A SUSTAINABLE APPROACH TO LARGE SCALE ADDITIVE MANUFACTURING: WORKFLOW DEVELOPMENT AND DESIGN GUIDELINES

Lappeenranta–Lahti University of Technology LUT

Master’s Thesis in Mechanical Engineering

2023

Alireza Badiee

Examiners: Professor Juha Varis, D.Sc. (Tech.)

Amir Togiani, D.Sc. (Tech.)

Advisor: Antti Alonen (Research advisor)

ABSTRACT

Lappeenranta–Lahti University of Technology LUT

LUT School of Energy Systems

LUT Mechanical Engineering

Alireza Badiee

A Sustainable Approach to Large Scale Additive Manufacturing: Workflow Development and Design Guidelines

Master's thesis

2023

88 pages, 46 figures, 6 tables

Examiners: Professor Juha Varis and Amir Togiani, D.Sc. (Tech.)

Advisor: Antti Alonen (Research Advisor)

Keywords: Largescale additive manufacturing, 3D printing, sustainable manufacturing, pellet extrusion, robotic programming, design guidelines, Design for LSAM

The global population increase has driven demand for tools, goods, and services. To meet this demand sustainably, industry must prioritize environmentally friendly manufacturing methods. Additive manufacturing, an eco-beneficial method, can revolutionize modern industry by reducing waste, minimizing emissions, enabling localized manufacturing, and offering design flexibility. Recent advancements in robotic technology have overcome size and movement constraints, allowing for larger-scale and faster production. Polymer-based additive manufacturing dominates the market, but improved pellet extruders that can extrude cost-efficient pellets at high speeds are being developed to increase deposition rates. This technology has the potential to enhance manufacturing efficiency, reduce costs, and shorten lead times, promoting sustainability. However, further refinement is required, particularly in dedicated software solutions and design guidelines. This thesis proposes an integrated workflow for robotic additive manufacturing, encompassing all stages of software development in a single program with high mass customization capacity. Laboratory testing has validated the workflow, introducing design considerations for large-scale additive manufacturing. The research contributes to the development of integrated software solutions and design guidelines, facilitating more sustainable and efficient manufacturing processes.

ACKNOWLEDGEMENTS

This thesis represents the culmination of my intense passion for large-scale additive manufacturing, which developed during my work in polymer additive manufacturing. I am deeply grateful for the opportunity to pursue my passion and for the tremendous support I have received from numerous individuals throughout my journey.

First and foremost, I would like to express my gratitude to my supervisors, Professor Juha Varis and D.Sc. (Tech.) Amir Togiani, whose invaluable feedback and unwavering support were instrumental in the successful completion of my master's thesis. Their encouragement and confidence in my abilities provided me with the strength to overcome any challenges that arose, and I could always rely on their assistance whenever necessary.

I would also like to extend my gratitude to my manager, Esä Jääskeläinen, and my research advisor, Antti Alonen, at Savonia University of Applied Sciences, for affording me the opportunity to delve into the fascinating world of technology development in the field that truly inspires me. Without their constant support and guidance, this thesis would not have been possible. Additionally, I am indebted to my colleagues, Lauri Alonen and Sampsa Ylönen, who generously shared their knowledge and experience with me, provided constructive feedback and support, and taught me invaluable lessons that I will carry with me throughout my career.

Alireza Badiee

ABBREVIATIONS

2D	2 dimensional
3D	Three-dimensional
ABS	Acrylonitrile Butadiene Styrene
AI	Artificial intelligence
AM	Additive manufacturing
BAAM	Big area additive manufacturing
BREP	Boundary representation
CAD	Computer-aided design
CAM	Computer-Aided Manufacturing
CF	Carbon fibre
CFRP	Carbon fibre reinforced plastic
CNC	Computer numerical control
DED	Directed Energy Deposition
DfAM	Design for Additive manufacturing
DfM	Design for Manufacturing
EBAM	Electro beam additive manufacturing
FDM	Fused deposition modelling
FGF	Fused granulate deposition
GF	Glass Fibre
GH	Grasshopper
LFAM	Large format additive manufacturing
LSAM	Large scale additive manufacturing

LUT	Lappeenranta–Lahti University of Technology LUT
MDF	Medium-density fibreboard
NC	Numerical Control
NURB	Non-uniform rational basis spline
PA	Polyamide
PE	Polyethylene
PEEK	Polyetheretherketone
PEKK	Poly-ether-ketone-ketone
PLA	Polylactic acid
PP	Polypropylene
RPC	Reinforced plastic composite
STL	Standard Tessellation Language
WAAM	Wire arc additive manufacturing

Table of contents

1 Introduction

Additive Manufacturing (AM) is increasingly recognized as a promising tool for sustainable manufacturing and circular economy practices. By minimizing the material waste, reducing energy consumption, and optimizing resource utilization, AM can contribute to mitigating the environmental impact of manufacturing (Stock and Seliger, 2016). In addition, the capability of AM to provide custom products and faster lead times has the potential to promote time-saving and develop new business models This technology offers great potential for achieving a more sustainable and efficient manufacturing process while improving product performance. (Ford and Despeisse, 2016.)

Although AM has many advantages, the size of the components that can be made with the current technology is quite restricted. Because of this, there is an ever-increasing demand for creative solutions to increase the scale of additive manufacturing in industrial settings and for the manufacture of ground-breaking new products. The technology known as large-scale additive manufacturing (LSAM) can help with this problem by allowing the creation of large parts and tooling. However, designing for LSAM calls for a new strategy and a deep familiarity with the technology and its limitations. It is crucial for designers to understand LSAM technology since the design of parts and products can greatly affect the quality, efficiency, and accuracy of the final result. (Vicente et al., 2023.)

One way to extend the size of industrial products and components is by using robotic additive arms. This system enables the production of large-scale products with high accuracy, efficiency, and cost-effectiveness. However, the lack of an integrated software solution or underdeveloped software in the market is the biggest issue facing the adoption of LSAM technology. Therefore, there is a need for software development to overcome this challenge. (Urhal et al., 2019.)

This Master's thesis aims to investigate an integrated software solution for robotic additive manufacturing. The study will examine the technical challenges faced in developing software for LSAM, including the need for real-time control and monitoring of the robotic arm, the integration of CAD/CAM software, and the incorporation of simulation and optimization tools. Additionally, the study will investigate the impact of software on the performance and functionality of the LSAM system, including the reduction of material waste, the optimization of print time, and the improvement of quality and precision.

The objective of this thesis is to augment the existing body of knowledge on LSAM software development and to pinpoint prospective domains for enhancement. The results obtained from this study may serve as a valuable reference for guiding future research and development endeavours in the field of LSAM software design. Additionally, the findings may offer valuable insights into the adoption of this technology within the manufacturing industry. The research will furnish pragmatic directives and suggestions to software developers, designers, and engineers for the efficacious integration of LSAM with robotic additive arms and for the comprehensive utilization of the advantages of this technology.

1.1 Research Background

Additive manufacturing is a relatively new process of manufacturing whereby parts are created by adding materials layer by layer on top of each other. This process utilizes various technologies and materials including polymers, metals, ceramics, concrete, and biomaterials. Historically, most 3D printers have had small build volumes, typically less than 1 m3, and were referred to as desktop printers. However, recent years have seen a surge in additive manufacturing technologies with larger printing volumes. These technologies include building construction systems such as stereolithography, selective laser sintering, electron beam additive manufacturing (EBAM), wire arc additive manufacturing (WAAM), gel dispensed printing, as well as in polymer fused filament and pellet fabrication. (Gibson, Rosen and Stucker, 2015.)

ResearchAndMarkets (2020) has reported that the worldwide market for pellet extrusion 3D printing is anticipated to experience a Compound Annual Growth Rate (CAGR) of 14.6% between 2020 and 2025. This growth is attributed to the escalating requirement for large-scale 3D printing in various industries, including aerospace, automotive, and construction. The report highlights the increasing popularity of pellet extrusion technology, owing to its capacity to utilize a broader spectrum of materials such as recycled plastics and carbon fiber composites. This feature of the technology can facilitate the circular economy by reducing waste and promoting sustainability. (Vicente et al., 2023.)

In terms of industrial applications, several companies have adopted pellet extrusion technology for large scale additive manufacturing. For example, Stratasys, a leading 3D printing company, offers pellet extrusion technology as part of its F900 Production 3D Printer, which is utilized in industries of aerospace, automotive, and defense to produce large-scale components with high accuracy and repeatability.

