pour le comportement mécanique, la résistance maximale à la traction (UTS) est prise en compte. Il est mesuré par la contrainte maximale qu'un matériau peut supporter au plus haut de la courbe de traction.

- **Précision dimensionnelle :** La précision obtenue pour la technologie de FA est un inconvénient dans l'utilisation de FA. Un grand nombre de paramètres affectent la précision du produit comme le retrait et les paramètres du processus comme l'épaisseur et l'orientation de la couche.

L'analyse fonctionnelle, la reconnaissance du modèle d'usage et la définition du modèle 3D, ainsi que l'identification de modèles de fabrication incluant ses paramètres et critères significatifs nous aident à construire notre nouveau modèle d'interface en tant que moteur de traitement d'interface.

Moteur de traitement d'interface :

Enfin, l'intégration des contraintes de fabrication dans la définition du produit se fait progressivement en tant que modèle d'interface. Le modèle d'interface est un résultat de cette approche pour

définir le produit qui démontre les relations entre les paramètres de la procédure de fabrication. En effet, il présente les informations nécessaires à la synthèse de la conception et de la fabrication. Il fournit les données fonctionnelles, la solution technologique en tant que sélection de matériaux et de processus et les valeurs d'attributs.

Les modèles d'usage et de fabrication doivent être analysés ensemble pour créer le modèle de produit final en utilisant le modèle d'interface. Pour définir le modèle d'interface pour la FA et utiliser ces modèles pour créer la procédure de fabrication, un nouveau moteur de traitement d'interface est développé, dérivé du modèle d'interface mais plus complexe et contenant des informations, des modèles et des outils. C'est une boîte noire pour l'utilisateur qui gère les caractéristiques FA et les produits avec toute connaissance de son fonctionnement interne. Il est constitué d'outils de calcul utilisés pour intégrer les contraintes et les attributs de fabrication dans la définition du produit. L'objectif est de trouver les paramètres de fabrication appropriés pour la production à travers une approche décisionnelle multicritères. Par conséquent, le moteur d'interface permet de compléter le modèle de produit en sélectionnant le processus, la machine et les paramètres de fabrication en fonction des critères tels que le temps, le matériau, la qualité de surface et le comportement mécanique des produits. Dans l'ensemble, l'objectif est de définir un modèle générique à adapter aux autres processus de FA. Ce moteur nécessite l'ébauche 3D (appelée modèle 3D dans la suite de ce manuscrit) du modèle d'usage, des paramètres de fabrication, des critères de fabrication importants, des caractéristiques du produit et des relations entre ces attributs.

Pour étudier simultanément ces critères, une approche décisionnelle multicritère semble utile. Il est décidé de fournir une optimisation bi-objective pour analyser notre problème de décision multicritères. Le temps de fabrication et le matériau comme principaux critères du coût du système de fabrication sont considérés comme les fonctions objectives de ce problème d'optimisation pour minimiser le coût total du système. Selon l'importance du comportement mécanique et de la rugosité de surface comme inconvénients des produits AM, ils sont supposés être des contraintes pour l'optimisation. Comme mentionné précédemment, l'épaisseur de la couche et l'orientation sont les paramètres de fabrication les plus importants de toutes les technologies de FA, ces paramètres sont déterminés en tant que variables de décision.

Problème d'optimisation bi-objectif : Un problème d'optimisation bi-objective continue est défini à l'intérieur de ce moteur pour optimiser le temps, la masse du matériau et la rugosité tout en ciblant un comportement mécanique souhaité.

Le vecteur à quatre composantes des variables de décision ($\boldsymbol{x}$) est présenté qui contient l'épaisseur de la couche et les angles d'orientation comme suit :

$$\boldsymbol{x} = \{\theta_x, \theta_y, \theta_z, L_t\} \tag{4.1}$$

où :

- L_t : Épaisseur de couche.
- θ_x, θ_y, θ_z : définit l'orientation, c'est-à-dire l'angle entre la partie et l'axe de $\boldsymbol{x}$, $\boldsymbol{y}$, et $\boldsymbol{z}$.

Le problème d'optimisation bi-objectif est écrit comme :

Minimize :

$$f_1(\boldsymbol{x}) = \text{Time}(\boldsymbol{x})$$

$$f_2(\boldsymbol{x}) = \text{Material}(\boldsymbol{x})$$

Sous les contraintes :

$$g_{R_\text{a}}(\boldsymbol{x}) \leq R_{\text{aMax}} \tag{4.2}$$

$$g_{\text{UTS}}(\boldsymbol{x}) \geq \sigma_{\text{Max}} \tag{4.3}$$

$$\boldsymbol{l_b} \leq \boldsymbol{x} \leq \boldsymbol{u_b}$$

avec :

$$\boldsymbol{x} = \{\theta_x, \theta_y, \theta_z, L_t\}$$

$$\boldsymbol{l_b} = \{-180^\circ, 0^\circ, -180^\circ, L_{t\text{Min}}\}$$

$$\boldsymbol{u_b} = \{180^\circ, 180^\circ, 180^\circ, L_{t\text{Max}}\}$$

Comme le montre la formulation mathématique, le premier objectif est le temps nécessaire à la machine pour la fabrication. Le deuxième objectif est la masse de matière consommée pour la fabrication. Une solution optimale pour la fabrication sera fournie en minimisant ces objectifs.

les vecteurs des bornes inférieure et supérieure des composantes de la variable de décision, l_b et u_b, montrent leurs valeurs minimum et maximum admissibles. La valeur de l'épaisseur de couche est comprise entre $L_{t\mathrm{Min}}$ et $L_{t\mathrm{Min}}$. Les angles d'orientation montrent l'orientation de la pièce dans la plate-forme ainsi que l'angle de remplissage de la pièce qui est déterminé par la rotation au long de l'axe $\boldsymbol{z}$ par θ_z. Pour considérer toutes les orientations possibles du produit dans l'espace, l'angle de $\boldsymbol{x}$ et $\boldsymbol{z}$ est compris entre $-180°$ et $180°$, et $\boldsymbol{y}$ est dans l'intervalle de $0°$ et $180°$.

Les fonctions objectives sont calculées par simulation de procédure additive pour chaque orientation et valeur d'épaisseur de couche par le logiciel de simulation additive pour chaque technologie et machine.

La première contrainte (équation (4.2)) fournit une relation entre l'épaisseur de la couche et l'orientation pour estimer la rugosité de surface afin de satisfaire la qualité de surface du produit.

L'équation (4.3) est utilisée pour présenter le comportement mécanique des produits AM. La résistance est formulée avec la contrainte mécanique maximale du produit (σ_{Max}) et la résistance maximale à la traction (UTS) du matériau qui dépend des paramètres de fabrication (orientation, épaisseur de couche, angle de remplissage, etc.). Cette contrainte montre que le produit de FA doit être plus résistant que le comportement souhaité. Les valeurs UTS pour différentes orientations et épaisseurs de couches sont obtenues par l'analyse de plusieurs expériences réalisées par d'autres chercheurs comme [156, 171, 172, 157, 170]. Il faut mentionner que ces expériences doivent être effectuées dans les mêmes conditions expérimentales, y compris le type de matériau, le type d'éprouvette et la température. De plus, d'autres paramètres de fabrication pour la fabrication des éprouvettes doivent être identiques.

Avant de résoudre ce problème d'optimisation, il est nécessaire de formuler ce problème d'optimisation bi-objectif incluant objectifs et contraintes.

Le temps et la masse du matériau sont calculés grâce à la simulation du parcours de l'outil par le logiciel FA et à l'analyse du fichier g-code. La rugosité est formulée grâce à des mesures expérimentales et le comportement mécanique des produits FA est analysé à travers des méthodologies expérimentales. Ces formulations en tant qu'outils de calcul et données collectées fournissent les conditions préalables pour résoudre ce problème d'optimisation.

Procédure de résolution : Pour résoudre ce problème d'optimisation bi-objectif, l'exécution de Cura en tant que logiciel open source dans MATLAB nous permet de trouver le temps de production et les valeurs de masse du matériau pour toutes les orientations possibles dans l'espace et toutes les valeurs admissibles de l'épaisseur de couche.

Non seulement, ce problème d'optimisation bi-objectif est un problème d'optimisation combinatoire et il est classé comme un problème NP-difficile, mais aussi, la simulation à travers le logiciel de FA et la création des fichiers g-code prennent beaucoup de temps. Par conséquent, pour trouver les solutions réalisables pour ce problème d'optimisation continue dans un délai raisonnable, un algorithme méta-heuristique semble utile. Ainsi, l'algorithme de NSGA-II est utilisé pour trouver les solutions optimales pour la fabrication.

Les entrées essentielles de ce problème sont le fichier STL, le fichier d'exécution du logiciel additif, la méthode de calcul de la rugosité, les données UTS et les paramètres de l'algorithme. Par cet algorithme, les meilleures solutions sont présentées et améliorées dans quelques générations comme le front de Pareto.

La recherche des paramètres de fabrication optimaux permet de fournir les informations essentielles pour notre modèle de produit qui sont expliquées dans la section suivante.

Modèle du produit

L'analyse du modèle FBS, du modèle d'usage, du modèle de fabrication et du moteur de traitement d'interface permet de fournir le modèle de produit. Ce modèle de produit comprend les informations requises pour fabriquer le modèle 3D par la technologie de FA. Il contient le matériau sélectionné et la technologie, le modèle d'usage manufacturable comme fichier CAO et fichier STL, les valeurs optimales des paramètres et critères de fabrication, ainsi que le code G optimal pour la fabrication.

L'approche DFM-peau et squelette pour FA basée sur la proposition 2 :

Considérer la deuxième proposition pour implémenter l'approche DFM-peau et squelette crée une différence dans cette approche. L'approche proposée contient plusieurs étapes :

- Analyse fonctionnelle et fourniture du modèle FBS.

- L'identification du modèle d'usage contient la peau et le squelette : Selon la première proposition, le modèle d'usage optimisé, incluant la peau et le squelette, est créé par optimisation topologique, cette proposition permet de définir la peau et le squelette séparément :

  - **Peau d'usage :** Elle est définie par l'optimisation topologique et c'est une surface sur laquelle le matériau circule.

  - **Squelette d'usage :** Les méthodes sont présentées pour déterminer ce squelette comme suit :

    * Algorithme de Power crust : Ce squelette d'usage fournit l'axe médian approximatif de la pièce comme une vue d'ensemble du produit et de son schéma général pouvant être présenté dans plusieurs solutions géométriques possibles qui satisfont aux contraintes physiques et aux exigences fonctionnelles. Power crust est un algorithme qui est utilisé pour construire le maillage de surface et l'axe médian approximatif. Power crust prend les points dérivés du fichier STL en entrée. Ensuite, la transformation de l'axe médian (MAT) en tant que représentation de forme squelettique de l'objet est approximée et la représentation de surface est créée par la transformation inverse [173, 33].

    * **Manuellement :** Squelette est spécifié en fonction du comportement spécial requis du produit en tant que fonctionnalité. Selon la forme obtenue par optimisation topologique, le flux de matière comme le squelette peut être facilement spécifié.

  - **Le modèle de fabrication :** Il se compose de la peau en tant que contours de l'orientation de la couche et de la pièce en tant que squelette. Selon la proposition 2, le squelette de fabrication doit être déterminé en fonction du squelette d'usage. Dans la thèse, il n'y a aucune possibilité de créer l'orientation de la pièce et de poursuivre l'approche DFM-peau et squelette. Le modèle 3D doit être défini en comparant de la peau et du squelette du usage et de la fabrication.

  - L'approche d'optimisation en tant que moteur de traitement d'interface sera créée en considérant d'autres paramètres pour la variable de décision sans considérer l'orientation de la pièce comme variable de décision.

– Définir le modèle de produit en fonction des résultats du moteur d'interface et de l'approche peux-squelette.

Ce modèle fournit une approche générale et intégrée permettant à la méthodologie de considérer simultanément les attributs d'usage, de conception et de fabrication. Cette approche aborde une méthodologie intégrée dans la Conception pour la fabrication additive (DFAM ou Design For Additive Manufacturing en anglais). Cette méthode permet de définir un modèle de produit en examinant de nombreux attributs, contraintes et critères de FA. Cette méthodologie est développée à travers une approche peux-squelette pour créer graduellement le modèle de produit final.

Dans la section suivant, cette approche proposée sera mise en œuvre dans la technologie de FA la plus populaire sous la forme de modélisation par dépôt de fil chaude (FDM) et deux études de cas sont utilisées pour montrer la fiabilité de cette approche pour la mise en œuvre industrielle.

L'application et validation dans la modélisation des dépôts de file chaude

La méthode de dépôt de file chaude (FDM), développée par Stratasys à Eden Prairie, au Minnesota, est l'une des techniques de la fabrication additive les plus largement utilisées qui a considérablement réduit le temps et le coût de développement du produit. L'application a été étendue aux diverses industries comme les industries médicales comme la fabrication d'implants biomédicaux ou de prothèses par le biais de procédés de moulage de précision, l'utilisation par des amateurs, des inventeurs, des bricoleurs et des propriétaires de petites entreprises, etc.

FDM est un procédé de AM qui utilise un filament thermoplastique (ABS, PLA, ...) par dépôt fondu. Les couches sont fabriquées par extrusion du filament qui est extrudé par une buse. La buse contient des éléments chauffants résistifs qui maintiennent le plastique à une température juste au-dessus de son point de fusion, de sorte qu'il s'écoule facilement à

travers la buse et forme la couche. Le plastique durcit immédiatement après l'écoulement de la buse et se lie à la couche inférieure. Il trace la géométrie en coupe transversale de la pièce couche par couche, puis se déplace verticalement pour répéter le processus et produire les couches de haut en bas pour terminer la fabrication de la pièce [37, 174].

La grande facilité d'utilisation de la technologie FDM et les effets du processus de fabrication, en particulier les caractéristiques uniques des technologies de FA, encouragent le chercheur à analyser ce processus de fabrication. L'approche de conception intégrée est utile pour analyser le produit qui est produit par les technologies FA depuis la première étape du développement du cycle de vie du produit jusqu'à la dernière étape pour définir un modèle de produit. Par conséquent, l'étude est commencée par une étude de cas comme un crochet de sac et cette étude continuera à s'appliquer dans une autre étude de cas comme une fusée de roue qui est plus complexe et utile. Cette deuxième étude de cas peut montrer la capacité des techniques FA à apporter de la vie aux pièces brisées et à réutiliser le produit.

Étude de cas 1 : crochet de sac

Dans cette recherche, un crochet de sac est étudié comme notre étude de cas pour valider l'approche proposée. Le crochet de sac est un accessoire utilisé pour accrocher le sac à main sur une table. Il doit être mince, léger et s'intègre même dans le plus petit sac. L'analyse des besoins montre que l'ABS (Acrylonitrile Butadiène Styrène) est un choix approprié comme matière première pour le crochet de sac en raison de ses caractéristiques telles que la recyclabilité, la disponibilité et le coût. FDM (ou Fused Deposition Modeling en anglais) comme les technologies de AM est choisi pour fabriquer le produit sur ABS [34]. Les dimensions initiales de crochet sont définies égales à $45 \times 90 \times 10\,\text{cm}$ qui sera optimisé grâce à cette approche proposée.

La méthodologie proposée sera appliquée pour présenter les solutions optimales de modèle 3D en utilisant le modèle d'usage et l'analyse du système de fabrication comme modèle de fabrication pour créer un moteur de traitement d'interface pour fournir un modèle de produit pour ce crochet de sac. Les étapes de cet approche pour le crochet est comme suite :

– **Analyse fonctionnelle pour le crochet de sac :** On suppose que le crochet doit

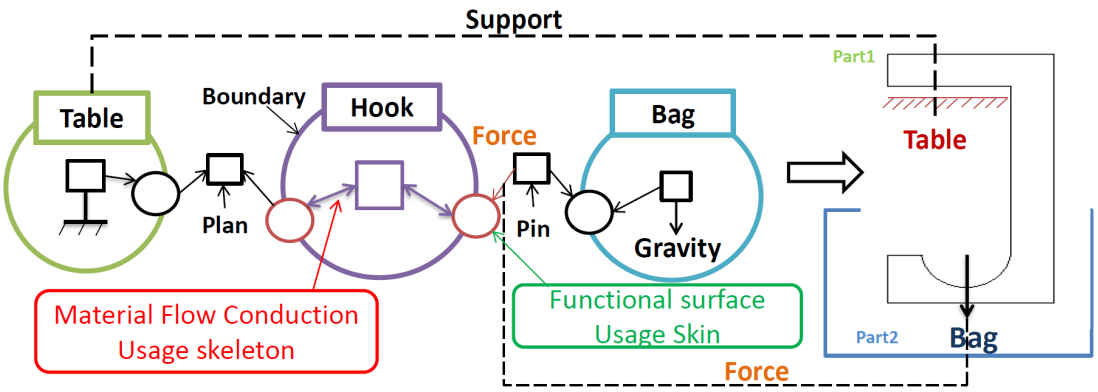


FIGURE II.4 – Modèle FBS de crochet

tolérer un maximum de 7.5 kg et il doit être aussi léger que possible pour pouvoir facilement le mettre dans le sac. L'analyse fonctionnelle est fournie par le modèle FBS à travers la détermination de la structure initiale en fonction de la fonction et du comportement souhaités du produit. Le crochet de sac doit tolérer le poids du sac comme fonction principale et la table est un support pour l'aider dans cette fonction. Ce modèle identifie la peau d'usage et le squelette, ainsi que le volume initial de la pièce ; par conséquent, le volume initial de la pièce est obtenu en considérant la surface fonctionnelle, la relation entre le support et la conduction du flux de matériau, la fonction du produit en tant que force appliquée et la performance mécanique. Le modèle FBS (illustré dans la figure II.4) est utilisé pour déterminer la forme initiale (structure) en fonction de la fonction et du comportement souhaités du produit.