The Journal of Manufacturing Systems published a study which examined the utilization of robotic arms in large scale additive manufacturing. The study concluded that robotic arms are highly suitable for this purpose, as they offer a significant level of flexibility and precision in the production of parts. The research further highlights that the integration of robotic arms with additional motion systems, such as gantry systems, can enhance the magnitude and intricacy of the manufactured components. (Watson et al., 2019.)

However, as mentioned earlier, there are still several challenges that they are to be addressed in the implementation of this technology, such as ensuring accurate and consistent material deposition, optimizing the design and control of the robotic arm, and developing integrated software solutions to streamline the production process (Watson et al., 2019); (B. K. Post et al., 2016) A workflow comparison between robotics and FDM technology for small-scale additive manufacturing is shown in Figure 1.

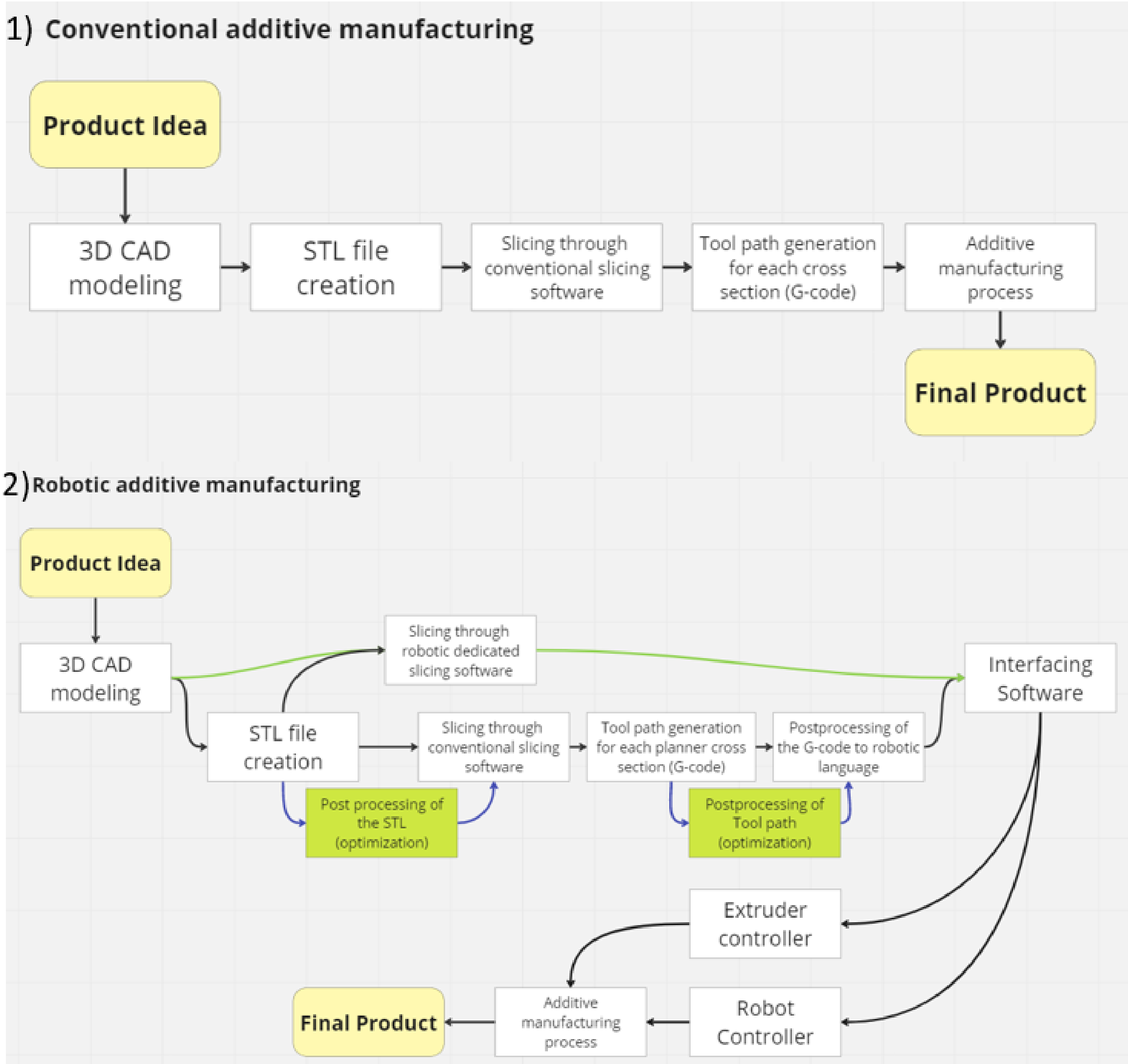


Figure 1. Work flow of 1- Conventional additive manufacturing vs. 2- robotic additive manufacturing (Adapted from (Urhal et al., 2019)).

During this master's studies, the author of the current study has developed a keen interest in large-scale additive manufacturing of polymer composites and had the opportunity to join Savonia University of Applied Sciences' 3DROBO group. Throughout three months of training and research on this topic, the author discovered that software plays a vital role in robotic printing. The latest practices used by many players in the field involve combining multiple software programs designed for other additive manufacturing procedures. This approach creates numerous faults, reduces workflow efficiency, and prevents the maximum potential of robotic manufacturing from being realized.

Although a few slicing and robotic programming solutions for LSAM are available on the market, they are either in early or mid-stage development. Additionally, every robotic system has a specific programming syntax, making it necessary to translate data for each system individually. Moreover, the complexity of the calculations required to run the program for robotic systems with more than three axes of motion can lead to buffering lags and result in motion control and printing quality issues. The software puzzle's inability to integrate seamlessly is another factor contributing to these problems. The solutions currently available on the market only partially mitigate these workflow inconsistencies and are prohibitively expensive due to a lack of market competition.

Given these challenges and the needs of current research group in which the project is ongoing, the authors and colleagues are working on finding solutions for integrating user-friendly, coherent software for robotic additive manufacturing. The goal is to create a cost-effective and efficient solution that can potentially transform the LSAM process.

1.2 Identifying the Research Problem and Objectives of the Study

Additive manufacturing using robotic pellet extrusion is a promising technology for large-scale manufacturing due to its ability to produce complex geometries with high precision and material efficiency. However, despite its potential, there is a lack of research and development of effective workflow and software solutions for this technology.

One major challenge in using robotic pellet extrusion is the need for a multi-step workflow that includes design, slicing, toolpath generation, creation of robot program, and possibly simulation of the manufacturing process. Currently, these steps are often carried out using separate software tools, which can lead to inefficiencies, errors, and longer lead times.

Ideally, a comprehensive workflow solution that integrates all of these steps into one software tool would be developed. Such a solution would provide a seamless and efficient process for designing and manufacturing parts using robotic pellet extrusion. This would allow for faster design iterations, reduce the risk of errors, and ultimately lower the overall cost of production. (Additive Manufacturing Market Size Report, 2020.)

Thus, the aim of this research is to develop a more streamlined and efficient workflow solution for large-scale additive manufacturing using robotic pellet extrusion. This would involve exploring existing software solutions and identifying gaps in the current workflow. The research would then focus on developing a software tool that integrates all the necessary steps, while also taking into account the unique challenges and constraints of using robotic pellet extrusion.

1.3 Objective of the research

The primary objective of this research is to develop a software solution for large-scale additive manufacturing using robotic pellet extrusion that is optimized for the manufacturing of composite lamination molding. This initiation is going to be the proposed solution which will be built on the Rhinoceros Grasshopper platform, with the integration of KUKA PRC and additional plugins. The software will enable designers to create their designs within a single software environment, while allowing for the generation of the necessary toolpaths and robot programs for large-scale additive manufacturing using robotic pellet extrusion.

Specifically, this research will focus on the development of an angled slicing technique for the generation of toolpaths that will be used for the machining of the extruded pellet material in composite lamination molding. Additionally, the software will include post-processing tools to optimize the generated toolpaths for KUKA robotic arms. A number of test prints will be conducted to evaluate the effectiveness of the proposed software solution. Overall, the proposed software solution will provide designers with a more efficient and user-friendly approach to large-scale additive manufacturing using robotic pellet extrusion for composite lamination molding.