– **Du modèle d'usage au modèle 3D :** L'optimisation topologique est sélectionnée pour fournir un modèle d'usage optimisé en optimisant la masse et la structure du produit en raison de son comportement mécanique. Le peau d'usage est optimisé et le squelette est déterminé à travers cette peau et la fonctionnalité du crochet (voir Figure II.5). Il est nécessaire de définir le modèle 3D entre plusieurs morphologies possibles. La forme finale en tant que modèle 3D et fichier STL est préparée (Figure II.5) concernant le modèle d'usage présenté, la fonctionnalité et différentes questions comme l'épaisseur de paroi minimum requise et l'utilisation des congés.

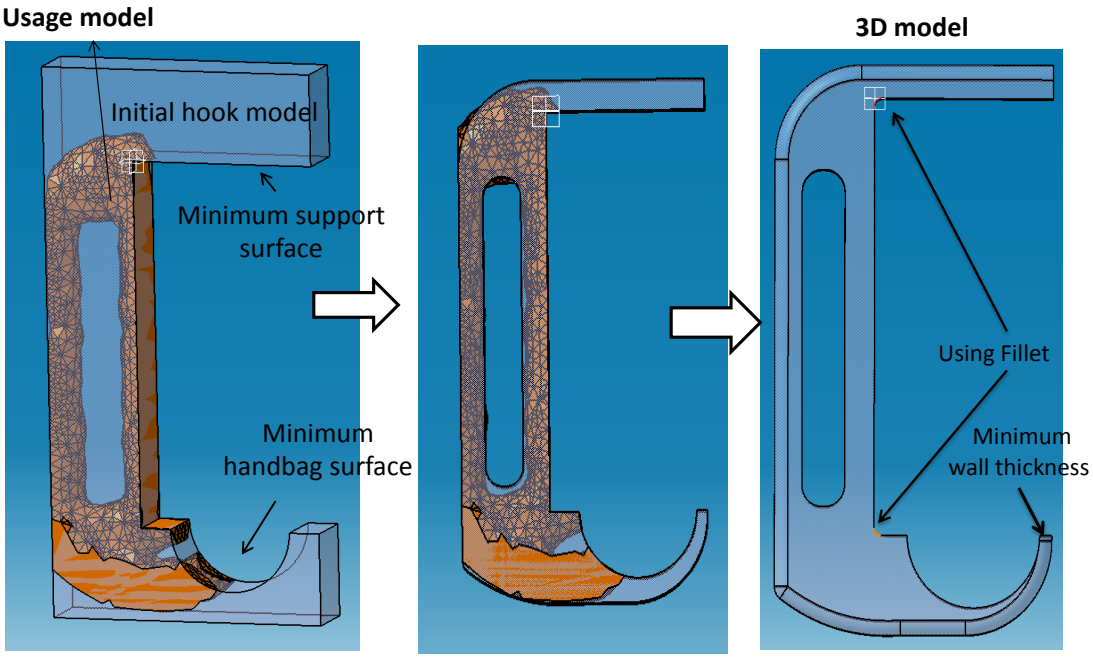


FIGURE II.5 – Du modèle d'usage au modèle 3D

– **Modèle de fabrication :** Le modèle de fabrication est déterminé en parallèle. Les contours de la couche et l'orientation de la pièce sont la peau de fabrication et le squelette respectivement. L'orientation spécifie l'angle de remplissage et la direction de la pièce. Ce modèle de fabrication contient les couches avec ses contours et l'orientation de la pièce qui est perpendiculaire à la plate-forme de construction (Figure II.6).

  Pour fabriquer le crochet, le modèle CAO doit être converti en fichier STL comme format de FA approprié. Ce fichier STL est créé en haute résolution et avec un grand nombre de triangles pour minimiser l'imprécision dimensionnelle et la rugosité.

  une analyse complète est effectuée sur la littérature (131 articles) pour identifier les paramètres et les critères significatifs (tableau 4.3). Les paramètres de fabrication importants sont identifiés comme l'épaisseur de la couche, l'orientation, la température d'impression, la structure de la coque, la structure intercalaire, le radier et la structure de support, ainsi que la vitesse d'impression, de déplacement et de rétraction. Différentes valeurs de paramètres créent le niveau différent de critères de fabrication.

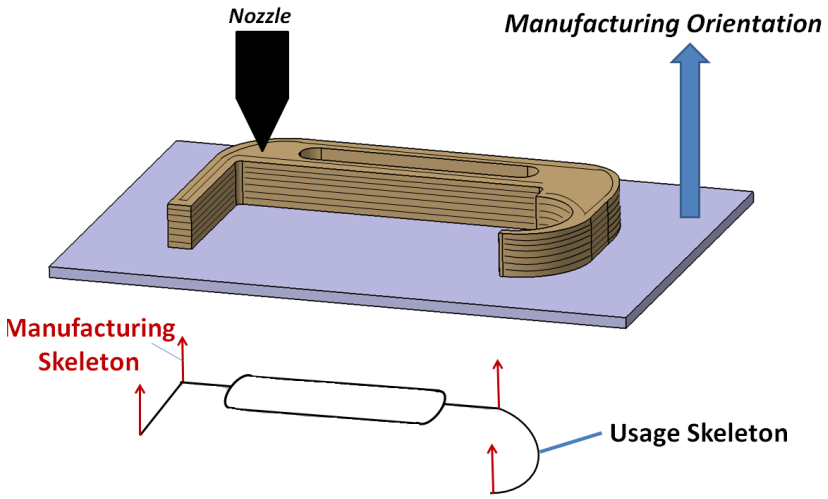


FIGURE II.6 – Le modèle peux-squelette de fabrication

Criteria	Mechanical behavior	Accuracy	Roughness	Build Time	Quality	Cost	Min material
Investigation number	63	33	27	14	9	7	2
Parameters	Orientation/27	Layer thickness/21	Orientation/16	Layer thickness/10	Layer thickness/5	Orientation/7	Orientation/2
	Raster angle/34	Orientation/19	Layer thickness/11	Orientation/9	Toolpath/4	Layer thickness	Shell width
	Air gap/17	Raster width/9	Raster width/9	Raster angle/8	Geomtry/3	Shell width	Layer thickness
	Layer thickness/19	Raster angle/9	Raster angle/8	Raster width/6	Ext. temp/3	Air gap	Raster width
	Raster width/18	Air gap/7	Shell width/3	Infill Density/2	Raster width/2	Raster width	Raster angle
	Ext. temp/6	Travel speed/4	Travel speed/2	Air gap/3	Infill structure/2	Raster angle	
	Plat. temp/4	Infill structure/3	Air gap/2	Shell width/5	Print speed/2	Geometry	
	Infill Density/4	Plat.Temp/3	Infill Density/2	Shell number/2	Orientation/2	Pre-processing	
	Bead width/3	Dimension/3	Radio/2	Infill structure/2	Travel speed	Process	
	Infill structure/6	Print speed/2	Infill structure	Travel speed	shrinkage rate	Post-processing	
	Shell number/3	STL/2	Shell number	Part location	Raster angle		
	Color/2	Ext. Temp/2	Tip Deimension	Ext. Temp	Plat. temp		
	Material type	Shell width/3	Road width	Plat. Temp	part palacement		
	Scan speed	Geometry/2	STL	Part Dimension	part dimension		
	Part location	Infill Density	Inclination	Materila type	Tip dimension		
	Machine	Shell number		STL	Road width		
	Cooling fan speed	Cooling fan speed		Print speed	Scan speed		
	Shell width	Part location			Radio		
	Part dimension	Part placement			Infill Density		
	Strain rate	Deposition angle			Shell number		
	Deposition Density	Road width					

TABLEAU 4.3 – Paramètres et critères dérivés de l'analyse de la littérature pour FDM

Température de buse	230 °C
Température de la plateforme	110 °C
Diamètre de la buse	0.4 mm
Remplissage	100 % - linéaire
Nombre de contour	2
Vitesse de déplacement	$130\,\mathrm{mm\,s^{-1}}$
Vitesse de remplissage	$90\,\mathrm{mm\,s^{-1}}$
Vitesse du contour	$40\,\mathrm{mm\,s^{-1}}$
Vitesse plancher-toit	$90\,\mathrm{mm\,s^{-1}}$
Support	(20 %) 0.2 mm
Angle de support	68°
Vitesse de rétraction	$25\,\mathrm{mm\,s^{-1}}$

Tableau 4.4 – Fabrication paramètres

– **Moteur de traitement d'interface :** Après reconnaissance du modèle d'usage et de fabrication simultanément, le moteur de traitement d'interface est présenté. Les paramètres de fabrication sont supposés dans ce moteur comme tableau 4.4. Ce moteur contient des outils de calcul, un modèle d'optimisation et une méthodologie de résolution.

Les logiciels de génération de trajectoire comme Cura et Makerbot fournissent une simulation avant l'impression, le temps et la masse du matériau sont également estimés en fonction des paramètres. Dans cette étude, Cura en tant que logiciel open source est modifié en fonction du paramètre Makerbot. L'exécution de Cura dans MATLAB permet de créer un fichier de G-code et de calculer le temps et la masse de matériau pour chaque épaisseur de couche et toutes les orientations possibles.

Les fichiers de G-code illustrent le chemin de l'outil, chemin définit par les coordonnées des points de passage de la buse pour fabriquer le produit. Ce chemin d'outil est créé en raison de l'extrusion matérielle dans FDM. Le matériau extrudé comme valeur E dans le fichier G-code permet de calculer la masse du matériau par Équation (4.4) et (4.5) en raison de cette réalité que le volume de matériau extrudé provenant de la buse est égal au volume d'extrusion chemin parcouru par la buse. Dans ces équations, L est la distance entre les coordonnées et e est la largeur d'extrusion qui est égale aux diamètres des buses (0.4 mm), le diamètre des filaments (d) est 1.75 mm et ρ_{ABS} est la densité ABS ($1.04\,\mathrm{g/cm^3}$). F est un autre paramètre du fichier G-code en tant que

$$R_{\mathrm{a}}(\alpha, L_t) = \begin{cases} 70\dfrac{L_t}{\cos(\alpha)} & 0 \leq \alpha \leq 70^\circ \\ 1000 L_t \sin\left(\frac{90^\circ-\alpha}{4}\right)\tan(90^\circ-\alpha) & 70^\circ < \alpha \leq 90^\circ \\ 70\dfrac{L_t}{\cos(\alpha-90^\circ)}(1+W) & 90^\circ < \alpha \leq 135^\circ \\ 1000\frac{L_t}{4} - \frac{(R_1^2+R_2^2)(1-\frac{\pi}{4})\sin(90^\circ-\alpha)}{1000 L_t} + \ldots & \\ \frac{\left((R_1^2-R_2^2)(1-\frac{\pi}{4})\right)^2}{(1000L_t)^3}\frac{\sin^2(90^\circ-\alpha)}{\cos(90^\circ-\alpha)} & 135^\circ < \alpha < 160^\circ \\ 1000\frac{L_t}{2}\cos(90^\circ-\alpha) & 160^\circ \leq \alpha \leq 180^\circ \end{cases} \tag{4.6}$$

vitesse pour calculer l'heure écrite en tant que temps écoulé.

$$E = \frac{4L.e.L_t}{\pi d^4} \tag{4.4}$$

$$M = \rho_{\mathrm{ABS}}.\pi\frac{d^4}{4}E \tag{4.5}$$

Une estimation hybride est réalisée par [49] par l'analyse et la comparaison d'autres modèles existait dans la littérature [48, 164, 181] et des données expérimentales. Ce modèle estime la rugosité de surface en fonction de l'angle de dépôt différent (α) et de l'épaisseur de la couche. Dans cette équation, $w = 0.2$ est le paramètre d'ajustement fixe sans dimension pour les facettes supportées basé sur une mesure expérimentale pour tous les systèmes FDM. Dans cette formulation, $R_1 = 0.045$ et $R_2 = 0.01$ sont respectivement des congés et des rayons de coins [182]. Un algorithme est écrit pour appliquer cette formulation dans le modèle mathématique :

* Normal ($\boldsymbol{n}_{\boldsymbol{T}_{\mathrm{j}}}$) de chaque facette du fichier STL est obtenu par calcul de maillage normal pour chaque maillage triangulaire.

* L'orientation est créée par la matrice de rotation (R). Cette matrice de rotation fait tourner le vecteur normal et tangent de chaque facette le long des axes x, y et z par les angles de rotation de θ_x, θ_y et θ_z (Équation (4.7)).

$$R_x = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_x & -\sin\theta_x \\ 0 & \sin\theta_x & \cos\theta_x \end{bmatrix} R_y = \begin{bmatrix} \cos\theta_y & 0 & \sin\theta_y \\ 0 & 1 & 0 \\ -\sin\theta_y & 0 & \cos\theta_y \end{bmatrix} R_z = \begin{bmatrix} \cos\theta_z & -\sin\theta_z & 0 \\ \sin\theta_z & \cos\theta_z & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$R = R_x \times R_y \times R_z \tag{4.7}$$

* L'angle de dépôt (α_{T_j}) est calculé par l'équation (4.8), car c'est l'angle entre le vecteur tangent et le vecteur vertical ($\boldsymbol{z}$) comme direction de stratification.

$$\alpha_{T_j} = 90^\circ - \arccos \frac{\boldsymbol{n}_{\boldsymbol{T}_j}.\boldsymbol{z}}{|\boldsymbol{n}_{\boldsymbol{T}_j}|.|\boldsymbol{z}|} \tag{4.8}$$

* La valeur de rugosité est calculée par Équation (4.6) pour chaque facette. La valeur de rugosité maximale est prise comme rugosité du produit.

Le comportement mécanique des produits AM a été analysé par des approches expérimentales réalisées par [156, 171, 157, 170, 186]. Les données souhaitées sont recueillies à partir de ces recherches en considérant les mêmes conditions expérimentales, y compris le type de matériau, le type d'éprouvette, la température et les paramètres de fabrication des spécimens. Selon ASTM "Méthode d'essai standard pour les propriétés de traction des plastiques", les échantillons sont fabriqués dans différentes orientations et valeurs d'épaisseur de couche sur ABS-M30. Le testeur de traction Instron est utilisé pour obtenir les données expérimentales. Les valeurs UTS collectées pour différentes valeurs d'épaisseur de couche et types d'orientation spécifiques (voir la figure II.7) sont résumées dans le tableau 4.5.

Cette information nécessaire et les outils de calcul préparent les conditions préalables à la création d'un problème d'optimisation bi-objectif. Le comportement mécanique des produits en tant que critère significatif ne doit pas être ignoré, mais les données UTS ne sont pas suffisantes pour développer un méta-modèle et les utiliser dans un problème d'optimisation continue. Par conséquent, le problème est défini dans deux types de problèmes continus et discrets. Le problème d'optimisation continue bi-objectif est utilisé pour optimiser le temps et le matériau en ce qui concerne la rugosité en tant

l'Orientation	Plat ±45°	Plat 0/90°	sur le bord ±45°	sur le bord 0/90°	Vertical ±45°	vertical 0/90°
θ_x	0°	0°	0°	0°	90°	90°
θ_y	0°	0°	90°	90°	0°	0°
θ_z	0°	45°	0°	45°	0°	45°
L_t [mm]	UTS values [MPa] for different orientation					
0.1	32.8	30	31.9	33.5	30.7	30.9
0.13	27.8	30	29.6	25.7	29.11	30
0.2	27.5	-	-	-	-	-
0.25	27.3	32.7	25.4	29	-	-
0.33	28.94	-	-	31.64	-	24.72
0.35	20.22	27.35	-	22.7	-	-

TABLEAU 4.5 – Types d'orientation et ses données UTS pour différentes épaisseurs de couche

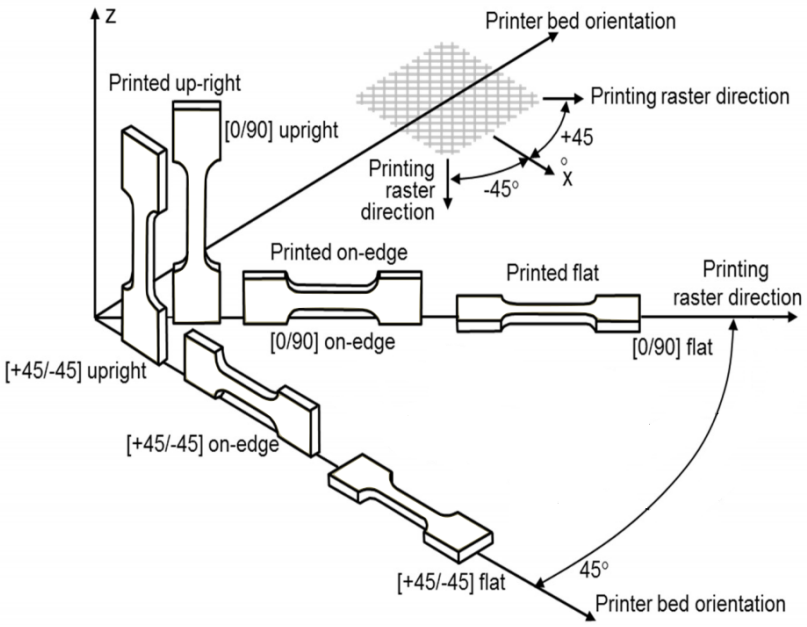


FIGURE II.7 – Types de l'orientation [170]

que fonction de contrainte. Ensuite, un problème discret lié aux valeurs de UTS est extrait du continu et il est résolu.

Pour résoudre ce problème d'optimisation, l'algorithme NSGA-II nécessite un fichier STL, un fichier d'exécution Cura, un calculateur de rugosité et des données UTS. La valeur maximum désirée pour la rugosité est considérée comme ($R_{\mathrm{aMax}} = 20\,\mu\mathrm{m}$) et σ_{Max} est calculé en raison de la théorie du faisceau, de la force appliquée et de la dimension du crochet ($\sigma_{\mathrm{Max}} = 31\,\mathrm{MPa}$). L'algorithme NSGA-II est complété en quelques générations pour trouver le front de Pareto comme solutions optimales.

Un ordinateur avec le processeur Intel (R) Xeon (R) et 12 Go de RAM est utilisé pour obtenir les résultats pendant 6 heures et 45 minutes comme durée d'exécution totale. Les paramètres de l'algorithme sont : Numéros d'exécution = 2, Numéros de population = 100, Numéros d'itération = 50, Indice de croisement = 20, Indice de mutation = 10, Probabilité de mutation = 0.25.

Les solutions Pareto obtenues pour les problèmes d'optimisation continue et discrète sont indiquées sur la figure II.8, le tableau 4.6 et 4.7. Toutes les solutions réalisables comme les solutions continues sont montrées par des étoiles et son Pareto optimal comme des cercles sont numérotés. Les solutions réalisables pour le problème discret sont démontrées par des carrés. Le front de Pareto pour le problème discret est illustré par des cercles et nommé alphabétiquement.

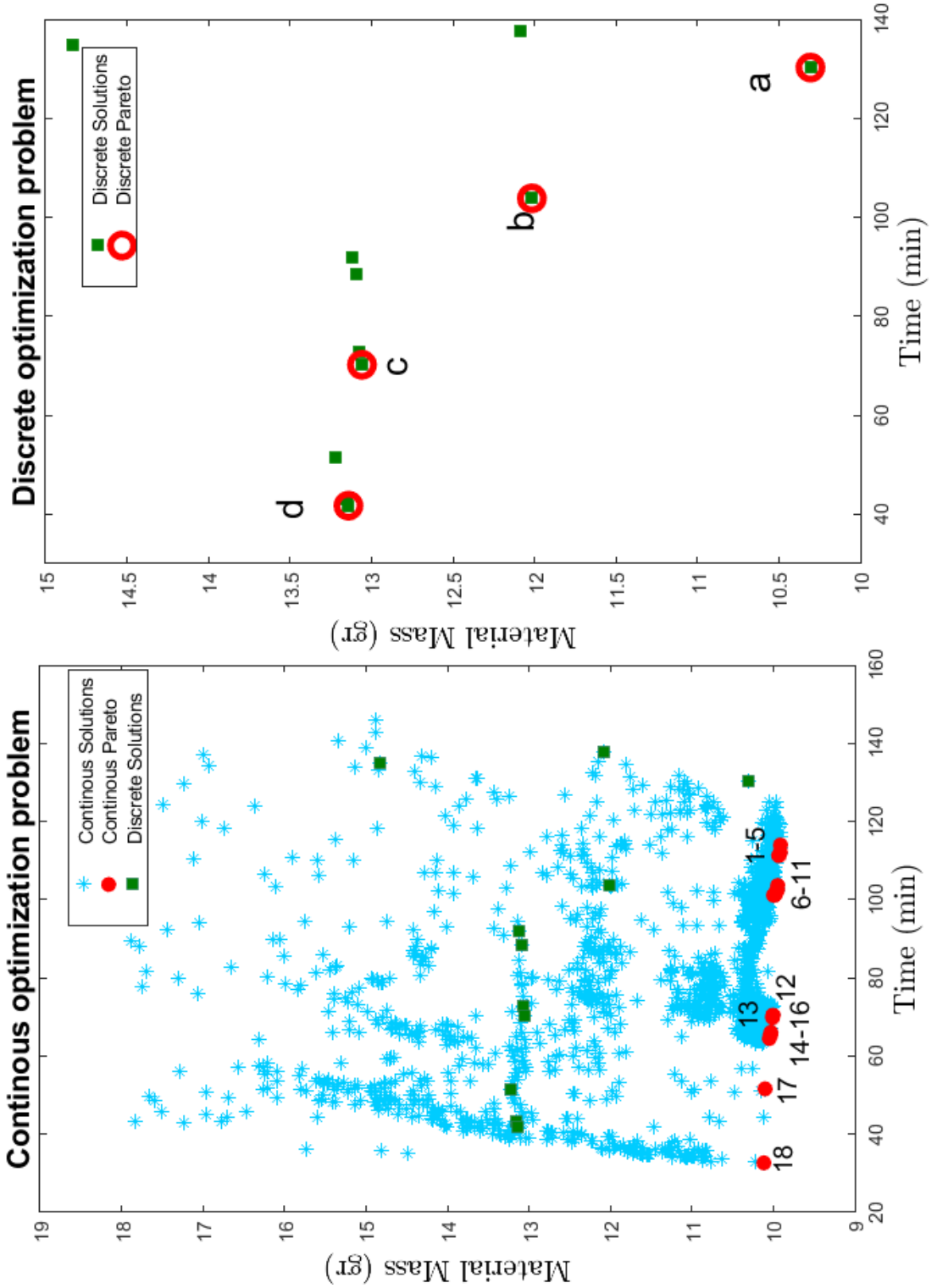


FIGURE II.8 – Solutions optimales obtenues pas NSGA-II pour le crochet de sac

Selon les résultats obtenus, il est conclu que :

* Dans un cas continu, la masse et le temps sont modifiés par 2 % et le facteur de 2,38 (238 %) respectivement. Pour un problème discret, la variation de masse est 20 % et le facteur temps est de 1.48 (148 %). Ainsi, le problème discret fournit une plus grande variation pour la masse et la rugosité du matériau.
* Les solutions (a) et (b) démontrent que la fabrication de crochets dans l'orientation de $\pm 45°$ nécessite plus de matière alors qu'elle est plus rapide que l'angle de $0/90°$. Les solutions (c) et (d) montrent que le crochet est fabriqué plus rapidement dans une orientation plate, mais qu'il consomme plus de matériau pour la structure du radier.
* Dans le problème discret, l'orientation vers le haut n'est pas optimale car elle consomme plus de temps et de matériel que d'autres en raison de la construction du support.
* Le Pareto continu n'inclut pas les orientations discrètes car elles nécessitent plus de matériel et de temps que les autres.

Enfin, la solution (d) comme une solution plus rapide est sélectionnée pour fabriquer le crochet par Makerbot Replicator 2X, non seulement, elle satisfait la contrainte de comportement mécanique, mais aussi, elle est moins rugueuse que la solution (a) et (b). La solution (c) ne satisfait pas non plus la résistance souhaitée et nécessite une nouvelle conception du crochet.

– **Modèle de produit :** Le modèle de produit est créé grâce à la collecte d'informations basée sur le modèle peau-squelette et les résultats du moteur de traitement d'interface. Ce modèle de produit se compose d'un modèle FBS, d'un modèle d'usage, d'un modèle 3D, de paramètres et critères optimaux et d'un fichier G-code optimal qui illustre le chemin d'outil de fabrication. Enfin, le crochet est fabriqué en utilisant le MakerBot Replicator 2x.

Pour définir cette approche pour le crochet basée sur la proposition 2, l'optimisation topologique et l'algorithme Power crust sont utilisés pour définir respectivement la peau et le squelette d'usage, mais aucune méthode n'est trouvée encore pour poursuivre notre

Sol.	L_t [mm]	θ_x [°]	θ_y [°]	θ_z [°]	Time [min]	Material [g]	R_a [µm]
1	0.11	132.89	125.75	−87.31	113.99	9.91	19.53
2	0.11	133.12	125.44	−87.31	112.08	9.91	19.80
3	0.11	133.25	125.55	−87.19	112.00	9.92	19.74
4	0.11	133.22	125.88	−87.64	111.31	9.93	19.79
5	0.11	133.05	125.90	−87.65	111.26	9.94	19.87
6	0.12	141.90	125.38	−88.20	103.08	9.95	18.51
7	0.12	141.93	125.41	−88.21	101.37	9.98	18.50
8	0.12	141.96	125.42	−88.24	101.14	9.98	18.59
9	0.12	141.99	125.42	−88.25	101.12	9.99	18.48
10	0.12	141.90	125.37	−88.20	102.25	9.96	18.56
11	0.12	141.92	125.41	−88.21	101.91	9.97	18.54
12	0.18	40.00	147.91	−25.01	70.45	10.00	19.69
13	0.18	39.04	148.03	−24.95	69.81	10.01	19.06
14	0.19	44.33	169.90	−45.05	66.06	10.03	19.60
15	0.2	143.36	150.35	−88.75	65.56	10.03	19.91
16	0.2	143.34	151.53	−88.75	64.48	10.05	19.76
17	0.26	140.40	156.61	−73.35	51.60	10.10	19.60
18	0.28	−179.84	0.26	−4.48	33.66	10.12	19.56

TABLEAU 4.6 – le front Pareto de problème d'optimisation continue bi-objectif pour le crochet

Sol.	L_t [mm]	Orientation	Time [min]	Material [g]	UTS [MPa]	R_a [µm]
a	0.1	On-edge ±45°	103.82	12.01	31.90	19.04
b	0.1	On-edge 0/90°	130.24	10.31	33.50	19.04
c	0.13	Flat 0/90°	70.18	13.05	30.00	9.10
d	0.25	Flat 0/90°	41.73	13.14	32.70	17.50

TABLEAU 4.7 – le front Pareto de problème d'optimisation discrète bi-objectif pour le crochet

FIGURE II.9 – Fusée de la roue cassée

approche proposée.

Étude de cas 2 : fusée de la roue

Une autre caractéristique qui encourage les fabricants à utiliser la fabrication additive comme nouvelle technique de production donne vie aux produits qui sont cassés dans certaines parties. Cette technique apporte l'opportunité de réutiliser les produits.

Dans cette étude, on considère qu'un véhicule pour enfant est brisé dans la fusée de la roue avant par un choc comme le montre la figure II.9.

Pour produire cette fusée pour la réutilisation du véhicule, ainsi que pour améliorer la qualité du produit et ses performances, l'approche de DFM-peau et squelette comme méthodologie proposée dans cette thèse sera utilisée.

Premièrement, en tant qu'intrant essentiel de cette approche et de tout le cycle de développement du produit pour la conception et la fabrication, les spécifications du produit doivent être préparées en fonction des exigences du client. À cet effet, d'abord la dimension et la fonctionnalité du produit est étudiée. La figure II.10 illustre les dimensions et la fonctionnalité du véhicule. Comme le montre la figure II.11, deux forces de $\boldsymbol{F_F}$ et $\boldsymbol{F_B}$ sont les forces qui sont appliquées aux roues avant et arrière. De plus, $\boldsymbol{G}$ est une force

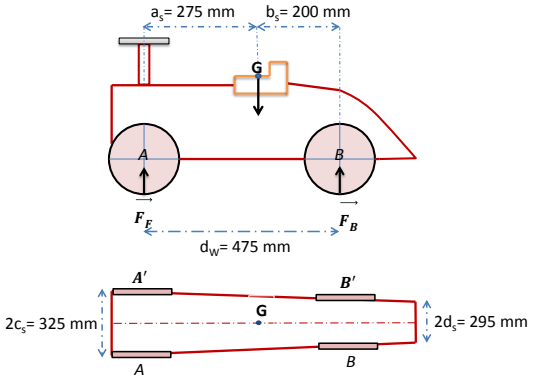


FIGURE II.10 – Dimensions du véhicule et fonctionnalité

créée en raison du poids de l'enfant. Dans cette étude, on suppose que kid crée la force égale à $G = m \times g$ comme $m = 20\,\text{kg}$. Pour calculer la force appliquée, l'analyse statique est effectuée cet analyse est fait pour éviter de casser à nouveau la fusée lorsque l'enfant crée un choc. les analyse statique nous permette de calculer la force applique au fusée ($F_T = 118.81\,\text{N}$). Cet analyse nous permettre de commencer notre approche :

– **Modèle FBS :** Analyse statistique montre que deux types de force sont imposés à l'axe et la fusée qui sont dérivés du poids du gamin et de la force qui est imposée au moment de l'accident qui sont représentés sur la figure II.12. Comme illustré sur cette figure, la fusée est en relation directe avec l'axe et la biellette de direction. Il y a une liaison complète comme logement entre l'axe et la fusée. La force créée par la situation de choc est appliquée directement à l'axe et elle est transformée en fusée. L'axe est le support de cette fusée. Le tirant de direction est relié à la fusée par un pivot comme liaison. La carrosserie tolère la force imposée par le poids des enfants. Comme mentionné précédemment, ce modèle décrit la situation de choc, donc, la force qui est appliquée à partir de la paroi est également montré. Les roues sont également créées la force qui est transformée en axe. Ces roues sont en relation avec le sol. Ainsi, ce modèle FBS nous permet de déterminer la fonctionnalité du produit. Par conséquent,

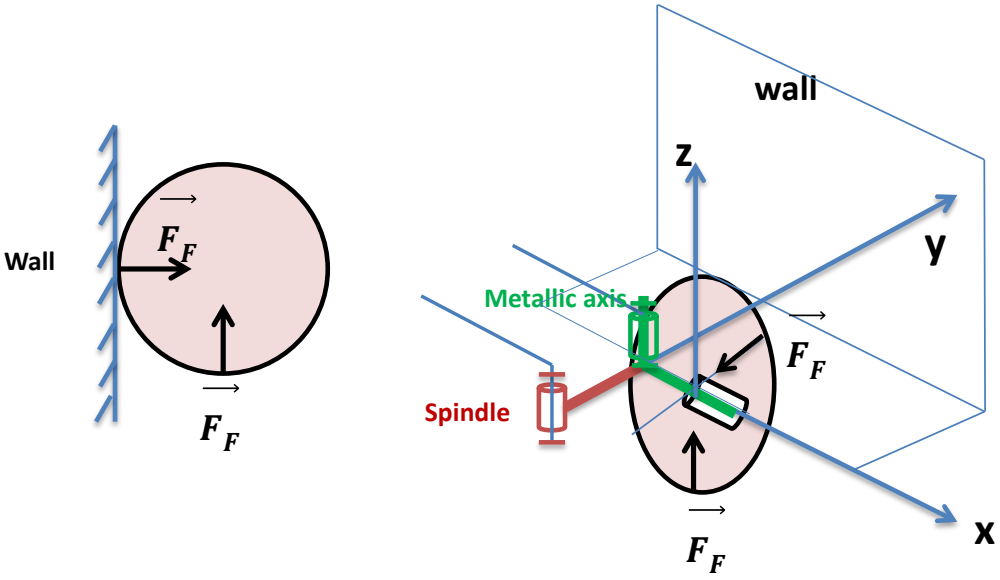


FIGURE II.11 – La force appliquée aux roues

ce modèle FBS nous aide à reconnaître le modèle d'usage dans ce qui suit.

– **Du modèle d'usage au modèle 3D :** Le modèle d'usage et, par conséquent, le modèle 3D est une ébauche 3D du modèle d'usage (appelée modèle 3D dans la suite de ce manuscrit) seront fournis dans certaines étapes : Le modèle initial est créé dans CATIA qui est dérivé de la forme initiale du produit existant. Puis, ce fichier STL est chargé dans Inspire pour fournir une structure optimale grâce à l'optimisation topologique. Ce modèle d'usage est converti dans le fichier STEP et il est chargé dans CATIA. Le modèle 3D initial est modifié sur la base de ce modèle d'usage optimisé comme le montre la figure II.13. Ce modèle 3D est obtenu en fonction de la fonctionnalité du produit.

– **Modèle de fabrication de FDM :** Comme la FA est utilisé pour fabriquer la fusée, le modèle 3D du produit doit être converti en fichier STL en tant que format standard pour les technologies de FA.