1.4 Research questions

The research questions for this study are based on the identified research problem and objectives. The ultimate goal of the research is to develop a more streamlined and efficient workflow solution for large-scale additive manufacturing using robotic pellet extrusion, with a focus on the manufacturing of composite lamination molding. To achieve this goal, the following research questions will be explored:

- What are the existing software solutions and what are the gaps in the current workflow of additive manufacturing using robotic pellet extrusion, and how can they be addressed through a comprehensive software solution?
- How can the development of an angled slicing technique improve the toolpath generation process for large-scale additive manufacturing using robotic pellet extrusion?
- How can post-processing tools be used to optimize the generated toolpaths for KUKA robotic arms in the context of composite lamination molding?
- Is the proposed software solution workable for large-scale additive manufacturing using robotic pellet extrusion? Is integration of the workflows make the robot programming more efficient?
- What are the design considerations related to large scale additive manufacturing with robotic pellet extrusion?

1.5 Research Methodology

The research methodology of this study will be primarily quantitative and experimental in nature. The study will be conducted in two main phases. In the first phase, existing software solutions for large-scale additive manufacturing using robotic pellet extrusion will be reviewed and evaluated to identify gaps in the current workflow. In the second phase, a software tool will be developed and tested to determine its effectiveness in optimizing the workflow for large-scale additive manufacturing using robotic pellet extrusion.

The first phase of the study will involve a literature review and analysis of existing software tools for large-scale additive manufacturing. The aim of this phase will be to identify gaps in the current workflow and to develop a comprehensive understanding of the challenges and opportunities in this area. The literature review will be supplemented by a series of laboratory test that will provide real-world examples of how the existing software tools are being used in practice.

In the second phase of the study, a software tool will be developed and tested. The software will be built on the Rhinoceros Grasshopper platform, with the integration of

KUKA PRC and additional plugins. The software tool will be designed to provide a more streamlined and efficient workflow for large-scale additive manufacturing using robotic pellet extrusion. The software tool will be tested using a series of laboratory test approach that will evaluate its effectiveness in optimizing the workflow for large-scale additive manufacturing using robotic pellet extrusion. The results of the study will be analyzed using visual quality inspection to determine the effectiveness of the proposed software tool.

1.6 Laboratory testing

To evaluate the effectiveness of the developed software solution for large-scale additive manufacturing using robotic pellet extrusion, a series of laboratory tests will be conducted. The laboratory test will involve the fabrication of composite lamination molding parts using the proposed software solution. The parts will be fabricated on a KUKA robot using pellet extrusion with a variety of design geometries.

The test will evaluate the efficiency and accuracy of the proposed software solution in terms of the time taken for fabrication, the material efficiency, and the precision of the parts produced. The test results will be analyzed and compared with the results obtained from the traditional manufacturing process to determine the effectiveness of the proposed software solution.

1.7 The Significance of Findings in Advancing the Field

The significance of this study lies in its potential to address the current gaps and challenges in large-scale additive manufacturing using robotic pellet extrusion. The proposed comprehensive software solution has the potential to significantly improve the efficiency and accuracy of the manufacturing process, while reducing lead times and overall costs. The angled slicing technique and post-processing tools specifically tailored for robotic pellet extrusion will provide designers with a more user-friendly and streamlined approach to creating complex geometries. The results of this study can have significant implications for various industries, such as aerospace and automotive, where large-scale manufacturing with high precision and material efficiency is essential.

1.8 Research limitations and directions of the study

There exist multiple constraints to this research that necessitate careful consideration. The manufacturing process and software are interdependent on several factors, including but not limited to the material type, part application and design, machinery type, part geometry, and desired mechanical properties. Hence, it is plausible that the suggested software solution may not be universally relevant to all manufacturing scenarios and may necessitate additional customization or development to fulfill particular prerequisites.

This study is centered on the creation of a software-based remedy for the purpose of facilitating extensive additive manufacturing through the utilization of robotic pellet extrusion in the context of composite lamination molding. Although the proposed solution exhibits potential advantages for diverse industries and applications, it may not be feasible to extrapolate the results to other manufacturing processes or technologies.

Prospective avenues for research may encompass broadening the purview of the software solution to encompass additional manufacturing processes and technologies, as well as delving deeper into the potential advantages of the suggested solution in diverse industrial contexts. Additional research could be undertaken to examine the effects of different variables, including material characteristics, equipment configurations, and component shapes, on the effectiveness and precision of the suggested software remedy.

2 Methods

This paper represents an exploratory attempt to contribute to the emerging field of large-scale additive manufacturing. The first step in this research endeavor involved conducting a comprehensive literature review, which served to identify current challenges and the current status of the field. From the background review, the research questions and problems were derived.

Subsequent analysis indicated that two major issues confronting the field of robotic additive manufacturing are the absence of a coherent software solution and design guidelines. To address these issues, a straightforward workflow for robotic programming was developed, and a series of laboratory tests were conducted to identify some of the fundamental design considerations for large-scale additive manufacturing.

This study serves as a preliminary exploration of this exciting and rapidly expanding field. The insights obtained from this research effort may assist in the development of more comprehensive solutions to the challenges confronting large-scale additive manufacturing. As such, it is hoped that this paper will encourage further research in this area and contribute to the advancement of the field.

The main projects of the thesis are explained in this chapter. An extensive analysis of relevant literature on large-scale additive manufacturing that is centered on the research objective is first presented. The literature review was conducted in order to give the author some background on the developments this thesis proposes. The tools, programs, and resources used for this thesis's scope are then discussed in detail. Last but not least, thorough accounts of the tests carried out and the ensuing evolution of workflow are given. The results section includes the findings from the tests mentioned above and the workflow development.

2.1 Related literature

Mishra, Suresh, and Sundararajan (2021) analysed the current state of material extrusion-based additive manufacturing systems and their potential for future development. They discussed the different technologies and equipment used in large-format additive manufacturing and focused on polymer-based fused deposition LFAM equipment. The authors highlighted the importance of increasing build volumes and identified the use of pellet-based feedstock systems as a way to improve production times and reduce costs. They also emphasized the need for improved material properties to prevent errors and ensure stable processes. The authors concluded that further research and development in materials, design, and simulation procedures are needed to fully realize the potential of large-format additive manufacturing.

Several reports have emphasized the potential for expanding the scale of additive manufacturing (AM) technologies and the necessity of augmenting the build volume of 3D printers. Alongside the expansion in dimensions, advancements in materials, design and simulation methodologies, standards, and intellectual property are also undergoing transformation. The present study provides an overview of the current status of polymer-based fused deposition LFAM machinery, which pertains to the large-format additive manufacturing (LFAM) methodologies that possess a build volume exceeding 1 m3. The majority of LFAM equipment utilize feedstock systems that are based on pellets composed of polymers. These systems involve melting the polymeric pellets and extruding them in real-time to create a fused filament that typically has a diameter exceeding 2.5 mm. This approach can significantly enhance production times, potentially up to 200 times, and reduce costs by a factor of 10, as it eliminates the need for an additional filament-extruding step that is typically required in non-pellet-based AM processes. The authors of the publication titled "Moreno Nieto and Molina" in the year 2020 have presented their research findings. (Moreno Nieto and Molina, 2020.)

2.1.1 Types of Large Format Additive Manufacturing Systems

In another review paper, Vicente et al. (2023) discusses the various techniques used for processing polymer-based materials in large-format additive manufacturing (LFAM). The authors provide a comprehensive review of the processing methods used in LFAM, including pellet extrusion, powder bed fusion, and sheet lamination. The authors additionally analyze the benefits and drawbacks of every technique and emphasize the principal obstacles linked with the manipulation of polymer-derived substances in the context of LFAM. The authors note that while pellet extrusion is the most commonly used technique for LFAM, powder bed fusion and sheet lamination offer several advantages, including the ability to print parts with complex geometries and the ability to use a wider range of materials. However, these methods also present unique challenges, such as the need for post-processing steps and limitations in the size of the parts that can be printed. The authors' deduction is that the distinct processing methods possess individual merits and difficulties. However, the progression of these techniques will be of utmost importance in propelling the domain of LFAM and facilitating the creation of extensive polymer-based components for diverse industrial purposes. (Vicente et al., 2023.)

2.1.2 Materials used in large scale additive manufacturing

The expansion of the build volume in additive manufacturing has resulted in an escalating demand for materials that possess distinct characteristics, including but not limited to stability in dimensions, low thermal contraction rates, and fluency. Enhancing these characteristics is of utmost importance in order to prevent potential defects, such as warping, delamination, cracks, or deformation, and to establish consistent procedures within the designated timeframe. In order to effectively choose suitable materials and enhance process conditions, it is imperative to possess a comprehensive comprehension of the rheological characteristics and crystalline properties of polymers. At present, there is ongoing research aimed at identifying appropriate materials for the aforementioned technologies. Academic scholars are currently engaged in an experimental methodology aimed at substantiating the suitability of materials for additive manufacturing on a large scale, particularly for non-fibrous bulk materials. The methodology entails regulating the melting flow index of the material and administering two manufacturing assessments on specifically devised testing specimens to identify potential warping, cracking, and delamination complications that may arise throughout the 3D printing procedure. (Moreno Nieto and Molina, 2020.)