  En raison de la manière de construction de la couche, la buse commence la production de la couche à partir des contours des couches qui sont considérées comme la peau de fabrication, puis, la structure intérieure est créée qui peut être déterminée par

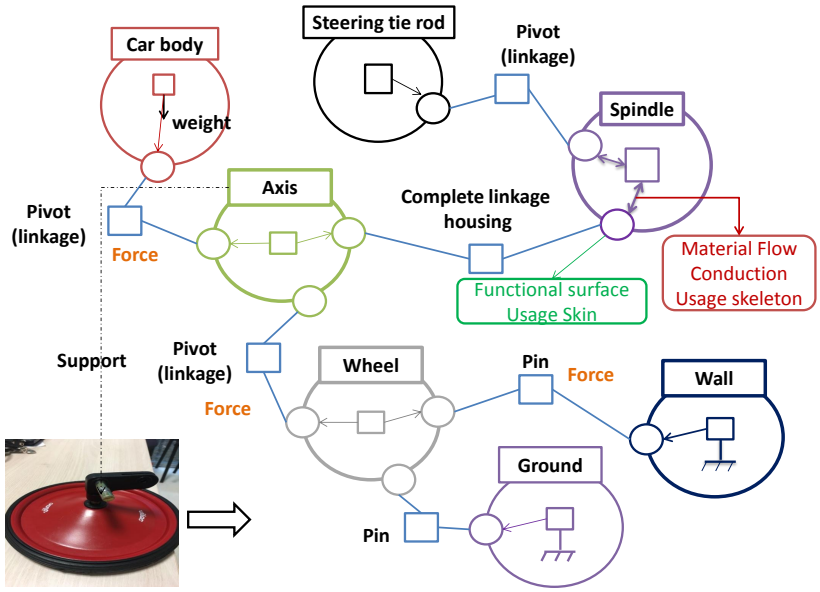


FIGURE II.12 – Modelé FBS de la fusée de la roue

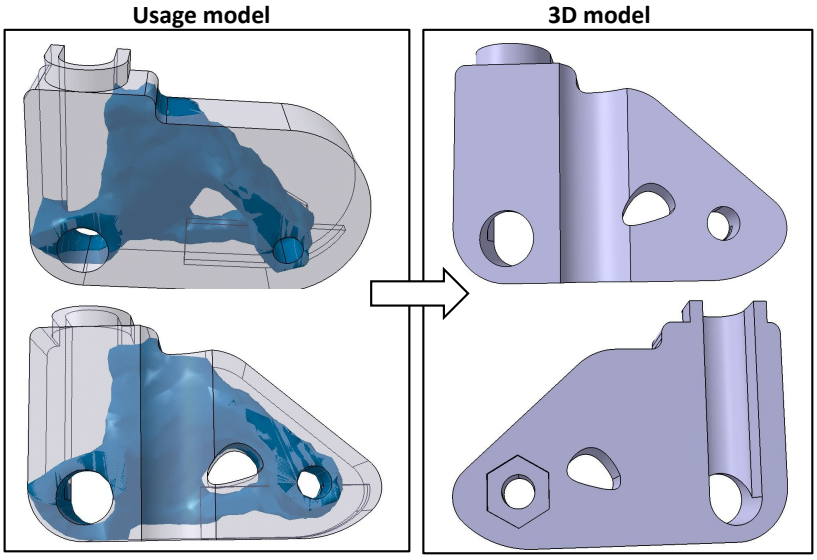


FIGURE II.13 – Modèle 3D de la fusée

le squelette de fabrication comme orientation de la pièce. Les mêmes paramètres de fabrication existent également pour la production de la technologie de FA avec FDM qui nous permet de définir le moteur de traitement d'interface.

– **Traitement d'interface Moteur de la fusée de roue :** Ce moteur de traitement d'interface est une interface entre l'usage et le modèle de fabrication qui nous aide à fournir le modèle de produit basé sur l'optimisation des paramètres de fabrication en fonction des critères souhaités.

Pour cette étude de cas, il est supposé que la valeur maximale de la rugosité est de $R_{\mathrm{aMax}} = 50\,\mu\mathrm{m}$ et l'analyse des éléments finis est effectuée pour calculer la valeur de σ_{max} égale à $5.24\,\mathrm{MPa}$.

À cette fin, notre problème d'optimisation bi-objectif est résolu grâce à l'utilisation de l'algorithme NSGA-II. Le fichier d'entrée de cet algorithme est le fichier STL du modèle 3D et les mêmes paramètres sont considérés pour l'algorithme. Comme la première étude de cas, le problème d'optimisation est réalisé dans deux types de problèmes continus et discrets. Premièrement, le continu est résolu et l'espace discret est extrait de cet espace continu. Les résultats obtenus de ces problèmes d'optimisation, y compris les paramètres de fabrication optimaux en tant que front de Pareto, sont décrits dans la section suivante :

Résultats :

Pour obtenir des solutions Pareto pour un problème d'optimisation continue et discrète, les mêmes paramètres et l'algorithme sont pris en compte et le temps d'exécution total est de 8 heures 33 minutes. Les pareto obtenus sont représentés sur la figure II.14. Cette figure illustre toute la solution réalisable pour les problèmes continus et discrets sous forme d'étoiles et de carrés. Les Pareto optimaux pour continu et discret sont également représentés par des carrés. Toutes ces solutions sont présentées dans le tableau 4.8 et 4.9 :

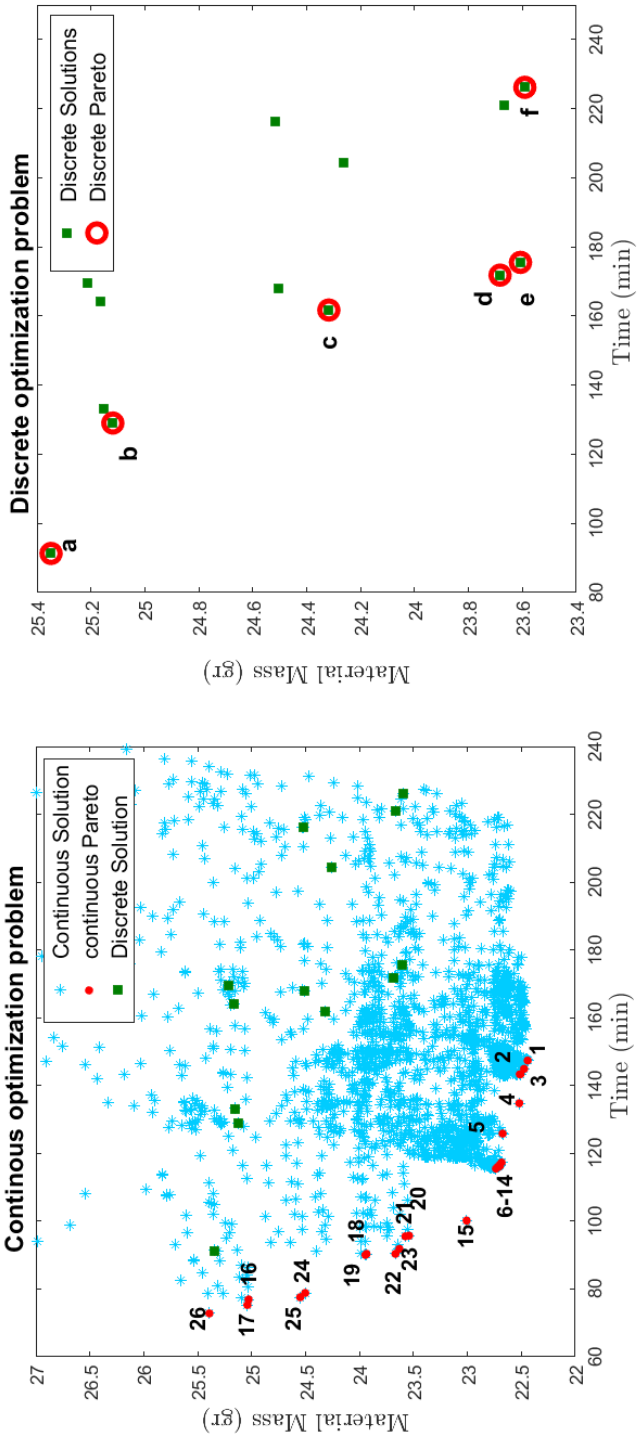


FIGURE II.14 – Le front Pareto obtenues par NSGA-II pour la fusée de roue

Les résultats montrent que les critères de fabrication sont variables en raison de l'épaisseur de la couche et des angles d'orientation.

– **Modèle de produit :** pour compléter notre modèle de produit, il est décidé de choisir entre la solution rapide de a et b de solutions discrètes pour considérer le comportement mécanique du produit. La solution a est plus rapide que b mais sa surface est plus rugueuse. La fabrication par la solution b est rapide et elle a une bonne qualité de surface. Donc, Makerbot Replicator est utilisé pour fabriquer cette fusée.

Pour définir cette approche pour le crochet basée sur la proposition 2, l'optimisation topologique et l'algorithme Powercrust sont utilisés pour définir respectivement la peau et le squelette d'usage, mais aucune méthode n'est trouvée encore pour poursuivre notre approche proposée.

la méthodologie proposée est mise en œuvre dans la modélisation des dépôts fondus et deux études de cas sont considérées comme validant cette méthodologie. La méthodologie proposée aide le concepteur à fournir le modèle 3D en utilisant FBS et le modèle d'usage. Le modèle de fabrication est proposé pour la modélisation par dépôt en fusion (FDM) en tant que technologie commune et utile de la fabrication additive. Après identification du modèle 3D et du modèle de fabrication, le modèle 3D est converti en fichier STL en format standard AM. Le moteur de traitement d'interface est développé pour déterminer les paramètres de fabrication optimaux pour tous les modèles 3D en ce qui concerne les critères souhaités tels que le temps, la masse du matériau, la rugosité et les propriétés mécaniques du produit de FDM.

La validation de la peau DFM et du squelette dans les études de cas illustre l'efficacité de cette approche pour tous les modèles 3D et les technologies AM.

Dans la suite, la thèse est résumée dans des conclusions et les perspectives sont présentées.

Sol.	L_t [mm]	θ_x [°]	θ_y [°]	θ_z [°]	Time [min]	Material [g]	R_a [µm]
1	0.14	−47.89	143.60	−176.54	147.38	22.44	19.02
2	0.15	−48.33	142.78	−176.54	144.93	22.47	19.77
3	0.16	−140.29	38.06	−113.90	143.32	22.51	18.65
4	0.17	−140.29	38.06	−113.90	134.78	22.52	19.82
5	0.18	162.42	45.05	−19.12	125.84	22.67	19.73
6	0.19	175.93	45.22	−31.41	116.04	22.71	19.94
7	0.19	176.45	45.24	−31.44	116.00	22.72	19.94
8	0.19	176.43	45.24	−31.43	115.98	22.72	19.94
9	0.19	179.35	45.04	−31.26	116.06	22.71	19.85
10	0.19	175.69	45.04	−31.24	116.32	22.69	19.91
11	0.19	175.61	45.06	−31.24	117.29	22.68	19.92
12	0.19	175.68	45.04	−31.25	116.51	22.70	19.91
13	0.19	175.66	45.05	−31.24	116.76	22.70	19.92
14	0.2	178.43	44.92	−30.93	115.48	22.74	19.87
15	0.23	156.25	40.51	83.70	100.18	23.00	25.92
16	0.24	0.00	0.00	−180.00	76.92	25.03	48.64
17	0.24	0.00	0.00	45.00	75.29	25.04	48.64
18	0.24	90.00	0.00	90.00	90.35	23.94	49.07
19	0.24	90.00	90.00	90.00	90.06	23.95	48.64
20	0.25	148.80	41.49	53.64	95.73	23.54	26.86
21	0.25	149.05	41.31	54.43	95.55	23.57	26.82
22	0.26	−170.60	144.50	24.87	90.38	23.67	31.33
23	0.26	179.97	60.54	−13.48	91.84	23.63	37.66
24	0.31	−34.59	143.31	60.90	78.84	24.51	36.39
25	0.32	−34.35	144.33	64.60	77.57	24.55	37.98
26	0.34	−151.86	40.98	−149.95	72.80	25.39	36.13

Tableau 4.8 – Le front Pareto pour fusée de roue pour un problème d'optimisation continue

Sol.	L_t [mm]	Orientation	Time [min]	Material [g]	UTS [MPa]	R_a [µm]
a	0.2	Flat ±45°	91.31	25.35	32.80	40.53
b	0.13	Flat 0/90°	129.04	25.12	30.00	26.35
c	0.13	Up-right ±45°	161.74	24.32	29.11	26.58
d	0.13	Up-right 0/90°	171.83	23.68	30.00	26.58
e	0.13	On-edge 0/90°	175.52	23.61	26.35	25.70
f	0.1	On-edge 0/90°	226.17	23.59	33.35	20.27

TABLEAU 4.9 – Le front Pareto pour fusée de roue pour un problème d'optimisation discrète

Conclusions

Cette thèse présente une méthodologie de conception intégrée dédiée à la fabrication additive. Cette méthode permet de prendre en compte tous les attributs, contraintes et critères de fabrication additive dès que possible dans la définition du produit. Cette méthodologie établit une correspondance entre les besoins des clients et le modèle de produit final grâce au modèle Function-Behavior-Structure (FBS), au modèle peau-squelette et au moteur de traitement d'interface proposé. La première étape de gestion du cycle de vie du produit est l'ingénierie des exigences et le modèle FBS pour nous aider à analyser le comportement et la fonction du produit, ainsi que il aide à definir la structure initiale du produit. Le modèle peau-squelette est défini dans deux types de modèles d'usage et de fabrication qui fournissent des informations initiales pour la conception et la fabrication. Le modèle d'usage est lié à la spécification du produit et l'analyse de ce modèle permet de fournir l'ébauche 3D du produit. Ainsi, la fabrication contient les informations essentielles pour déterminer le résultat final du produit. Un nouveau moteur de traitement de l'information ou d'interface de traitement est présenté pour considérer simultanément les attributs d'usage, de conception et de fabrication dans la définition de produit en tant qu'approche intégrée de conception pour la fabrication. Elle s'apparente à une boîte noire où se trouve les paramètres d'usage, de conception et de fabrication combinés pour proposer une ou des solutions optimales au concepteur. Composé d'outils de calcul et d'optimisation pour analyser la procédure de FA, elle traite un grand nombre de critères et contraintes liés au temps, au matériau, à la rugosité et au comportement mécanique afin de proposer un modèle de produit

intégré avec des solutions d'optimisation. Par conséquent, cette méthodologie est utilisée pour trouver le modèle de produit optimal, y compris le modèle 3D, les paramètres de fabrication optimaux, le fichier G-code et toutes les information importantes de la fabrication d'un produit.

Pour les travaux futurs, la mise en œuvre de ce moteur de traitement dans un logiciel est la prochaine étape de cette recherche. Il serait intéressant de fournir une méthodologie pour la fabrication hybride impliquant la Fabrication Additive et d'autres procédés traditionnels. Les études sur le comportement mécanique des produits réalisés par FA sont actuellement en cours due à la complexité de certaines géométries (nouvelles formes de treillis, nouvelle approche multi-matériaux par optimisation topologique...). En outre, d'autres critères importants pour la FA sont la précision et le coût qui doivent être analysés. De plus, le modèle d'usage, de fabrication et de traitement d'interface présentés seront utilisés pour toutes les technologies de FA et aidera les concepteurs et les fabricants. Deux proposition sont considérées dans cette thèse, l'étude basée sur la seconde fait encore incomplète et l'étude peut être poursuivie dans ce domaine.

Bibliography

[1] G. Sohlenius. “Concurrent engineering”. In: *CIRP Annals-Manufacturing Technology* 41.2 (1992), pp. 645–655 (cit. on pp. 3, 10, 12).

[2] Y. Huang et al. “Additive manufacturing: current state, future potential, gaps and needs, and recommendations”. In: *Journal of Manufacturing Science and Engineering* 137.1 (2015), p. 014001 (cit. on pp. 3, 10).

[3] A. Skander, L. Roucoules, and J. S. Klein Meyer. “Design and manufacturing interface modelling for manufacturing processes selection and knowledge synthesis in design”. In: *The International Journal of Advanced Manufacturing Technology* 37.5 (2008), pp. 443–454 (cit. on pp. 5, 10, 12, 16, 18–20, 22, 23, 50, 79, 98, 172–174, 182, 183).

[4] J. Elgueder et al. “Product-process interface for effective product design and manufacturing in a DFM approach”. In: *3rd International Congress Design and Modelling of Mechanical Systems*. 2009, 8p (cit. on pp. 5, 19, 173).

[5] W. Gao et al. “The status, challenges, and future of additive manufacturing in engineering”. In: *Computer-Aided Design* 69 (2015), pp. 65–89 (cit. on pp. 10, 24, 29–31, 46).

[6] S. Mellor, L. Hao, and D. Zhang. “Additive manufacturing: A framework for implementation”. In: *International Journal of Production Economics* 149 (2014), pp. 194–201 (cit. on pp. 10, 47).

[7] C. M. Eastman. *Design for X: concurrent engineering imperatives*. Springer Science & Business Media, 2012 (cit. on pp. 10, 12).

[8] X. G. Ming et al. “Collaborative process planning and manufacturing in product lifecycle management”. In: *Computers in Industry* 59.2-3 (2008), pp. 154–166 (cit. on p. 11).

[9] F. Danesi et al. “P4LM: A methodology for product lifecycle management”. In: *Computers in industry* 59.2-3 (2008), pp. 304–317 (cit. on p. 11).

[10] K. Vadoudi, N. Troussier, and T. W. Zhu. “Toward sustainable manufacturing through PLM, GIS and LCA interaction”. In: *Engineering, Technology and Innovation (ICE), 2014 International ICE Conference on*. IEEE. 2014, pp. 1–7 (cit. on p. 11).

[11] K. Rouibah and K. R. Caskey. “Change management in concurrent engineering from a parameter perspective”. In: *Computers in industry* 50.1 (2003), pp. 15–34 (cit. on p. 12).

[12] A. Skander. “Méthode et modèle DFM pour le choix des procédés et l’intégration des contraintes de fabrication vers l’émergence de la solution produit”. PhD thesis. Troyes, 2006 (cit. on pp. 12, 13, 15, 17, 18, 48, 175).

[13] W. Beitz and G. Pahl. “Engineering design: a systematic approach”. In: *MRS BULLETIN* (1996), p. 71 (cit. on p. 13).

[14] S. Tichkiewitch. “De la CFAO à la conception intégrée”. In: *Revue internationale de CFAO et d’infographie* 9.5 (1994), pp. 609–621 (cit. on p. 14).

[15] R. D. Coyne, M. A. Rosenman, and A. D. Radford. "Knowledge based design systems". In: (1990) (cit. on p. 14).

[16] U. Dombrowski, S. Schmidt, and K. Schmidtchen. "Analysis and integration of design for X approaches in lean design as basis for a lifecycle optimized product design". In: *Procedia CIRP* 15 (2014), pp. 385–390 (cit. on pp. 15, 16).

[17] U. Dombrowski and S. Schmidt. "Integration of design for X approaches in the concept of lean design to enable a holistic product design". In: *Industrial Engineering and Engineering Management (IEEM), 2013 IEEE International Conference on*. IEEE. 2013, pp. 1515–1519 (cit. on p. 16).