The classification of additive manufacturing technologies can be bifurcated into two distinct categories, namely powder bed fusion and material extrusion. Powder bed fusion technologies encompass selective laser sintering (SLS) and direct metal laser sintering (DMLS). The category of material extrusion technologies encompasses fused deposition modeling (FDM), stereolithography (SLA), and digital light processing (DLP). The selection of technology is contingent upon the particular application requirements, as each technology possesses distinct advantages and disadvantages. (Cleeman et al., 2022.)

The utilization of pellet extrusion for polymer composites in large-scale additive manufacturing has demonstrated significant potential in addressing the size constraints associated with conventional 3D printing. The utilization of pellets as feedstock in this technology is deemed to be cheaper and more effective in comparison to filaments or powders. Furthermore, the utilization of composite materials is facilitated, thereby augmenting the characteristics of the printed entities. (Kampker et al., 2019.)

Various high-capacity additive manufacturing techniques are at disposal, such as the 3D printing method of robotic pellet extrusion. The utilization of robots as a printing platform in this technology facilitates the production of sizable structures in a manner that is characterized by enhanced flexibility and efficiency. The potential of technology has been demonstrated in diverse applications, such as the construction, aerospace industry, and automotive sectors. (El youbi El idrissi et al., 2022.)

However, there are also numerous challenges involved in large-scale additive manufacturing, especially in robotic pellet extrusion 3D printing. One of the major challenges is the lack of development in software and design guidelines for large-scale additive manufacturing. Existing software and design guidelines are often tailored for smaller-scale 3D printing and may not be applicable for large-scale additive manufacturing. This can lead to errors and inconsistencies in the printing process, which can result in poor quality of printed objects. (Duty et al., 2017.)

One of the challenges that this thesis aims to contribute in solving is the incorporation of workflow in robotic printing. This challenge involves the development of a workflow that integrates the various stages of the robotic pellet extrusion 3D printing process, from the design phase to the actual printing phase. The workflow should take into consideration the unique requirements of large-scale additive manufacturing and provide a systematic approach to ensure the quality of the printed objects. (Okur and Altan, 2021.)

2.1.3 Sustainable manufacturing through large scale additive manufacturing

The technology of large-scale additive manufacturing has brought about a significant transformation in the manufacturing sector, as it has facilitated the production of sizeable components that were previously challenging or unfeasible to manufacture using conventional manufacturing techniques. In contrast to conventional manufacturing techniques including injection molding and CNC milling, which employ subtractive procedures to fabricate a component by eliminating material out of a block, additive manufacturing adopts a stratified methodology to construct a component by supplementing material where it is required. (Murdy et al., 2021.) Figure 2 represents the manufacturing process stages for the traditional composite structure and additive/hybrid manufactured ones.

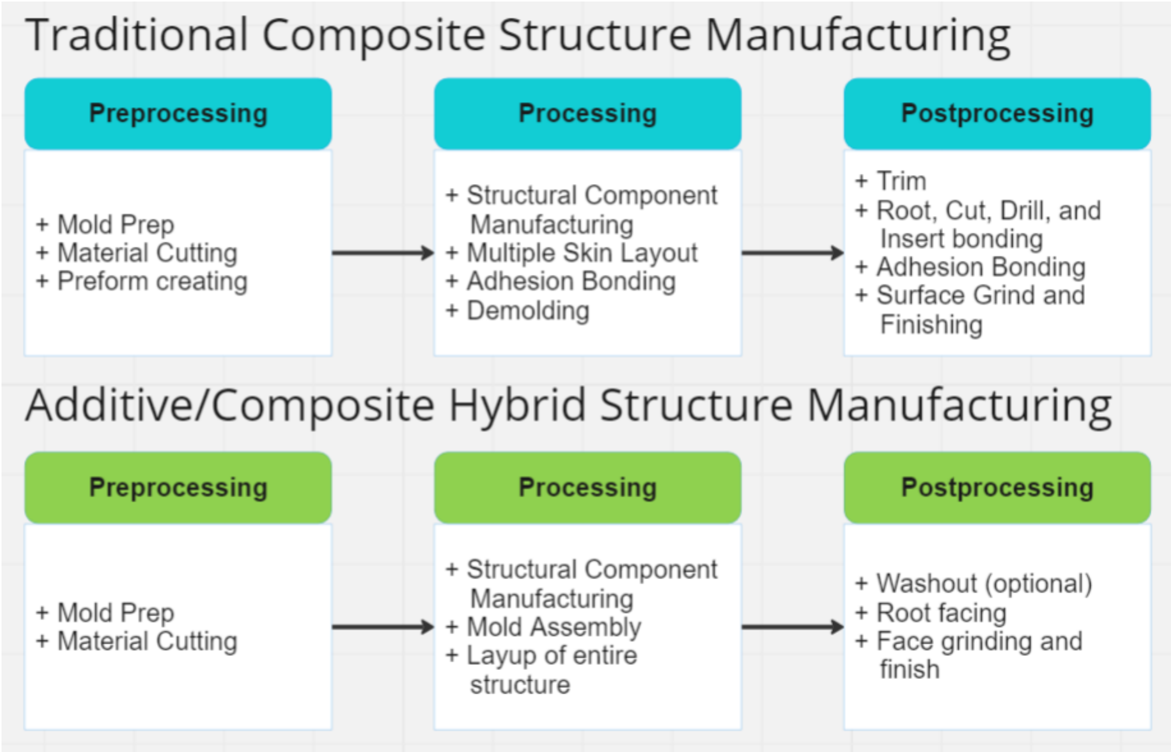


Figure 2. A comparison between traditional and AM process for Molds (Murdy et al., 2021).

One of the most important merits of large scale additive manufacturing is the use of pellet extruders, which offer greater flexibility in material mixing and nozzle diameter compared to filament extruders. This flexibility mitigates clogging issues associated with filament extrusion and enables the use of a variety of materials, including recycled materials that are typically more challenging to process. By incorporating recycled materials into the manufacturing process, the industry can reduce its environmental impact and lower costs associated with sourcing and producing new materials. (Ford and Despeisse, 2016.)

In addition to its material flexibility, additive manufacturing technologies offer design freedom and weight reduction. The capacity to fabricate components with reduced mass and optimal material utilization results in decreased material consumption and carbon emissions, yielding economic benefits and promoting a more environmentally friendly manufacturing approach. Additive manufacturing facilitates the fabrication of intricate geometries that pose challenges when using conventional manufacturing techniques, thereby affording engineers and designers greater leeway in design. (Ford and Despeisse, 2016.)

Furthermore, additive manufacturing processes can reduce lead times to production, which is essential for industries with fast-changing market demands. By eliminating the need for tooling and reducing the number of steps involved in the manufacturing process, additive manufacturing can accelerate the time it takes to produce a part, allowing manufacturers to respond quickly to changes in demand. (Post et al., 2018.)

Numerous studies have demonstrated the sustainability advantages of Large Scale Additive Manufacturing (LSAM) in industrial applications. Kim et al. (2018) utilized a complex infill structure and optimized printing toolpaths to reduce the mass of wind turbine blades, leading to high-speed production. A recent study conducted by Murdy et al. (2021) showcased the potential of LSAM in producing molds for wind turbines. This breakthrough in additive manufacturing highlights the possibility of introducing a new era of marine energy composite structures that are not only cost-effective and reliable but also environmentally friendly and technologically advanced. Kim et al. (2016) suggested that LSAM is a promising technology for precast concrete construction of buildings, providing design freedom to manufacture innovative modules and an energy-efficient method for manufacturing concrete casting molds. Romani et al. (2021), in a review article on circular economy through Additive Manufacturing, comprehensively reviewed use cases of recycled material with different extrusion-based AM in different applications, highlighting academia and industries' interest in LSAM for circular economy and sustainability goals, transforming waste into products. Two related articles by Murat Aydin (2015) and Pacheco (2020) explored the potential use of waste material in furniture manufacturing with LSAM systems, demonstrating the feasibility of this approach and the benefits of LSAM for sustainable manufacturing.

2.1.4 Design for Large scale additive manufacturing

Based on the research conducted by Gibson et al. , additive manufacturing (AM) possesses unique capabilities, which include the ability to construct shapes of high complexity, hierarchical structures with varying scales ranging from microstructure to macrostructure, processing of materials one layer at a time, and production of fully functional components and assemblies. Notably, most design constraints that pertain to small-scale polymer 3D printers are also applicable to Big Area Additive Manufacturing (BAAM). Nevertheless, it is crucial to take into account additional design rules and limits that are specific to the BAAM process once the primary constraints have been met. (Gibson, Rosen and Stucker, 2015.)

Understanding the process of translating a computer-aided design (CAD) model into G-Code is crucial in additive manufacturing. The first step is designing the component using software such as Rhino, Fusion 360, or Solidworks. The design is saved as an STL file which is then fed into a slicing program that slices it into layers and generates tool paths to produce G-Code. The slicing process involves contouring the STL file with a horizontal plane and moving it vertically to slice the entire part. The tool paths include perimeters, insets, and infill, which are generated based on user choices. The resulting G-Code contains instructions for the 3D printer on how to construct the part. The G-Code is exported from the slicer and saved as a text file that can be loaded into the printer. To design a successful model for BAAM in CAD, consider the desired width of the extruded material or bead. Avoid designing CAD models with parts that are too small, and precise multiplication of the bead width may be necessary for narrow sections. Larger sections can be more flexible due to infill usage.

To ensure toolpath compatibility, adjust the desired wall thickness according to the operator-input bead width settings for your slicing software. The computer program will place multiple closed loop routes in the affected area, and overlapping of center-most beads may be necessary to maintain the desired wall thickness. However, excessive overlapping may cause overfilling and potential part failure. (Alex Roschli et al., 2019.)

The design guidelines by Roschli et al. LSAM cover significant design concerns for additive manufacturing. There are physical design issues to consider when designing 3D printed objects, such as bridge printing, slow cooling plastic, and delamination. Bridging between two towers can cause drooping and breaking of molten plastic deposited on a large gap. A part's hollow structure must be self-supporting to prevent support material, and the cavity must have an opening to remove support material after printing. Layers printed in the X and Y orientations have most of the overall strength of the part. Fiber reinforcing does not increase Z-strength. Delamination happens when the layers of a part separate from each other, which is caused by inconsistent cooling or too much cooling of the part.

When employing small-scale machineries, geometric limitations can be overcome by using support material. This material helps to support parts of the design that may become deformed by gravity before they are completed. The support structure then is to be removed by removing it off the finished part and disposing of it or dissolving it in a solvent solution. However, the BAAM machine has a much larger construction volume which makes it difficult to remove the support material using conventional techniques. This is because the size of the pieces makes it challenging to remove the support material, and the high extrusion size results in a larger surface area for the support material to bond to the model. As a result, the BAAM process cannot use breakaway support material. (Alex Roschli et al., 2019.) Figure 3 depicts the design of experiment from the mentioned article.

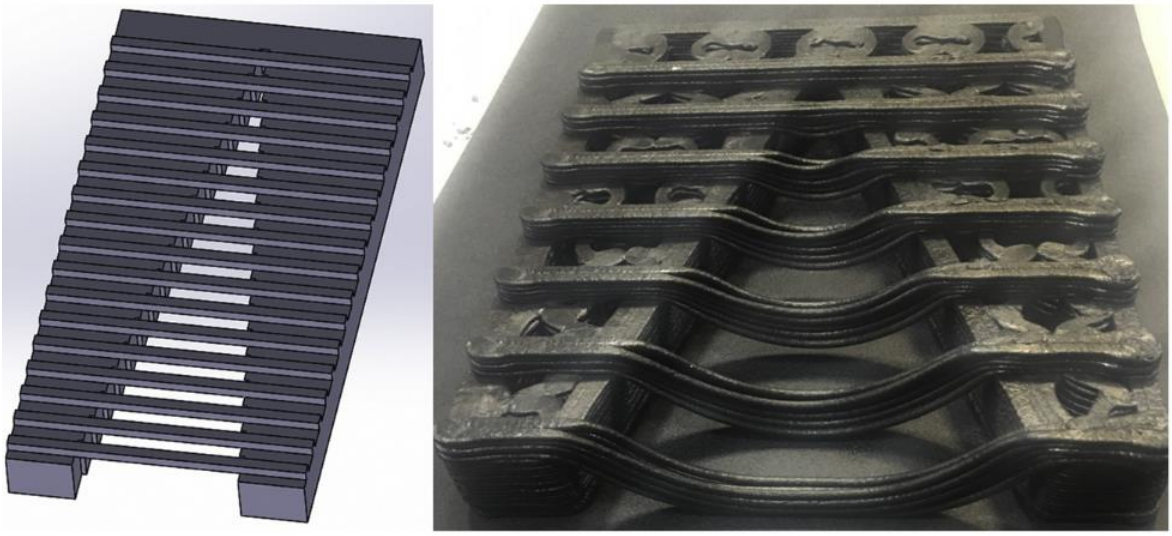


Figure 3. An example bridging design guideline test for Gantry BAAM (Alex Roschli et al., 2019).

One of the critical design considerations in Large Scale Additive Manufacturing (LSAM) pertains to the controllability of material throughput through the nozzle. In contrast to small-scale Fused Deposition Modeling (FDM) printing, the material flow in LSAM is influenced by constant high pressure in the screw extruder and fluid dynamics of the material in larger nozzle sizes. This limitation necessitates the use of continuous toolpath printing, which should be considered during the design phase. (Meraz Trejo et al., 2020.)

It is worth noting that LSAM involves the fabrication of large-scale objects, with dimensions spanning several meters. As such, the printing process requires a massive amount of material, which is fed into the printer through a screw extruder. The extruder's high-pressure mechanism, combined with the material's fluid dynamics in larger nozzle sizes, poses a significant challenge in controlling the material throughput out of the nozzle. (Sampedro et al., 2022.). Consequently, the use of continuous toolpath printing becomes a crucial aspect of LSAM, requiring careful consideration during the design phase. This highlights the importance of advanced planning and design optimization to ensure optimal quality and successful fabrication of large-scale objects. (Chesser et al., 2019.)

In their 2019 study, Roschli and colleagues proposed a design consideration for the extrusion of materials in 3D printing, which involved the creation of a single path that traverses each layer of the printed component. The goal of this approach was to enhance the printing process by eliminating non-printing moves, such as starts and pauses, and thereby reducing the printing time. (Roschli et al., 2019.)

The researchers tested their approach on a test print of a boat hull and found that the single route method reduced the time required for each layer by over 15% (19.79 seconds per layer). However, they noted that the actual time savings would depend on the geometry of the object being printed. Specifically, objects with a greater number of short individual paths would benefit from significant time savings, while those with fewer paths would see less time savings. (Roschli et al., 2019.)

Despite the promising results, the researchers cautioned that their findings were limited to objects with large formats, such as BAAM, due to geometric restrictions. Moreover, they noted that further research was needed to explore the application of this approach on a wider range of part geometries to conclusively demonstrate the projected time reductions. (Borish et al., 2019.)

To this end, the researchers proposed future work that would involve software algorithm development to eliminate the need for manual slicing in CAD, as well as mechanical testing to assess variations in material strength. Such efforts would be critical for the broader adoption of this approach in 3D printing and the realization of its potential benefits for reducing printing time. (Roschli et al., 2019.) Figure 4 describes the concept of creating a continuous path in from closed contour.

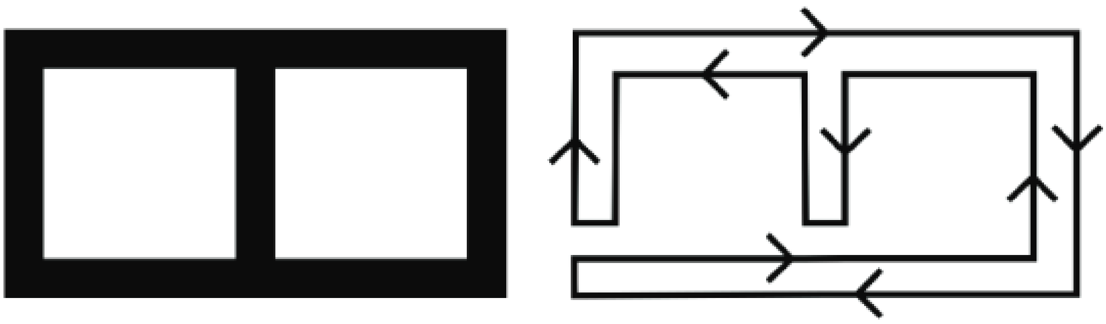


Figure 4. Design for tool continuous printing (Roschli et al., 2019).