[18] R. Holt and C. Barnes. "Towards an integrated approach to "Design for X": an agenda for decision-based DFX research". In: *Research in Engineering Design* 21.2 (2010), pp. 123–136 (cit. on p. 16).

[19] G. Pahl and W. Beitz. *Engineering design: a systematic approach*. Springer Science & Business Media, 2013 (cit. on p. 17).

[20] D. Effa, O. Nespoli, and S. Lambert. "Using the Case Method to Facilitate Learning of Design for Manufacturing and Cost". In: *Proceedings of the Canadian Engineering Education Association* (2015) (cit. on p. 17).

[21] D. M. Anderson. *Design for manufacturability & concurrent engineering: How to design for low cost, design in high quality, design for lean manufacture, and design quickly for fast production*. CIM press, 2004 (cit. on p. 17).

[22] S. K. Gupta et al. "Automated manufacturability analysis: a survey". In: *Research in Engineering Design* 9.3 (1997), pp. 168–190 (cit. on p. 17).

[23] S. A. Shukor and D. Axinte. "Manufacturability analysis system: issues and future trends". In: *International Journal of Production Research* 47.5 (2009), pp. 1369–1390 (cit. on p. 17).

[24] A. Venkatachalam, J. M. Mellichamp, and D. M. Miller. "A knowledge-based approach to design for manufacturability". In: *Journal of Intelligent Manufacturing* 4.5 (1993), pp. 355–366 (cit. on pp. 17, 18).

[25] X. Xie. "Design for manufacture and assembly". In: *Retrieved in February* 18 (2003), p. 2013 (cit. on p. 18).

[26] G. Boothroyd. "Product design for manufacture and assembly". In: *Computer-Aided Design* 26.7 (1994), pp. 505–520 (cit. on pp. 18, 19).

[27] J. Corbett. *Design for manufacture: strategies, principles, and techniques*. Addison Wesley Publishing Company, 1991 (cit. on p. 18).

[28] D. T. Koenig. *Manufacturing Engineering: Principles for Optimization: Principles for Optimization*. CRC Press, 1994 (cit. on p. 19).

[29] S. Arimoto et al. "Development of machining-producibility evaluation method (MEM)". In: *CIRP Annals-Manufacturing Technology* 42.1 (1993), pp. 119–122 (cit. on p. 19).

[30] L. Roucoules and A. Skander. "Manufacturing process selection and integration in product design". In: *Methods and Tools for Co-operative and Integrated Design*. Springer, 2004, pp. 71–82 (cit. on pp. 19, 22, 68, 79, 98, 180, 182, 183).

[31] J. Elgueder et al. "DFM Synthesis Approach Based on Product-Process Interface Modelling: Application to the Peen Forming Process". In: *Global Product Development*. Springer, 2011, pp. 265–277 (cit. on p. 21).

[32] J. S. Gero and U. Kannengiesser. “The situated function–behaviour–structure framework”. In: *Design studies* 25.4 (2004), pp. 373–391 (cit. on pp. 20–22).

[33] E. Asadollahi-Yazdi, J. Gardan, and P. Lafon. “Integrated Design for Additive Manufacturing Based on Skin-Skeleton Approach”. In: *Procedia CIRP* 60 (2017), pp. 217–222 (cit. on pp. 22, 23, 79, 96, 98, 114, 115, 174, 182, 183, 193).

[34] E. Asadollahi-Yazdi, J. Gardan, and P. Lafon. “Toward integrated design of additive manufacturing through a process development model and multi-objective optimization”. In: *The International Journal of Advanced Manufacturing Technology* (2018), pp. 1–20 (cit. on pp. 23, 104, 195).

[35] A. Standard. “F2792. 2012. standard terminology for additive manufacturing technologies”. In: *ASTM F2792-10e1* (2012) (cit. on p. 24).

[36] S. Yang and Y. F. Zhao. “Additive manufacturing-enabled design theory and methodology: a critical review”. In: *The International Journal of Advanced Manufacturing Technology* 80.1-4 (2015), pp. 327–342 (cit. on pp. 24, 29, 48, 50, 176, 177).

[37] J. Gardan. “Additive manufacturing technologies: state of the art and trends”. In: *International Journal of Production Research* 54.10 (2016), pp. 3118–3132 (cit. on pp. 24–27, 37–44, 46, 79, 102, 114, 171, 174, 183, 195).

[38] J. W. Halloran et al. “Photopolymerization of powder suspensions for shaping ceramics”. In: *Journal of the European Ceramic Society* 31.14 (2011), pp. 2613–2619 (cit. on pp. 26, 37).

[39] K. V. Wong and A. Hernandez. “A review of additive manufacturing”. In: *ISRN Mechanical Engineering* 2012 (2012) (cit. on pp. 26, 37, 38, 41–44).

[40] R. Noorani. *Rapid prototyping: principles and applications*. John Wiley & Sons Incorporated, 2006 (cit. on pp. 26, 44, 102).

[41] J. D. Hiller and H. Lipson. “STL 2.0: a proposal for a universal multi-material Additive Manufacturing File format”. In: *Proceedings of the Solid Freeform Fabrication Symposium*. 1. 2009, pp. 266–278 (cit. on pp. 26–28).

[42] Y. Chen, C. Ng, and Y. Wang. “Generation of an STL file from 3D measurement data with user-controlled data reduction”. In: *The international journal of advanced manufacturing technology* 15.2 (1999), pp. 127–131 (cit. on p. 26).

[43] I. Gibson, D. W. Rosen, B. Stucker, et al. *Additive manufacturing technologies*. Vol. 238. Springer, 2010 (cit. on pp. 29, 41).

[44] S. A. Tofail et al. “Additive manufacturing: scientific and technological challenges, market uptake and opportunities”. In: *Materials Today* (2017) (cit. on pp. 29, 30).

[45] C. Cozmei and F. Caloian. “Additive manufacturing flickering at the beginning of existence”. In: *Procedia Economics and Finance* 3 (2012), pp. 457–462 (cit. on pp. 29–31).

[46] M. K. Thompson, A. Stolfi, and M. Mischkot. “Process chain modeling and selection in an additive manufacturing context”. In: *CIRP Journal of Manufacturing Science and Technology* 12 (2016), pp. 25–34 (cit. on pp. 31–34, 48, 60, 177).

[47] S.-H. Ahn et al. “Anisotropic material properties of fused deposition modeling ABS”. In: *Rapid prototyping journal* 8.4 (2002), pp. 248–257 (cit. on p. 33).

[48] D. Ahn et al. “Representation of surface roughness in fused deposition modeling”. In: *Journal of Materials Processing Technology* 209.15 (2009), pp. 5593–5600 (cit. on pp. 33, 82, 84, 121, 176, 184, 201).

[49] E. Vahabli and S. Rahmati. “Hybrid estimation of surface roughness distribution in FDM parts using analytical modeling and empirical investigation”. In: *The International Journal of Advanced Manufacturing Technology* 5.88 (2016), pp. 2287–2303 (cit. on pp. 33, 64, 82, 84, 85, 121, 176, 177, 184, 187, 188, 201).

[50] E. Yasa, J.-P. Kruth, and J. Deckers. “Manufacturing by combining selective laser melting and selective laser erosion/laser re-melting”. In: *CIRP Annals-Manufacturing Technology* 60.1 (2011), pp. 263–266 (cit. on p. 33).

[51] M. Baumers et al. “The cost of additive manufacturing: machine productivity, economies of scale and technology-push”. In: *Technological forecasting and social change* 102 (2016), pp. 193–201 (cit. on pp. 33, 64, 176, 177).

[52] D. Thomas. “The development of design rules for selective laser melting”. PhD thesis. University of Wales, 2009 (cit. on pp. 33, 48, 51, 176, 177).

[53] V. Srivastava. “A Reviev on Advances in Rapid Prototype 3D Printing of Multi-Functional Applications”. In: *Science and Technology* 7.1 (2017), pp. 4–24 (cit. on p. 34).

[54] E. Asadollahi-Yazdi, J. Gardan, and P. Lafon. “Integrated Design in Additive Manufacturing Based on Design for Manufacturing”. In: *World Academy of Science, Engineering and Technology, International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering* 10.6 (2016), pp. 1137–1144 (cit. on pp. 36, 174).

[55] N. Guo and M. C. Leu. “Additive manufacturing: technology, applications and research needs”. In: *Frontiers of Mechanical Engineering* 8.3 (2013), pp. 215–243 (cit. on p. 37).

[56] D. Ibrahim et al. “Dimensional error of selective laser sintering, three-dimensional printing and PolyJet^{TM} models in the reproduction of mandibular anatomy”. In: *Journal of Cranio-Maxillofacial Surgery* 37.3 (2009), pp. 167–173 (cit. on pp. 38, 42).

[57] J. Hänninen. “DMLS moves from rapid tooling to rapid manufacturing”. In: *Metal Powder Report* 56.9 (2001), pp. 2426–29 (cit. on p. 39).

[58] E. Pessard et al. “Complex cast parts with rapid tooling: rapid manufacturing point of view”. In: *The International Journal of Advanced Manufacturing Technology* 39.9 (2008), pp. 898–904 (cit. on p. 39).

[59] D. Dean et al. “Continuous digital light processing (cDLP): Highly accurate additive manufacturing of tissue engineered bone scaffolds: This paper highlights the main issues regarding the application of Continuous Digital Light Processing (cDLP) for the production of highly accurate PPF scaffolds with layers as thin as 60 μm for bone tissue engineering”. In: *Virtual and physical prototyping* 7.1 (2012), pp. 13–24 (cit. on p. 40).

[60] R. Singh, V. Singh, and M. S. Saini. “Experimental investigations for statistically controlled rapid moulding solution of plastics using polyjet printing”. In: *Proceedings of the ASME 2010 International Mechanical Engineering Congress & Exposition (IMECE2010)*. 2010, pp. 12–18 (cit. on p. 42).

[61] J. Moon et al. “Fabrication of functionally graded reaction infiltrated SiC–Si composite by three-dimensional printing (3DP^{TM}) process”. In: *Materials Science and Engineering: A* 298.1 (2001), pp. 110–119 (cit. on p. 43).

[62] J. Gardan and L. Roucoules. “Characterization of beech wood pulp towards sustainable rapid prototyping”. In: *IDMME-Virtual Concept 2010*. Vol. 3. Springer verlag. 2010, 6p (cit. on p. 43).

[63] J. W. Priest, C. Smith, and P. DuBois. “Liquid metal jetting for printing metal parts”. In: *Solid Freeform Fabrication Proceedings, University of Texas at Austin, TX*. 1997, pp. 1–10 (cit. on p. 44).

[64] B. K. Paul and V. Voorakarnam. “Effect of layer thickness and orientation angle on surface roughness in laminated object manufacturing”. In: *Journal of manufacturing processes* 3.2 (2001), pp. 94–101 (cit. on p. 44).

[65] B. Bhushan and M. Caspers. “An overview of additive manufacturing (3D printing) for microfabrication”. In: *Microsystem Technologies* 23.4 (2017), pp. 1117–1124 (cit. on p. 45).

[66] Y. Houtmann, B. Delebecque, and C. Barlier. “Adaptive local slicing in stratoconception by using critical points”. In: *Advances in Production Engineering & Management J* 4 (2009), pp. 59–68 (cit. on pp. 44, 45).

[67] D. W. Rosen. “Research supporting principles for design for additive manufacturing: This paper provides a comprehensive review on current design principles and strategies for AM”. In: *Virtual and Physical Prototyping* 9.4 (2014), pp. 225–232 (cit. on pp. 47–49).

[68] F. Laverne et al. “DFAM in the design process: A proposal of classification to foster early design stages”. In: *CONFERE, Sibenik, Croatia* (2014) (cit. on p. 47).

[69] M. Kumke, H. Watschke, and T. Vietor. “A new methodological framework for design for additive manufacturing”. In: *Virtual and Physical Prototyping* 11.1 (2016), pp. 3–19 (cit. on pp. 47, 48, 51, 63, 177).

[70] D. W. Rosen. “Computer-aided design for additive manufacturing of cellular structures”. In: *Computer-Aided Design and Applications* 4.5 (2007), pp. 585–594 (cit. on pp. 48, 49, 61, 177).

[71] M. J. Burton. “Design for rapid manufacture: developing an appropriate knowledge transfer tool for industrial designers”. PhD thesis. © Michael John Burton, 2005 (cit. on pp. 48, 51, 176, 177).

[72] G. D’antonio et al. “A proposal of manufacturing execution system integration in design for additive manufacturing”. In: *IFIP International Conference on Product Lifecycle Management*. Springer. 2015, pp. 761–770 (cit. on pp. 48, 60, 177).

[73] S. Yim. “A retrieval method (DFM framework) for automated retrieval of design for additive manufacturing problems”. PhD thesis. Georgia Institute of Technology, 2007 (cit. on pp. 48, 60, 177).

[74] D. W. Rosen. “Design for additive manufacturing: a method to explore unexplored regions of the design space”. In: *Eighteenth Annual Solid Freeform Fabrication Symposium*. 2007, pp. 402–415 (cit. on pp. 48, 49, 177).

[75] L. Barnard. “Designing for laser sintering”. In: *Journal for New Generation Sciences* 6.2 (2008), pp. 47–59 (cit. on pp. 48, 50, 51, 177).

[76] R. Ponche et al. “A new global approach to design for additive manufacturing: A method to obtain a design that meets specifications while optimizing a given additive manufacturing process is presented in this paper”. In: *Virtual and Physical Prototyping* 7.2 (2012), pp. 93–105 (cit. on pp. 48, 62, 177).

[77] C. Chu, G. Graf, and D. W. Rosen. “Design for additive manufacturing of cellular structures”. In: *Computer-Aided Design and Applications* 5.5 (2008), pp. 686–696 (cit. on pp. 48, 49, 176, 177).

[78] K. Salonitis and S. Al Zarban. “Redesign optimization for manufacturing using additive layer techniques”. In: *Procedia CIRP* 36 (2015), pp. 193–198 (cit. on pp. 48, 49, 52, 61, 177).

[79] R. Ponche et al. “A novel methodology of design for Additive Manufacturing applied to Additive Laser Manufacturing process”. In: *Robotics and Computer-Integrated Manufacturing* 30.4 (2014), pp. 389–398 (cit. on pp. 48, 49, 52, 59, 62, 176, 177).

[80] B. Vayre, F. Vignat, and F. Villeneuve. “Designing for additive manufacturing”. In: *Procedia CIrP* 3 (2012), pp. 632–637 (cit. on pp. 48, 49, 51, 52, 176, 177).

[81] O. Kerbrat, P. Mognol, and J.-Y. Hascoët. “A new DFM approach to combine machining and additive manufacturing”. In: *Computers in Industry* 62.7 (2011), pp. 684–692 (cit. on pp. 48, 52, 177).

[82] U. K. uz Zaman et al. “Integrated product-process design to suggest appropriate manufacturing technology: a review”. In: *The International Journal of Advanced Manufacturing Technology* 91.1-4 (2017), pp. 1409–1430 (cit. on pp. 48, 60, 177).

[83] Y. Zhang et al. “Evaluating the design for additive manufacturing: a process planning perspective”. In: *Procedia CIRP* 21 (2014), pp. 144–150 (cit. on pp. 48, 61, 177).

[84] E. B. Arisoy et al. “Design and Topology Optimization of Lattice Structures Using Deformable Implicit Surfaces for Additive Manufacturing”. In: *ASME 2015 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. American Society of Mechanical Engineers. 2015, V004T05A003–V004T05A003 (cit. on pp. 48, 50, 177).

[85] Z. Doubrovski, J. C. Verlinden, and J. M. Geraedts. “Optimal design for additive manufacturing: opportunities and challenges”. In: *ASME 2011 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. American Society of Mechanical Engineers. 2011, pp. 635–646 (cit. on pp. 48, 51, 177).

[86] U. K. uz Zaman et al. “Integrated product-process design: Material and manufacturing process selection for additive manufacturing using multi-criteria decision making”. In: *Robotics and Computer-Integrated Manufacturing* 51 (2018), pp. 169–180 (cit. on pp. 48, 60, 177).

[87] Y. Tang, J. Hascoet, and Y. F. Zhao. “Integration of topological and functional optimization in design for additive manufacturing”. In: *ASME 2014 12th Biennial Conference on Engineering Systems Copenhagen, Denmark*. 2014 (cit. on pp. 48, 49, 52, 60, 177).

[88] C. C. Seepersad et al. “A designer’s guide for dimensioning and tolerancing SLS Parts”. In: *Solid Freeform Fabrication Symposium, Austin, TX*. 2012, pp. 921–931 (cit. on pp. 48, 176, 177).

[89] S. Hällgren, L. Pejryd, and J. Ekengren. “(Re) Design for Additive Manufacturing”. In: *Procedia CIRP* 50 (2016), pp. 246–251 (cit. on pp. 48, 49, 52, 62, 177).

[90] L. Jiang et al. “Parametric Topology Optimization Toward Rational Design and Efficient Prefabrication for Additive Manufacturing”. In: *ASME 2017 12th International Manufacturing Science and Engineering Conference collocated with the JSME/ASME 2017 6th International Conference on Materials and Processing*. American Society of Mechanical Engineers. 2017, V004T05A006–V004T05A006 (cit. on pp. 48, 52, 177).

[91] C. C. Seepersad. “Challenges and opportunities in design for additive manufacturing”. In: *3D Printing and Additive Manufacturing* 1.1 (2014), pp. 10–13 (cit. on pp. 48, 51, 176, 177).

[92] C. Klahn, B. Leutenecker, and M. Meboldt. "Design for Additive Manufacturing–Supporting the substitution of components in series products". In: *Procedia CIRP* 21 (2014), pp. 138–143 (cit. on pp. 48, 61, 177).