2.1.5 Slicing and Design for Slicing

A. Roschli et al., (2019) discuss the process of slicing in 3D printing, which involves converting CAD files to G-Code that 3D printers can understand and use to create parts. The success of printing depends on both designing the part and configuring the slicing parameters. Slicing software uses triangles to approximate CAD parts in STL files, which are then sliced by a plane into polygon slices. The software generates G-Code from these polygon toolpaths, which assume excellent machine output. However, overfilling or underfilling can cause the part to fail, and the software's limitations can produce disappointing results. (A. Roschli et al., 2019.)

The article posits that the design procedure for 3D printing ought to consider the slicing process, a crucial stage in the pre-printing preparation of a 3D model. The process of slicing entails partitioning the three-dimensional model into a sequence of two-dimensional layers that are then sequentially printed atop one another. (A. Roschli et al., 2019.)

To ensure that the slicing process runs smoothly, the authors recommend considering several factors during the design phase. For example, the process of mesh creation, which involves creating a digital mesh that represents the 3D model, should be chosen carefully to ensure that it is suitable for slicing. Additionally, the relationship between wall thickness and part geometry is an important factor to consider, as overly thick walls can result in print failures or poor surface quality. (A. Roschli et al., 2019.)

The angle of overhangs is another important consideration, as steep angles can result in overhangs that require support structures to be printed. Slicing strategies such as infill structure and patterns, tool path air movements, and rescaling of geometries can also impact the success of the printing process. (A. Roschli et al., 2019.)

By taking these factors into account during the design phase, designers can create models that are optimized for slicing and printing, reducing the likelihood of printing difficulties and ensuring high-quality, successful outcomes. (A. Roschli et al., 2019.) Figure 5 is concept of design consideration suggested in this article.

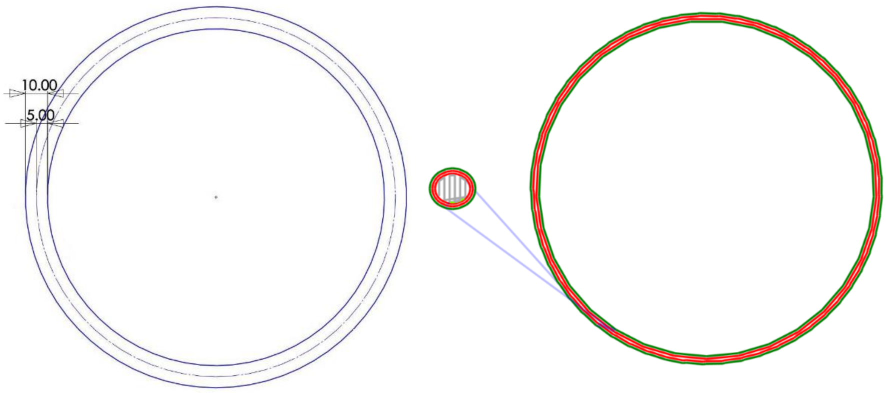


Figure 5. Consideration of slicing in design (A. Roschli et al., 2019).

In the typical slicing process, the STL file is converted into 2D contours. These contours are generated with different offsets and connections between them, using a variety of algorithms to define the boundaries of the part geometry. However, due to the inherent tolerance fidelity of the STL files to the original design, this process can introduce some level of inaccuracy and unsatisfactory results. (Dreifus et al., 2021.)

A new slicing method, called the Implicit slicing method, has been proposed by Adams and Turner (2018). This method involves segmenting the mathematical representation of the initial design into a series of contours, and then using implicit mathematical relationships to construct the toolpath for the 2D slicing operation. The use of this technique has been found to improve the precision of toolpath tolerances. However, it requires significantly greater computational resources, and thus more powerful processors are necessary to execute the machine program and generate the program. (Adams and Turner, 2018.)

The article demonstrates that the use of the implicit approach not only results in improved toolpath tolerances but also leads to an enhancement in the mechanical properties of the component being worked on. Despite its advantages, this technology is not yet widely adopted due to the high computational demands it places on hardware resources. (Adams and Turner, 2018.)

2.1.6 Workflow of robotic AM

The process of additive manufacturing typically commences with the creation of a 3D solid CAD model, which is subsequently transformed into the traditional STL format and segmented into numerous segments for the additive production system. The STL file format presents certain limitations with regards to its dimensions and numerical precision. Additionally, it does not provide the means to specify material properties, thereby necessitating the utilization of several STL files for structures that incorporate multiple materials. The STL file's slicing procedure can be either uniform or adaptive, contingent upon the model's geometry across the build direction, leading to a decrease in build time and an enhancement in surface finish. (Layher et al., 2018.)

Despite its apparent simplicity, the utilization of STL files is associated with certain drawbacks, including elevated computational expenses and reduced dimensional precision resulting from the reliance on triangular approximations to represent the surface of the object. The exploration of direct slicing of CAD models utilizing diverse data formats, including B-Rep, STEP, and NURBS, has necessitated the use of more intricate algorithms to generate slices. Moreover, there is a current trend in the development of robotic systems that enable multi-directional printing. In addition, researchers are actively engaged in the development of multi-directional slicing algorithms aimed at reducing the utilization of support structures in the production of overhangs or intricate shapes. (Urhal et al., 2019.)

The manner in which information is transmitted in robotic additive manufacturing systems differs somewhat from that of traditional three-axis additive manufacturing techniques. The transmission of information is contingent upon the robotic system and its distinct linguistic framework. The software has been designed to extract data pertaining to motion and material deposition, which is subsequently transmitted to the robotic system. Various research groups are presently engaged in the development of multi-directional slicing algorithms with the aim of reducing the requirement for support structures during the production of overhangs or intricate shapes. However, these algorithms have limited effectiveness when it comes to parts that contain holes or depression features. (Fry, Richardson and Boyle, 2020.)

The advent of automation technologies has led to the emergence of multi-degree of freedom robots as potential systems for the execution of adaptable, efficient, and adaptable manufacturing techniques. These robots are capable of carrying out a diverse range of tasks, ranging from rudimentary handling operations to more complex activities such as grinding, cutting, drilling, welding, and polishing. Additive manufacturing systems possess significant potential to decrease time to market, enhance customization, and broaden design alternatives in comparison to conventional techniques. The constraints of current additive manufacturing (AM) techniques with regards to the dimensions of the final product, reduced production speed, and the requirement for auxiliary structures to support overhanging regions, have prompted scholars to explore novel manufacturing approaches. The incorporation of a robotic system introduces an additional level of flexibility to existing additive manufacturing systems, enabling the manipulation of material deposition orientation throughout the fabrication procedure. (Urhal et al., 2019.)

2.1.7 Slicing software and robotics systems

The conventional approach to slicing in three axis printing involves the use of the traditional 2.5 D slicing method. This technique entails slicing the part into horizontal planar contours, followed by the generation of a CNC tool path through the application of algorithms and software parameters. Over the years, numerous 2.5 D slicers have been developed, with extensive research and development efforts aimed at enhancing their performance and capabilities. (Adams and Turner, 2018.)

A number of well-known 2.5 D slicers are presently available in the market, including Cura, Slic3r, PrusaSlicer, and Simplify3D. These slicers have gained popularity due to their user-friendly interfaces, robust features, and compatibility with various 3D printers. For example, Cura provides an array of advanced settings and parameters for enhancing print quality and supports different types of materials, such as PLA, ABS, and Nylon. Slic3r, on the other hand, boasts a powerful engine that is capable of slicing models quickly and accurately. PrusaSlicer offers several automated functions, including auto bed leveling, which simplifies the printing process. (all3dp.com, 2023.)

In contrast to the conventional three-axis gantry systems used in 3D printing, robotic additive manufacturing employs six axes, providing greater freedom of motion and enabling the use of more complex tool paths. While robots are capable of executing 2.5 D sliced tool paths, this represents only a fraction of their potential capabilities, and the goal is to enhance robotic programming to enable the implementation of more intricate printing strategies. (Urhal et al., 2019.) By leveraging the additional degrees of freedom provided by robotic systems, manufacturers can achieve greater flexibility, faster process and precision in their additive manufacturing processes. This can translate to improved quality and consistency in the final product, as well as increased efficiency and reduced production times. However, as with any technology, there are also challenges to be addressed in the implementation of robotic additive manufacturing, including the need for specialized expertise and the development of customized software and tool paths that take full advantage of the capabilities of these systems. (Wu et al., 2017.)

One of the challenges in the field is the development of toolpath strategies for non-planar (3 to 6 axis) slicing. The most difficult problem, besides hardware system, is how to effectively and efficiently construct a series of material accumulation for a particular model. Even if the addition of the robotic arm increased the count of degrees of freedom in the system, the accessibility by collision-free postures remains a manufacturing limitation. The planning of the sequence must take accessibility into account (Wu et al., 2017). This process requires more complex mathematical algorithms than traditional 2D slicing, and the development of these algorithms is still in the relatively early stages. Currently, only a handful of software developers, such as AiBuild, Adaxis, MX3d, Siemens, Powermill Additive, Cosinadditive, SprutCam, Dotex, and a few others are working in this area, with their products in the early to mid-stages of development. (Robotic Arm 3D printing – the ultimate guide - all3dp.com 2023.) Figure 6 is derived from this research project that shows the concept of nonplanner path planning.

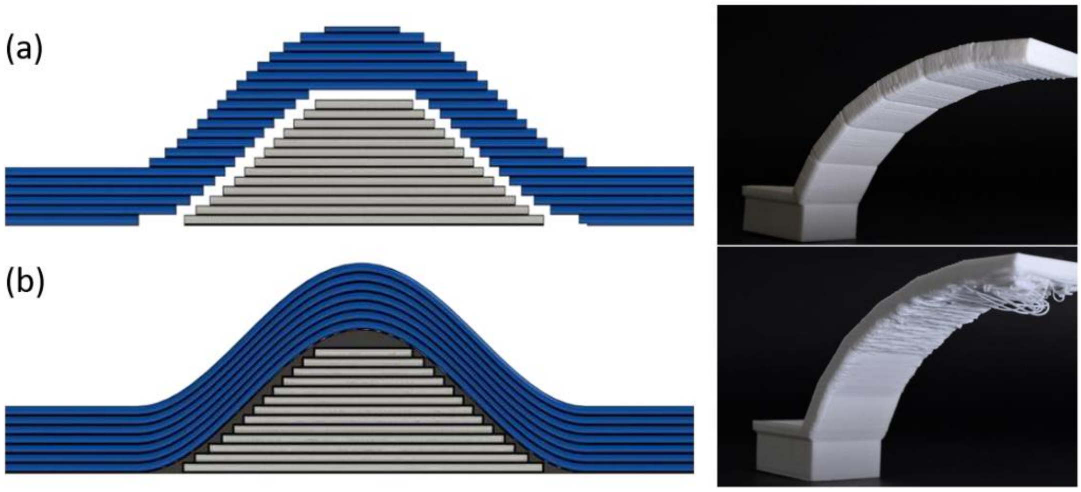


Figure 6. Planner vs non planner path planning schematics (Wu et al., 2017).

The development of advanced toolpath strategies is crucial for the accuracy and efficiency of robotic printing. Non-planar slicing enables the printing of more complex geometries, which is essential for many applications, such as aerospace, automotive, and medical industries. The development of more advanced slicing software can lead to further improvements in the accuracy and efficiency of the manufacturing process. The status que of software development in this area indicates that there is a need for more research and development to advance the field and enable the use of robotic printing in more industries and applications. (Duarte et al., 2022.)

In the past few years, a significant amount of research has been focused on creating algorithms that can produce atypical 2-5 D toolpaths. These toolpaths provide more design flexibility and allow for the optimal utilization of the robotic freedom of motion. Wu et al. (2017) investigated sequential sectional path planning for sectional angled printing, which allows parts to be printed in multiple sections without the need for support structures. Fry et al. (2020) proposed a method for segregating parts and using a sequential planner slicing and printing approach to reduce the need for support structures when printing overhangs.

Duarte et al. (2022) developed an algorithm for tool path generation for a 5-axis rotatory bed in additive manufacturing, enabling the printing of rotary shapes with different growth strategies. Similarly, Hong et al. (2022) developed a conformal printing path planning algorithm for cladding on rotary-shaped parts, which can be applied to various additive manufacturing technologies. Wang et al. (2019) took a different approach and developed an algorithm for non-planar path planning along nonlinear curves such as splines and arcs. This toolpath generation method allows for faster printing of highly overhanging parts without the need for support structures.

These path planning algorithms provide designers with greater design freedom and the ability to optimize the use of robotic motion, thereby improving the efficiency and quality of additive manufacturing. Further research in this area is expected to lead to even more advanced toolpath generation algorithms and enable additive manufacturing to become an even more versatile and efficient manufacturing process. (Alhijaily, Kilic and Bartolo, 2023.) In the Figure 7, 8 and 9, three examples of the nonplanner slicing development is presented from three different literature.

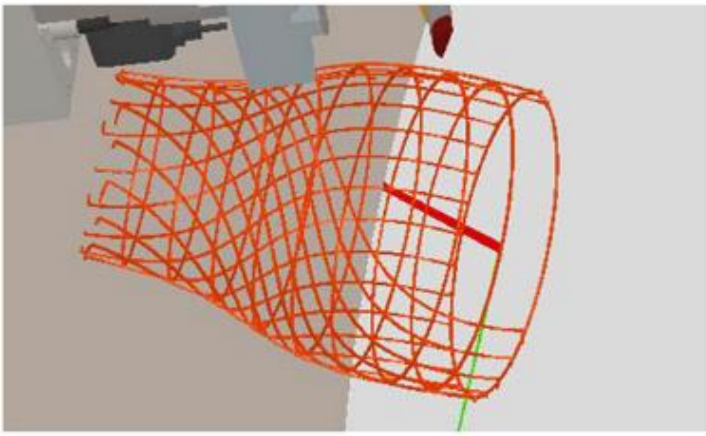


Figure 7. Rotary slcining suitable for Additive manufactruing on rotary movement systems (Hong et al., 2022).

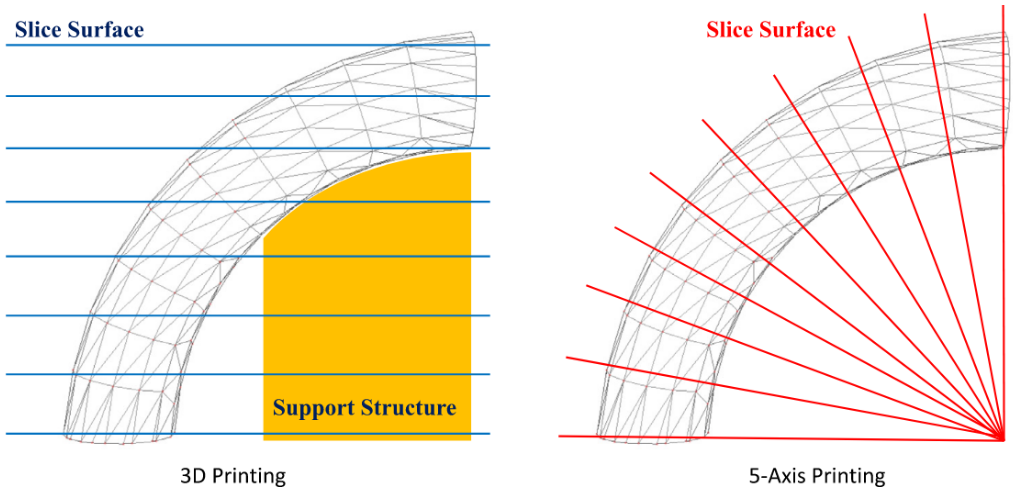


Figure 8. 5 axis planner slicing along a curve or around and axis for reducing the need for support structure (Wang et al., 2019).