[93] P. Vogiatzis et al. "Computational Design and Additive Manufacturing of Conformal Metasurfaces by Combining Topology Optimization With Riemann Mapping Theorem". In: *ASME 2017 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. American Society of Mechanical Engineers. 2017, V02BT03A001–V02BT03A001 (cit. on pp. 48, 52, 177).

[94] A. Wegner and G. Witt. "Design rules for laser sintering". In: *Journal of Plastics Technology* 8.3 (2012), pp. 253–277 (cit. on pp. 48, 51, 176, 177).

[95] C. Klahn, B. Leutenecker, and M. Meboldt. "Design strategies for the process of additive manufacturing". In: *Procedia CIRP* 36 (2015), pp. 230–235 (cit. on pp. 48, 61, 177).

[96] P. Pradel et al. "Investigation of design for additive manufacturing in professional design practice". In: (2017) (cit. on pp. 48, 52, 176, 177).

[97] G. A. Adam and D. Zimmer. "Design for Additive Manufacturing—Element transitions and aggregated structures". In: *CIRP Journal of Manufacturing Science and Technology* 7.1 (2014), pp. 20–28 (cit. on pp. 48, 51, 176, 177).

[98] T. Primo et al. "Additive manufacturing integration with topology optimization methodology for innovative product design". In: *The International Journal of Advanced Manufacturing Technology* (2017), pp. 1–13 (cit. on pp. 48, 49, 52, 61, 177).

[99] M. Leary et al. "Optimal topology for additive manufacture: a method for enabling additive manufacture of support-free optimal structures". In: *Materials & Design* 63 (2014), pp. 678–690 (cit. on pp. 48, 59, 62, 177).

[100] N. Boyard et al. "A design methodology for parts using additive manufacturing". In: *6th international conference on advanced research in virtual and rapid prototyping. Leira, Portugal*. 2013, pp. 399–404 (cit. on pp. 48, 52, 177).

[101] H. Rodrigue and M. Rivette. "An assembly-level design for additive manufacturing methodology". In: *IDMME-Virtual Concept*. 2010 (cit. on pp. 48, 50, 177).

[102] J. Kranz, D. Herzog, and C. Emmelmann. "Design guidelines for laser additive manufacturing of lightweight structures in TiAl6V4". In: *Journal of Laser Applications* 27.S1 (2015), S14001 (cit. on pp. 48, 51, 176, 177).

[103] K. Salonitis. "Design for additive manufacturing based on the axiomatic design method". In: *The International Journal of Advanced Manufacturing Technology* 87.1-4 (2016), pp. 989–996 (cit. on pp. 48, 52, 63, 177).

[104] Y. Ariadi et al. "Combining additive manufacturing with computer aided consumer design". In: (2012) (cit. on pp. 48, 50, 176, 177).

[105] S. Bin Maidin, I. Campbell, and E. Pei. "Development of a design feature database to support design for additive manufacturing". In: *Assembly Automation* 32.3 (2012), pp. 235–244 (cit. on pp. 48, 51, 176, 177).

[106] C. Emmelmann et al. "Laser additive manufacturing and bionics: redefining lightweight design". In: *Physics Procedia* 12 (2011), pp. 364–368 (cit. on pp. 48, 52, 61, 177).

[107] D. Walton and H. Moztarzadeh. "Design and Development of an Additive Manufactured Component by Topology Optimisation". In: *Procedia CIRP* 60 (2017), pp. 205–210 (cit. on pp. 48, 52, 177).

[108] H. Ko, S. K. Moon, and J. Hwang. "Design for additive manufacturing in customized products". In: *International Journal of Precision Engineering and Manufacturing* 16.11 (2015), pp. 2369–2375 (cit. on pp. 48, 51, 177).

[109] R. Hague, S. Mansour, and N. Saleh. "Design opportunities with rapid manufacturing". In: *Assembly Automation* 23.4 (2003), pp. 346–356 (cit. on pp. 48, 60, 177).

[110] W. Tao and M. C. Leu. "Design of lattice structure for additive manufacturing". In: *Flexible Automation (ISFA), International Symposium on*. IEEE. 2016, pp. 325–332 (cit. on pp. 48, 49, 176, 177).

[111] E. Atzeni and A. Salmi. "Economics of additive manufacturing for end-usable metal parts". In: *The International Journal of Advanced Manufacturing Technology* 62.9-12 (2012), pp. 1147–1155 (cit. on pp. 48, 53, 176, 177).

[112] R. Hague*, S. Mansour, and N. Saleh. "Material and design considerations for rapid manufacturing". In: *International Journal of Production Research* 42.22 (2004), pp. 4691–4708 (cit. on pp. 48, 60, 177).

[113] A. Boschetto and L. Bottini. "Design for manufacturing of surfaces to improve accuracy in Fused Deposition Modeling". In: *Robotics and Computer-Integrated Manufacturing* 37 (2016), pp. 103–114 (cit. on pp. 48, 53, 84, 124, 176, 177).

[114] V. Dhokia, W. P. Essink, and J. M. Flynn. "A generative multi-agent design methodology for additively manufactured parts inspired by termite nest building". In: *CIRP Annals* 66.1 (2017), pp. 153–156 (cit. on pp. 48, 63, 177).

[115] M. Barclift et al. "CAD-Integrated Cost Estimation and Build Orientation Optimization to Support Design for Metal Additive Manufacturing". In: *ASME 2017 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. American Society of Mechanical Engineers. 2017, V02AT03A035–V02AT03A035 (cit. on pp. 48, 59, 176, 177).

[116] Y. Zhang, R. K. Gupta, and A. Bernard. "Two-dimensional placement optimization for multi-parts production in additive manufacturing". In: *Robotics and Computer-Integrated Manufacturing* 38 (2016), pp. 102–117 (cit. on pp. 48, 63, 177).

[117] Y. Zhang and A. Bernard. "Grouping parts for multiple parts production in Additive Manufacturing". In: *Procedia CIRP* 17 (2014), pp. 308–313 (cit. on pp. 48, 63, 177).

[118] W. Essink et al. "Hybrid ants: A new approach for geometry creation for additive and hybrid manufacturing". In: *Procedia CIRP* 60 (2017), pp. 199–204 (cit. on pp. 48, 63, 177).

[119] T. H. Vo. "La démarche de conception pour la fabrication additive: choix des modes de représentation dans la phase d'analyse". PhD thesis. Université Grenoble Alpes, 2017 (cit. on pp. 48, 63, 177).

[120] N. Gardan, A. Schneider, and J. Gardan. "Material and process characterization for coupling topological optimization to additive manufacturing". In: *Computer-Aided Design and Applications* 13.1 (2016), pp. 39–49 (cit. on pp. 49, 75, 182).

[121] L. J. Gibson and M. F. Ashby. *Cellular solids: structure and properties*. Cambridge university press, 1999 (cit. on p. 49).

[122] M. Scheffler and P. Colombo. *Cellular ceramics: structure, manufacturing, properties and applications*. John Wiley & Sons, 2006 (cit. on p. 49).

[123] D. M. Watts and R. J. Hague. "Exploiting the design freedom of RM". In: (2006) (cit. on p. 50).

[124] S. Maidin et al. “Design for Rapid Manufacturing–Capturing Designers Knowledge”. In: *Proceedings of the 4th International Conference on Advanced Research in Virtual and Rapid Prototyping*. 2009, pp. 311–317 (cit. on p. 51).

[125] J. W. Booth et al. “The design for additive manufacturing worksheet”. In: *Journal of Mechanical Design* 139.10 (2017), p. 100904 (cit. on p. 52).

[126] A. Boschetto, V. Giordano, and F. Veniali. “Modelling micro geometrical profiles in fused deposition process”. In: *The International Journal of Advanced Manufacturing Technology* 61.9-12 (2012), pp. 945–956 (cit. on pp. 53, 82, 124, 184).

[127] A. Boschetto and L. Bottini. “Accuracy prediction in fused deposition modeling”. In: *The international journal of advanced manufacturing technology* 73.5-8 (2014), pp. 913–928 (cit. on pp. 53, 82, 115, 124, 125, 176, 184).

[128] H. Diab. “Modélisation et optimisation de structures flottantes pour l’aide à la décision d’aménagement portuaire”. PhD thesis. Troyes, 2016 (cit. on p. 53).

[129] S. S. Rao and S. S. Rao. *Engineering optimization: theory and practice*. John Wiley & Sons, 2009 (cit. on pp. 54, 55).

[130] S. Huband et al. “A review of multiobjective test problems and a scalable test problem toolkit”. In: *IEEE Transactions on Evolutionary Computation* 10.5 (2006), pp. 477–506 (cit. on p. 57).

[131] V. Barichard. “Approches hybrides pour les problèmes multiobjectifs”. In: *Mémoire de Thèse, Université d’Angers* 162 (2003) (cit. on p. 57).

[132] K. Deb et al. “A fast and elitist multiobjective genetic algorithm: NSGA-II”. In: *IEEE transactions on evolutionary computation* 6.2 (2002), pp. 182–197 (cit. on p. 57).

[133] A. Forrester, A. Keane, et al. *Engineering design via surrogate modelling: a practical guide*. John Wiley & Sons, 2008 (cit. on p. 58).

[134] T. W. Simpson et al. “Metamodels for computer-based engineering design: survey and recommendations”. In: *Engineering with computers* 17.2 (2001), pp. 129–150 (cit. on p. 58).

[135] A. Mosavi. “Multiobjective Optimization of Spline Curves Using Mode Frontier”. In: *Proceedings of International modeFRONTIER Users’ Meeting*. 2010 (cit. on pp. 59, 93).

[136] D. C. Montgomery. “Design and Analysis of Experiments, John Wiley & Sons”. In: *New York* (2001), pp. 64–65 (cit. on p. 59).

[137] Y. Zhang and A. Bernard. “Using AM feature and Multi-attribute decision making to orientate part in Additive Manufacturing”. In: *In High value manufacturing: Advanced research in virtual and rapid prototyping. Proceedings of the 6th International Conference on Advanced Research in Virtual and Rapid Prototyping* (2013), pp. 411–416 (cit. on p. 63).

[138] Y. Zhang et al. “Feature based building orientation optimization for additive manufacturing”. In: *Rapid Prototyping Journal* 22.2 (2016), pp. 358–376 (cit. on p. 63).

[139] Y. Zhang et al. “A facet cluster-based method for alternative build orientation generation in Additive Manufacturing”. In: (2016) (cit. on p. 63).

[140] Y. Zhang et al. “Build orientation determination for multi-material deposition additive manufacturing with continuous fibers”. In: *Procedia CIRP* 50 (2016), pp. 414–419 (cit. on p. 63).

[141] L. T. Blessing and A. Chakrabarti. *DRM: A Design Reseach Methodology*. Springer, 2009 (cit. on p. 63).

[142] H. Xiaomao, Y. Chunsheng, and H. Yongjun. "Tool path planning based on endpoint build-in optimization in rapid prototyping". In: *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science* 225.12 (2011), pp. 2919–2926 (cit. on pp. 64, 177).

[143] Y.-a. Jin et al. "Optimization of tool-path generation for material extrusion-based additive manufacturing technology". In: *Additive Manufacturing* 1 (2014), pp. 32–47 (cit. on pp. 64, 177).

[144] J. Wu et al. "Infill Optimization for Additive Manufacturing–Approaching Bone-like Porous Structures". In: *IEEE Transactions on Visualization and Computer Graphics* (2017) (cit. on pp. 64, 177).

[145] K. Thrimurthulu, P. M. Pandey, and N. V. Reddy. "Optimum part deposition orientation in fused deposition modeling". In: *International Journal of Machine Tools and Manufacture* 44.6 (2004), pp. 585–594 (cit. on pp. 64, 177).

[146] L. Galantucci et al. "Analysis of dimensional performance for a 3D open-source printer based on fused deposition modeling technique". In: *Procedia CIRP* 28 (2015), pp. 82–87 (cit. on pp. 64, 176, 177).

[147] M. Kaveh et al. "Optimization of the printing parameters affecting dimensional accuracy and internal cavity for HIPS material used in fused deposition modeling processes". In: *Journal of materials processing technology* 226 (2015), pp. 280–286 (cit. on pp. 64, 176, 177).

[148] Y. Zhang and A. Bernard. "Generic build time estimation model for parts produced by SLS". In: *High value manufacturing: Advanced research in virtual and rapid prototyping. Proceedings of the 6th International Conference on Advanced Research in Virtual and Rapid Prototyping*. 2013, pp. 43–48 (cit. on pp. 64, 177).

[149] L. Baich, G. Manogharan, and H. Marie. "Study of infill print design on production cost-time of 3D printed ABS parts". In: *International Journal of Rapid Manufacturing* 5.3-4 (2015), pp. 308–319 (cit. on pp. 64, 177).

[150] J. T. Belter and A. M. Dollar. "Strengthening of 3D printed fused deposition manufactured parts using the fill compositing technique". In: *PloS one* 10.4 (2015), e0122915 (cit. on p. 64).

[151] A. Pan et al. "Effect of FDM Process on Adhesive Strength of Polylactic Acid (PLA) Filament." In: *Key Engineering Materials* 667 (2016) (cit. on p. 64).

[152] J. S. Gero and U. Kannengiesser. "The function-behaviour-structure ontology of design". In: *An anthology of theories and models of design*. Springer, 2014, pp. 263–283 (cit. on pp. 75, 182).

[153] M. Ceccarelli et al. "How to use 3D printing for feasibility check of mechanism design". In: *Advances in Robot Design and Intelligent Control*. Springer, 2016, pp. 307–315 (cit. on pp. 80, 184).

[154] M. S. Hossain et al. "Improved mechanical properties of fused deposition modeling-manufactured parts through build parameter modifications". In: *Journal of Manufacturing Science and Engineering* 136.6 (2014), p. 061002 (cit. on p. 81).

[155] P. Cain. *Selecting the optimal shell and infill parameters for FDM 3D Printing*. 2018. URL: https://www.3dhubs.com/knowledge-base/selecting-optimal-shell-and-infill-parameters-fdm-3d-printing (visited on 05/31/2018) (cit. on p. 81).

[156] J. C. Riddick et al. “Fractographic analysis of tensile failure of acrylonitrile-butadiene-styrene fabricated by fused deposition modeling”. In: *Additive Manufacturing* 11 (2016), pp. 49–59 (cit. on pp. 82, 84, 92, 128, 176, 184, 191, 202).

[157] D. P. Cole et al. “Interfacial mechanical behavior of 3D printed ABS”. In: *Journal of Applied Polymer Science* 133.30 (2016) (cit. on pp. 82, 92, 128, 176, 184, 191, 202).

[158] O. A. Mohamed, S. H. Masood, and J. L. Bhowmik. “Experimental investigations of process parameters influence on rheological behavior and dynamic mechanical properties of FDM manufactured parts”. In: *Materials and Manufacturing Processes* 31.15 (2016), pp. 1983–1994 (cit. on p. 84).

[159] Y. Zhang et al. “Fast adaptive modeling method for build time estimation in Additive Manufacturing”. In: *CIRP Journal of Manufacturing Science and Technology* 10 (2015), pp. 49–60 (cit. on p. 84).

[160] Z. Zhu, V. Dhokia, and S. T. Newman. “A new algorithm for build time estimation for fused filament fabrication technologies”. In: *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture* 230.12 (2016), pp. 2214–2228 (cit. on p. 84).

[161] G. P. Kumar and S. P. Regalla. “Optimization of support material and build time in fused deposition modeling (FDM)”. In: *Applied Mechanics and Materials*. Vol. 110. Trans Tech Publ. 2012, pp. 2245–2251 (cit. on p. 84).

[162] G. Pyka et al. “Surface roughness and morphology customization of additive manufactured open porous Ti6Al4V structures”. In: *Materials* 6.10 (2013), pp. 4737–4757 (cit. on pp. 85, 187).

[163] A. Standard. “B46. 1 (2002) Surface Texture, Surface Roughness, Waviness and Lay”. In: *American Society of Mechanical Engineers, New York, NY* (2002) (cit. on pp. 85, 188).

[164] H. S. Byun and K. H. Lee. “Determination of optimal build direction in rapid prototyping with variable slicing”. In: *The International Journal of Advanced Manufacturing Technology* 28.3-4 (2006), p. 307 (cit. on pp. 85, 121, 122, 201).

[165] S. O. Onuh and Y. Y. Yusuf. “Rapid prototyping technology: applications and benefits for rapid product development”. In: *Journal of intelligent manufacturing* 10.3 (1999), pp. 301–311 (cit. on pp. 85, 188).

[166] G. Navangul, R. Paul, and S. Anand. “Error minimization in layered manufacturing parts by stereolithography file modification using a vertex translation algorithm”. In: *Journal of Manufacturing Science and Engineering* 135.3 (2013), p. 031006 (cit. on p. 85).

[167] P. Pandey, N. V. Reddy, and S. Dhande. “Real time adaptive slicing for fused deposition modelling”. In: *International Journal of Machine Tools and Manufacture* 43.1 (2003), pp. 61–71 (cit. on p. 85).

[168] W. Wu et al. “Influence of layer thickness and raster angle on the mechanical properties of 3D-printed PEEK and a comparative mechanical study between PEEK and ABS”. In: *Materials* 8.9 (2015), pp. 5834–5846 (cit. on pp. 86, 114, 188).

[169] M. Bourne. *Introduction to Vectors Vectors in 3-D Space*. 2018. URL: https://www.intmath.com/vectors/7-vectors-in-3d-space.php (visited on 04/25/2018) (cit. on p. 89).

[170] J. Cantrell et al. “Experimental Characterization of the Mechanical Properties of 3D Printed ABS and Polycarbonate Parts”. In: *Advancement of Optical Methods in Experimental Mechanics, Volume 3*. Springer, 2017, pp. 89–105 (cit. on pp. 90, 92, 128, 176, 191, 202, 203).

[171] D. Croccolo, M. De Agostinis, and G. Olmi. “Experimental characterization and analytical modelling of the mechanical behaviour of fused deposition processed parts made of ABS-M30”. In: *Computational Materials Science* 79 (2013), pp. 506–518 (cit. on pp. 92, 128, 176, 191, 202).

[172] V. B. Nidagundi, R. Keshavamurthy, and C. Prakash. “Studies on parametric optimization for fused deposition modelling process”. In: *Materials Today: Proceedings* 2.4-5 (2015), pp. 1691–1699 (cit. on pp. 92, 176, 191).

[173] N. Amenta, S. Choi, and R. K. Kolluri. “The power crust”. In: *Proceedings of the sixth ACM symposium on Solid modeling and applications*. ACM. 2001, pp. 249–266 (cit. on pp. 96–98, 193).

[174] L. Novakova-Marcincinova. “Application of fused deposition modeling technology in 3D printing rapid prototyping area”. In: *Manuf. and Ind. Eng* 11.4 (2012), pp. 35–37 (cit. on pp. 102, 195).

[175] O. Dandgaval and P. Bichkar. “Rapid prototyping technology-study of fused deposition modeling technique”. In: *International Journal of Mechanical and Production Engineering* 4.4 (2016), pp. 44–47 (cit. on p. 103).

[176] R. V. Rao. *Advanced modeling and optimization of manufacturing processes: international research and development*. Springer Science & Business Media, 2010 (cit. on p. 113).

[177] S. Direct. *Design for additive manufacturability: FDM basics*. 2015 (cit. on p. 113).

[178] K.-H. Herrmann et al. “3D printing of MRI compatible components: Why every MRI research group should have a low-budget 3D printer”. In: *Medical engineering & physics* 36.10 (2014), pp. 1373–1380 (cit. on p. 114).

[179] M. Fernandez-Vicente et al. “Effect of Infill Parameters on Tensile Mechanical Behavior in Desktop 3D Printing”. In: *3D Printing and Additive Manufacturing* 3.3 (2016), pp. 183–192 (cit. on p. 114).

[180] M. Domingo-Espin et al. “Mechanical property characterization and simulation of fused deposition modeling Polycarbonate parts”. In: *Materials & Design* 83 (2015), pp. 670–677 (cit. on p. 114).

[181] A. Boschetto, V. Giordano, and F. Veniali. “3D roughness profile model in fused deposition modelling”. In: *Rapid Prototyping Journal* 19.4 (2013), pp. 240–252 (cit. on pp. 121, 126, 201).

[182] P. M. Pandey, N. V. Reddy, and S. G. Dhande. “Improvement of surface finish by staircase machining in fused deposition modeling”. In: *Journal of materials processing technology* 132.1 (2003), pp. 323–331 (cit. on pp. 121, 201).

[183] U. Yaman. “Shrinkage compensation of holes via shrinkage of interior structure in FDM process”. In: *The International Journal of Advanced Manufacturing Technology* (2017), pp. 1–11 (cit. on p. 124).

[184] A. Boschetto and L. Bottini. “Triangular mesh offset aiming to enhance Fused Deposition Modeling accuracy.” In: *International journal of advanced manufacturing technology* 80 (2015) (cit. on p. 127).

[185] M. Taufik and P. K. Jain. "A study of build edge profile for prediction of surface roughness in fused deposition modeling". In: *Journal of Manufacturing Science and Engineering* 138.6 (2016), p. 061002 (cit. on p. 127).

[186] A. DeCicco. "Effect of build parameters on Additive materials". A Major Qualifying Project Report Submitted to the Faculty of the of the WORCESTER POLYTECHNIC INSTITUTE. PhD thesis. MIT Lincoln Laboratory, 2013 (cit. on pp. 128, 176, 202).

[187] A. S. of Testing and Materials. *Standard Test Method for Tensile Properties of Plastics*. ASTM. 2003 (cit. on p. 128).

[188] A. Q. Ala'aldin Alafaghani and M. A. Ablat. "Design Consideration for Additive Manufacturing: Fused Deposition Modelling". In: (2017) (cit. on p. 176).

[189] R. Ranjan, R. Samant, and S. Anand. "Integration of Design for Manufacturing Methods With Topology Optimization in Additive Manufacturing". In: *Journal of Manufacturing Science and Engineering* 139.6 (2017), p. 061007 (cit. on p. 176).

[190] A. Panesar et al. "Design framework for multifunctional additive manufacturing: coupled optimization strategy for structures with embedded functional systems". In: *Additive Manufacturing* (2017) (cit. on p. 177).

[191] X. Guo et al. "Self-supporting structure design in additive manufacturing through explicit topology optimization". In: *Computer Methods in Applied Mechanics and Engineering* (2017) (cit. on p. 177).

[192] *Discover the ultimate design optimization*. 2018. URL: https://www.esteco.com/modefrontier (visited on 06/07/2018) (cit. on p. 241).

[193] *modeFRONTIER 2016 Adds User Profiles to Improve CAE Optimization Workflows*. 2018. URL: https://www.engineering.com/BIM/ArticleID/12696/modeFRONTIER-2016-Adds-User-Profiles-to-Improve-CAE-Optimization-Workflows.aspx (visited on 06/07/2018) (cit. on p. 241).

Appendix A: FDM softwares

The significant parameters of Fused deposition Modeling (FDM) are identified by analysis of softwares which are used for preparing the STL file for printing. Three famous softwares of FDM are Makerbot, Cura, and Slic3r. The FDM parameters which is derived from Software settings are shown in Figure A.1, A.2 and A.3.

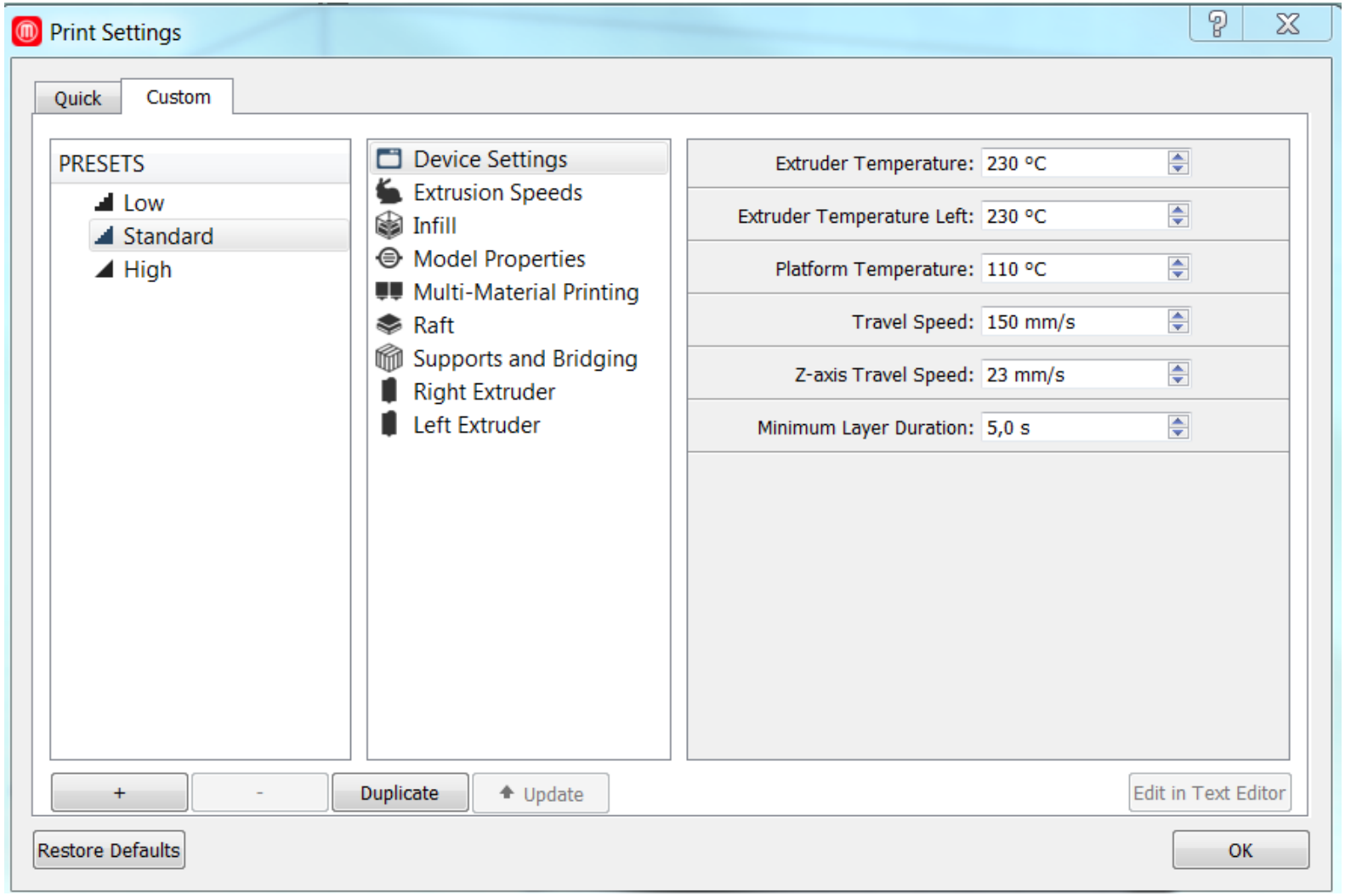


Figure A.1 – Makerbot custom settings

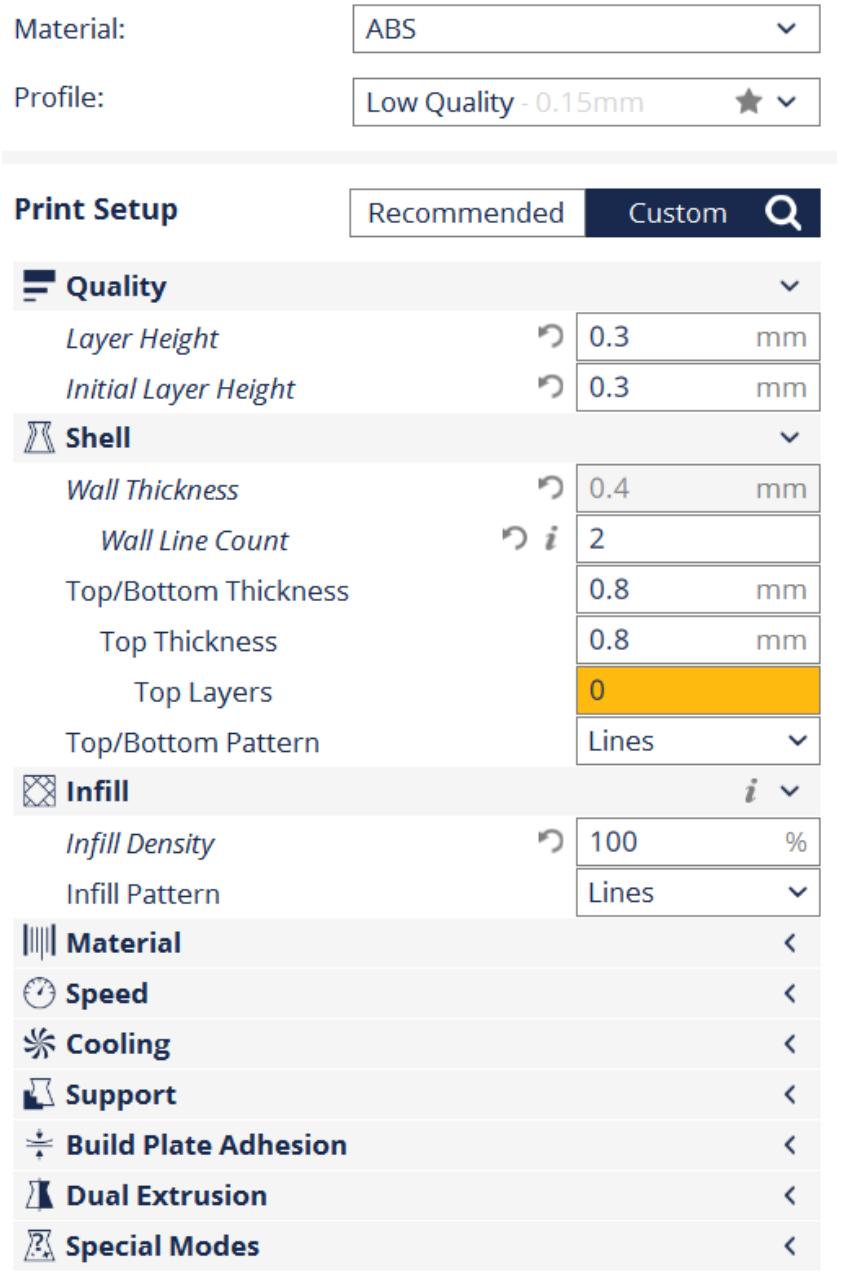


Figure A.2 – Cura 2.5 custom setting

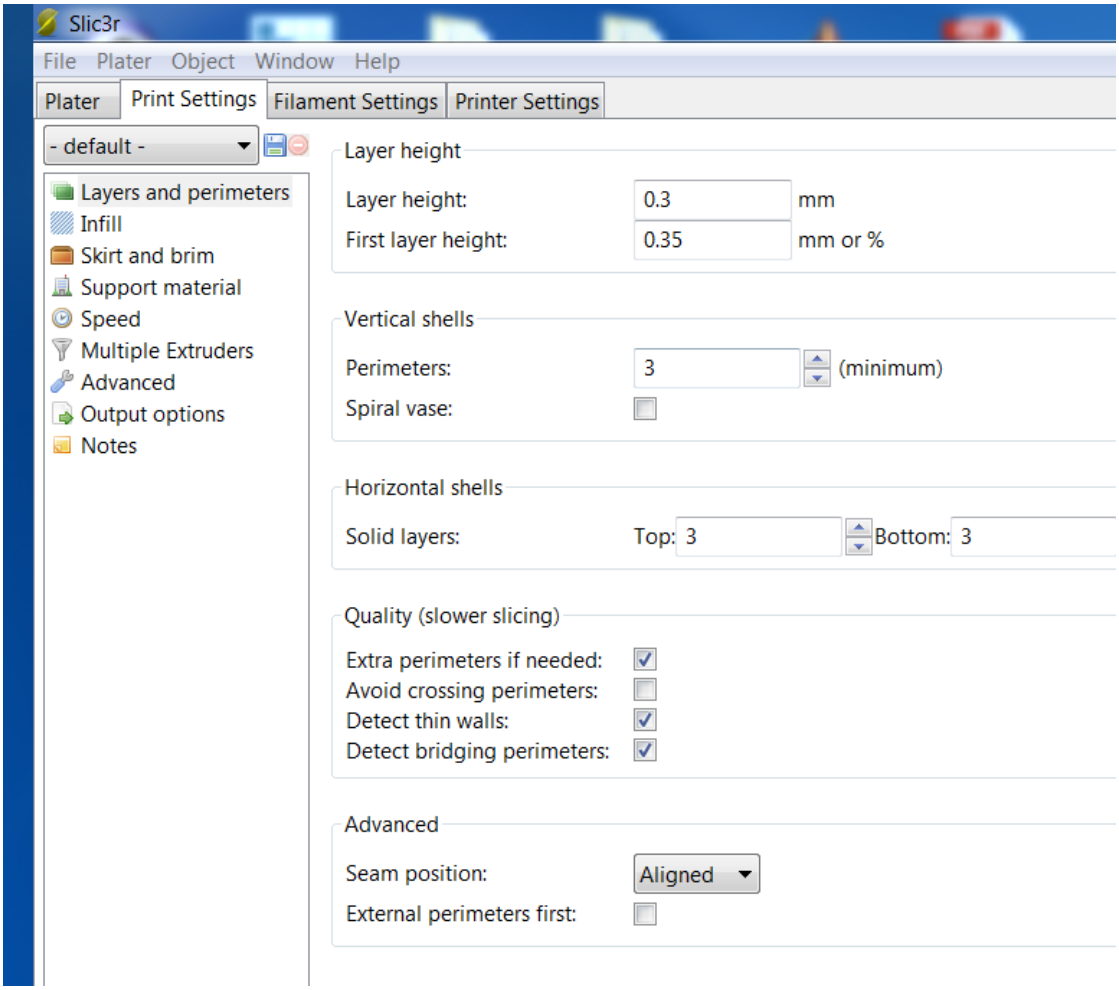


Figure A.3 – Slic3r custom setting

Appendix B: G-code files

G-code is a language in which people tell computerized machine tools how to make something. It shows the tool path that machine crossed. Figure B.1 shows the code letters and their meanings. Also, an example of g-code file which is created by Cura is illustrated in Figure B.2 to show haw the manufacturing time and material mass through E value is calculated in MATLAB.

Letter	Meaning
Gnnn	Standard GCode command, such as move to a point
Mnnn	RepRap-defined command, such as turn on a cooling fan
Tnnn	Select tool nnn. In RepRap, a tool is typically associated with a nozzle, which may be fed by one or more extruders.
Snnn	Command parameter, such as time in seconds; temperatures; voltage to send to a motor
Pnnn	Command parameter, such as time in milliseconds; proportional (Kp) in PID Tuning
Xnnn	A X coordinate, usually to move to. This can be an Integer or Fractional number.
Ynnn	A Y coordinate, usually to move to. This can be an Integer or Fractional number.
Znnn	A Z coordinate, usually to move to. This can be an Integer or Fractional number.
U,V,W	Additional axis coordinates (RepRapFirmware)
Innn	Parameter - X-offset in arc move; integral (Ki) in PID Tuning
Jnnn	Parameter - Y-offset in arc move
Dnnn	Parameter - used for diameter; derivative (Kd) in PID Tuning
Hnnn	Parameter - used for heater number in PID Tuning
Fnnn	Feedrate in mm per minute. (Speed of print head movement)
Rnnn	Parameter - used for temperatures
Qnnn	Parameter - not currently used
Ennn	Length of extrudate. This is exactly like X, Y and Z, but for the length of filament to consume.
Nnnn	Line number. Used to request repeat transmission in the case of communications errors.
*nnn	Checksum. Used to check for communications errors.

Figure B.1 – G-code file description

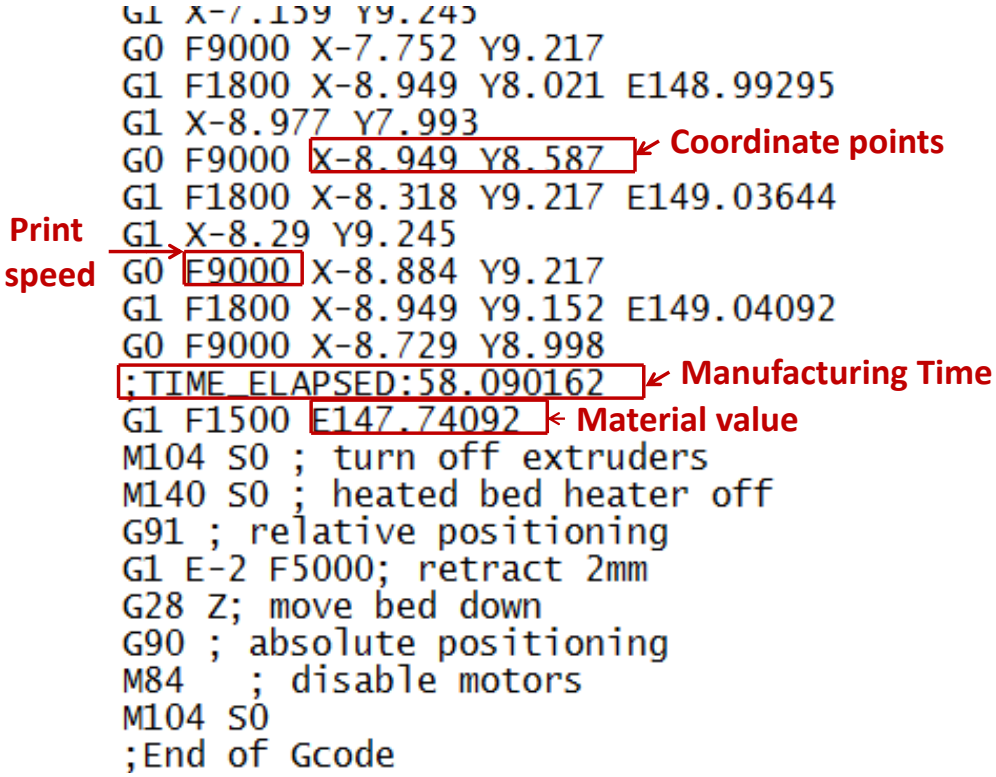


Figure B.2 – G-code file

Appendix C: modeFRONTIER

As mentioned in this thesis, modeFRONTIER is our software to provide meta-moodelling. ModeFRONTIER combines third-party computer-aided design (CAD) with computer-aided engineering (CAE) tools to allow for multi-objective and multidisciplinary optimizations. It is a powerful optimization environment that integrates with all calculation and simulation tools to enable multi-objective and multidisciplinary optimization. Figure C.1 illustrated its enviroment which dacilitate modeFRONTIER integration, process automation within a workflow-based environment, design space exploration, real and RSM based optimization, RSM model creation and training, robust design and reliability, as well as a set of post processing tools for data analytics and visualization and decision making [192, 193].

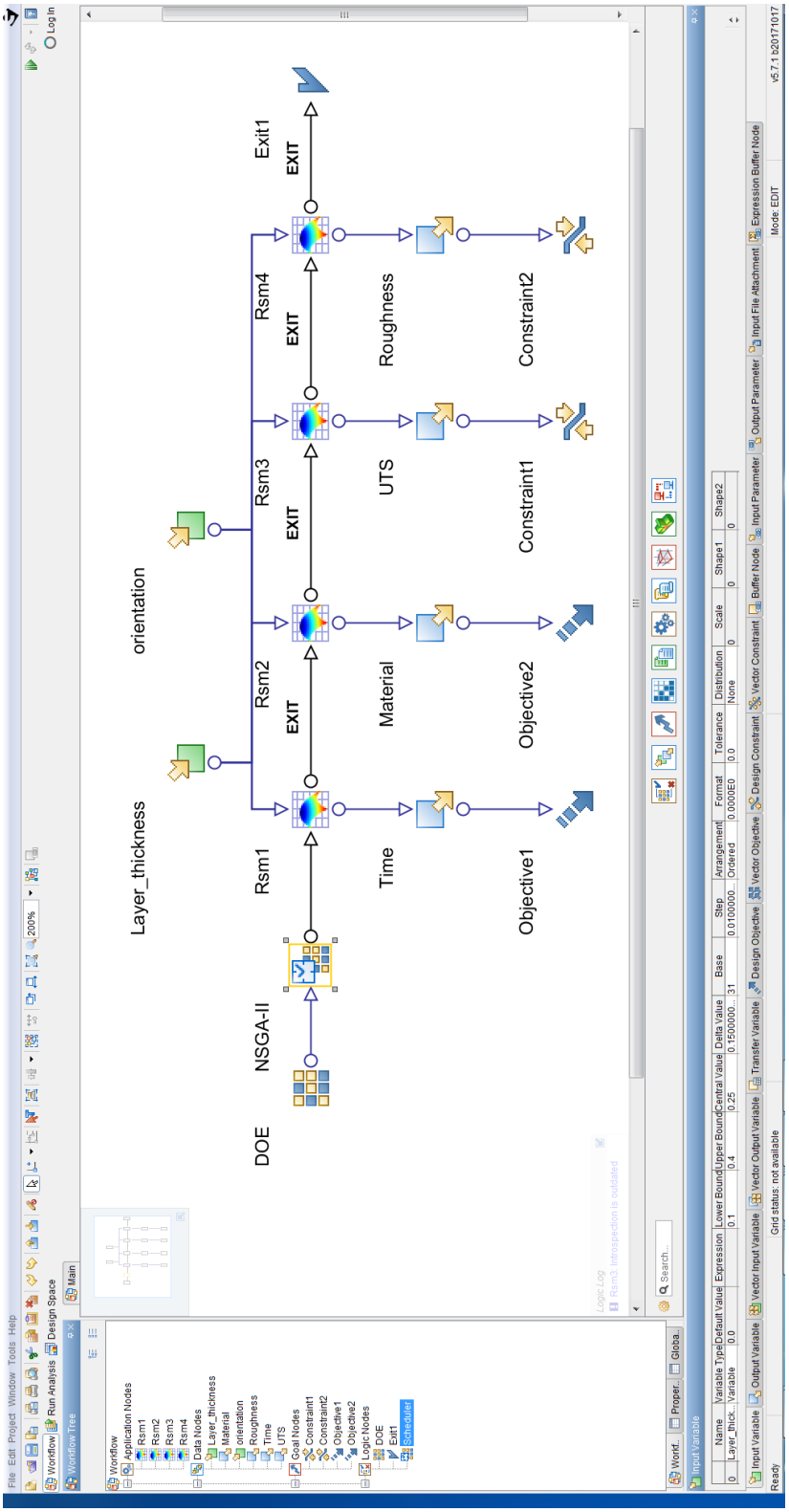


Figure C.1 – ModeFrontier Software environment

Appendix D: Finite Element Analysis for wheel spindle

To analyze the mechanical behavior of our spindle, Finite Element Analysis is performed. Firstly, axis and the pivots must be created to provide the functionality of the product. The steel axis is created to define the product functionality and two rigid virtual parts are also provided in order to apply pivots. To perform this analysis, firstly, Octree Tetrahedron Mesher is used to create a 3D mesh. ABS as a new material is added to the material library of CATIA and its characteristics during printing is supposed as desired characteristics (FigureD.2). The force must be imposed to the axis.

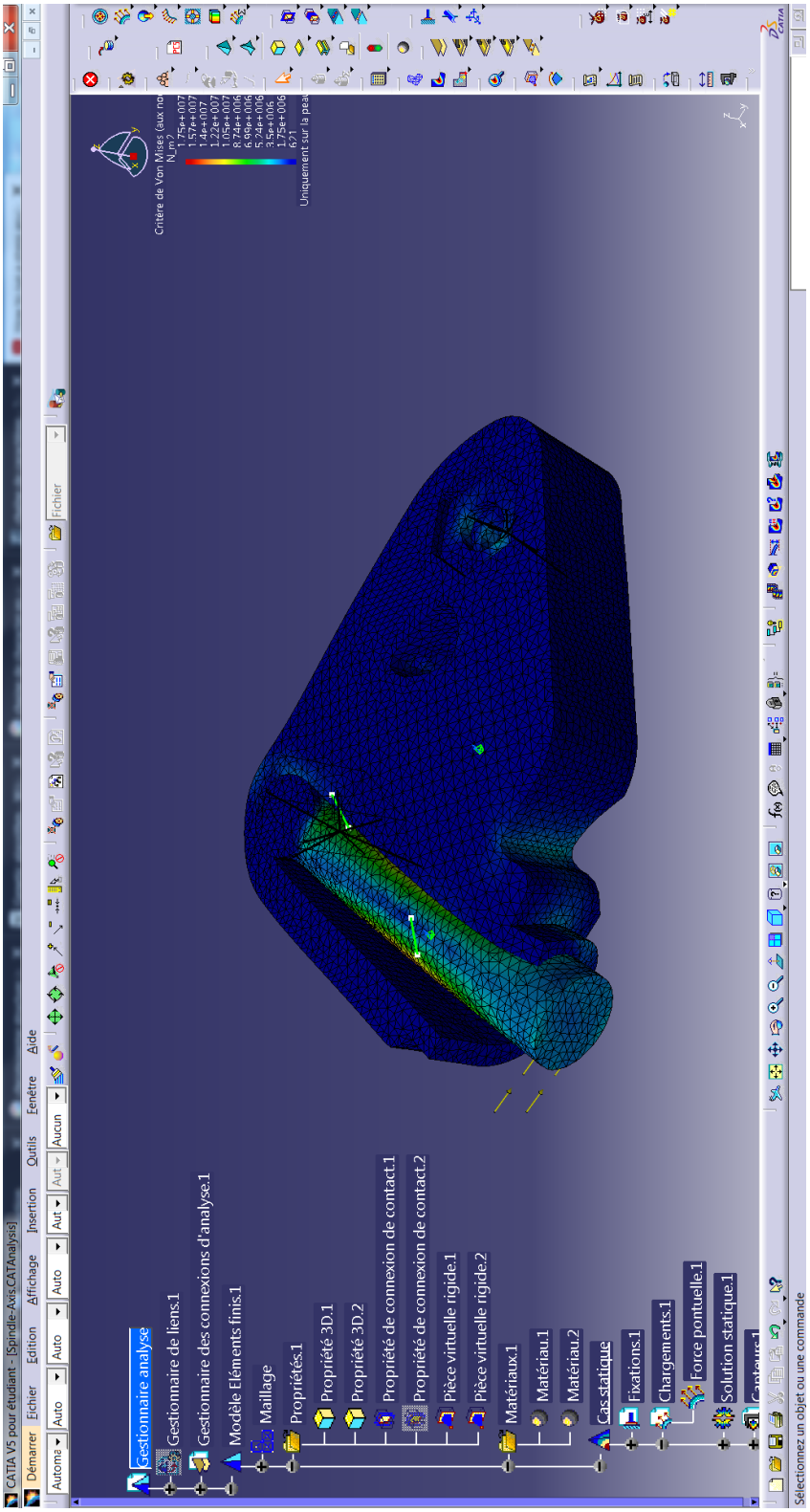


Figure D.1 – Finite Element Analysis (FEA) for wheel spindle

Technical data sheet ABS

Ultimaker

Mechanical properties (*)	Injection molding		3D printing	
	Typical value	**Test method**	**Typical value**	**Test method**
Tensile modulus	2030 MPa	ISO 527 (1 mm/min)	1681.5 MPa	ISO 527 (1 mm/min)
Tensile stress at yield	43.6 MPa	ISO 527 (50 mm/min)	39.0 MPa	ISO 527 (50 mm/min)
Tensile stress at break	-	-	33.9 MPa	ISO 527 (50 mm/min)
Elongation at yield	4.8 %	ISO 527 (50 mm/min)	3.5 %	ISO 527 (50 mm/min)
Elongation at break	34 %	ISO 527 (50 mm/min)	4.8 %	ISO 527 (50 mm/min)
Flexural strength	-	-	70.5 MPa	ISO 178
Flexural modulus	-	-	2070.0 MPa	ISO 178
Izod impact strength, notched (at 23°C)	-	-	10.5 kJ/m²	ISO 180
Charpy impact strength (at 23°C)	58 kJ/m²	ISO 179	-	-
Hardness	97 (Shore A)	-	-	-

Figure D.2 – ABS characteristics

Appendix E: List of publications

Outline of the current chapter

The following journal and conference papers have been produced as parts of outcomes of this research:

Refereed publications

- Asadollahi-Yazdi, E., Gardan, J., Lafon, P. (2018). Toward integrated design of additive manufacturing through a process development model and multi-objective optimization. The International Journal of Advanced Manufacturing Technology, 96(9-12), 4145-4164.
- Asadollahi-Yazdi, E., Gardan, J., Lafon, P. Bi-objective optimization applied to Design For Additive Manufacturing (In process).
- Asadollahi-Yazdi, E., Gardan, J., Lafon, P. Surface Roughness of Fused Deposition Modelling (In process).

Conference publications

- Asadollahi-Yazdi, E., Gardan, J., Lafon, P. (2016). Integrated Design in Additive Manufacturing Based on Design for Manufacturing. World Academy of Science, Engineering and Technology, International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering, 10(6), 1144-1151.
- Asadollahi-Yazdi, E., Gardan, J., Lafon, P. (2017). Integrated design for additive manufacturing based on skin-skeleton approach. Procedia CIRP, 60, 217-222.
- Asadollahi-Yazdi, E., Gardan, J., Lafon, P. (2018). Multi-objective optimization of Additive Manufacturing process, IFAC Symposium on Information Control Problems in Manufacturing (INCOM 2018), accepted.

Elnaz ASADOLLAHIYAZDI

Doctorat : Matériaux, Mécanique, Optique et Nanotechnologie

Année 2018

Conception intégrée pour les procédés de fabrication additive basée sur les modèles DFM de peaux-squelettes

Aujourd'hui, la fabrication additive (FA) fait évoluer le monde de la fabrication grâce à ses capacités de production de formes complexes couche par couche. L'approche de conception pour la fabrication (DFM) aide à considérer les contraintes de FA et à maîtriser les caractéristiques du produit dans la gestion de son cycle de vie. Plusieurs études sont consacrées à l'approche de conception intégrée pour la FA, mais aucune approche ne prend en compte toutes les étapes du cycle de vie du produit dans le niveau d'optimisation de sa conception et de sa fabrication. Ainsi, cette thèse fournit une approche DFM pour la FA afin d'étudier simultanément différents attributs, contraintes et critères de conception et de fabrication dès la définition du produit. L'approche Peau-Squelette modélise la première définition du produit. Il contient une analyse fonctionnelle, un modèle d'usage et un modèle de fabrication. Dans ce travail, un nouveau moteur de résolution, qui agit à l'interface du modèle de produit et du modèle de fabrication, est proposé grâce à l'analyse des technologies FA et de leurs paramètres et critères. Ce moteur repose sur un problème d'optimisation bi-objectif pour minimiser le temps de production et la masse du matériau en proposant les solutions optimales pour les propriétés mécaniques et la rugosité du produit. Cette méthodologie permet de définir le modèle de produit. L'approche est mise en œuvre à travers une première technologie de dépôt par fil fondu (FDM) pour la production de deux études de cas.

Mots clés : prototypage rapide - conception technique -procédés de fabrication - analyse du cycle de vie - décision multicritère – optimisation mathématique.

Integrated Design of Additive Manufacturing Based on Design for Manufacturing and Skin-skeleton Models

Nowadays, Additive Manufacturing (AM) evolves the manufacturing world by its capabilities for production of the complex shapes layer by layer. Design For Manufacturing (DFM) approach helps to overcome the AM constraints and mastering product features in product lifecycle. Several studies are devoted to integrated design approach for AM, but there is no approach that considers all product life cycle steps in optimization level for product and manufacturing process. So, this thesis provides a DFM approach for AM to investigate simultaneously different attributes, constraints, and criteria of design and manufacturing in product definition. Skin-Skeleton approach models the first definition of product and AM. It contains functional analysis, usage model, and manufacturing model. In this work, a novel interface processing engine as an interface between product and manufacturing model is developed through analysis of AM technologies and their parameters and criteria. This engine relies on a bi-objective optimization problem to minimize production time and material mass under limitation of mechanical properties and roughness of the product to obtain the optimal manufacturing parameters. This methodology permits to define the product model. The approach is implemented into Fused Deposition Modeling to verify the methodology through two case studies.

Keywords: rapid prototyping - technical design - manufacturing processes - life cycle analysis - multi-criteria decision making – mathematical optimization.

Thèse réalisée en partenariat entre :

Ecole Doctorale "Sciences pour l'Ingénieur"