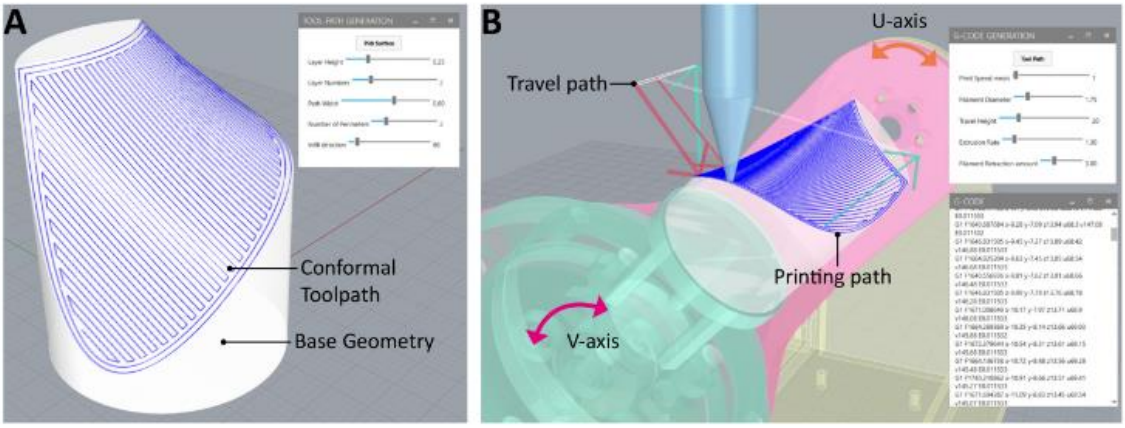


Figure 9. A) Conformal slicning suitable for clading with robots, B) conformal slicning suitable for rotary motion sytems (Duarte et al., 2022).

2.1.8 Grasshopper for robotic additive manufacturing

In the context of mathematical and algorithmic advancements in planner and non-planner path planning for additive manufacturing, it is noteworthy that the programming platforms used in the research conducted exhibit variations. In some studies, distinct stages of programming and program post-processing are involved. For instance, Wang et al. (2019) used Pro/E 5.0 commercial software for structural modeling and Python 3.6 for Gcode generation, which was executed in the open-source software Arduino 1.8.5. Similarly, Jin et al. (2017) employed C++ programming for their algorithm development and Gcode generation, with the designs already created in other CAD software. Duarte et al. (2022) utilized FIBR3DApp software for the post-processing of the Gcode generated by CURA and Slice3r software.

However, in a series of research, the visual programming software Grasshopper, which is a plugin in the CAD modeling software Rhinoceros, was used. This software has the potential for algorithm development, along with explicit programming of different programming languages in conjunction with CAD modeling. This allows all of the processes to be completed on a single platform in a parametric manner, enabling agile, powerful, and yet versatile developments in the software side of robotic additive manufacturing. This platform has the potential to enhance the efficiency and effectiveness of the algorithmic development process in additive manufacturing, leading to faster and more accurate results.

The integration of robotic manufacturing with architectural design is a rapidly developing area of research, offering architects and designers new possibilities for creating complex and innovative designs. The integration of digital design tools with robotic manufacturing workflows has been made possible in recent years through the utilization of advanced software platforms such as Grasshopper. This paper argues that Grasshopper is an excellent platform for the implementation of robotic manufacturing workflows within an integrated software environment. By integrating design and fabrication within a single software platform, Grasshopper offers a streamlined and efficient workflow for designers and manufacturers alike.

The potential for high-end developments in this workflow is immense. As design and fabrication workflows become increasingly automated and digitized, new possibilities for complex and innovative architectural design are emerging. By leveraging the advanced capabilities of Grasshopper, architects and designers can create designs that were previously impossible, using advanced robotic fabrication techniques to produce highly detailed and intricate forms. This paper explores some of the key developments in the field of robotic manufacturing and highlights the potential for further advances in this area.

Ultimately, the workflow developed in this paper could be made into a package, which would facilitate further research and industrial application of this technology for dedicated tasks. By providing a streamlined and standardized workflow, such a package would simplify the implementation of robotic manufacturing techniques for architects and designers, reducing the need for specialized knowledge and expertise. Furthermore, the robotic friendly and expert-friendly nature of the Grasshopper platform makes it an ideal choice for future development in this field. By continuing to develop and refine these workflows, designers and manufacturers can unlock new possibilities for complex and innovative architectural design. (Braumann, Gollob and Singline, 2022.)

The literature review conducted in this thesis sheds light on the interest of scholars in the utilization of the Rhinoceros Grasshopper in the field of robotic manufacturing, which reveals the high potential of research and developments in this area. Braumann et al. (2022) have recently reviewed the benefits of the Grasshopper plugin in Rhinoceros

Software for robotic manufacturing and have presented a workflow using the Unity Machine Learning Agent Toolkit and KUKA mxAutomation plugins in Grasshopper. This workflow integrates design, parametrization, automation, adaptive closed-loop feedback motion control with the help of sensors, within a user-friendly interface. The authors suggest that this approach can simplify the job of robot programming, even for non-programmers. Overall, this work presents an exciting prospect for the integration of digital design tools with robotic manufacturing workflows, offering new possibilities for innovative and complex designs.

García-Dominguez et al. (2020) have introduced a new approach to enhance the configuration and conception of objects, employing computational programming tools like Grasshopper and Rhinoceros in their research investigation. The proposed methodology incorporates the integration of topology and dimension optimization with multiple objectives, aimed at minimizing material consumption while ensuring structural integrity of the object. The methodology utilizes programs or plug-ins that incorporate advanced algorithms to execute functions, such as structural analysis and optimization problems. The article presents simplified schematics that illustrate the coded structure of the approach in order to clarify the constant information flow through an optimization and design process. (García-Dominguez, Claver and Sebastián, 2020.) Figure 10 illustrates an integrated design optimization workflow methodology using Grasshopper developed in this research.

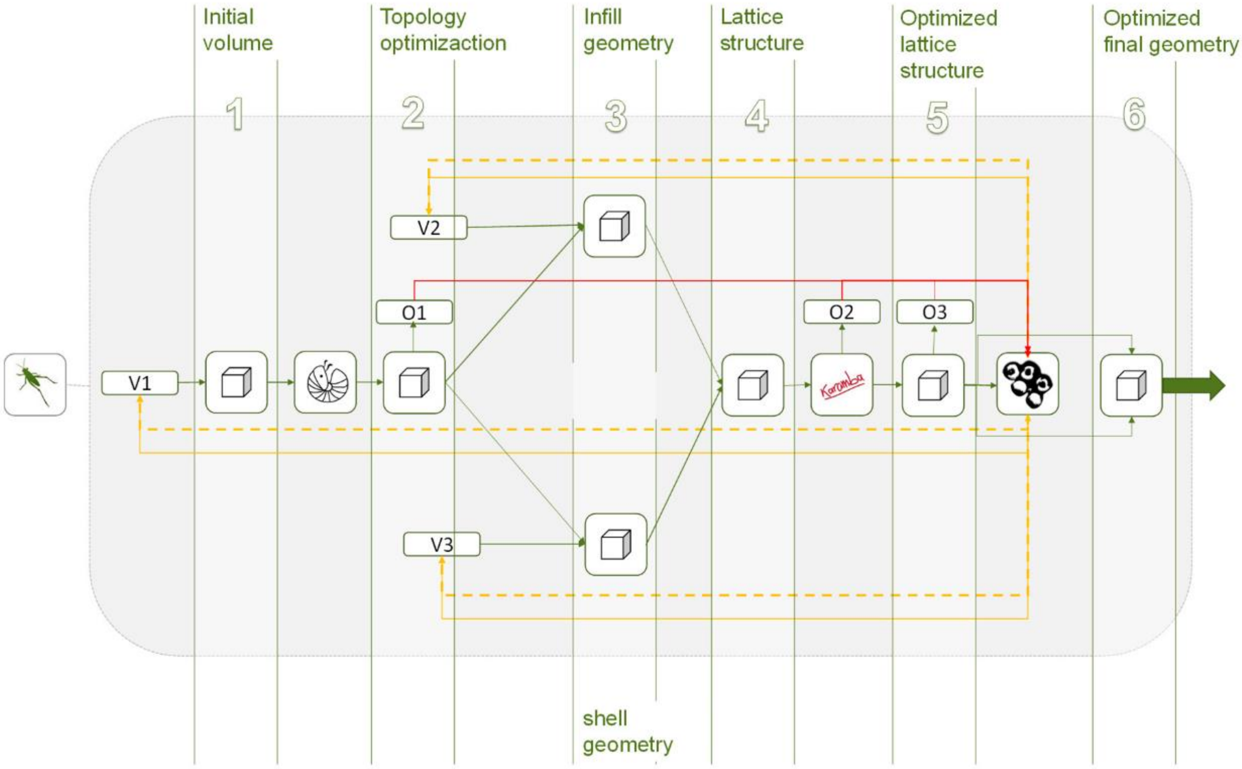


Figure 10. An all-in-one integrated design optimization workflow methodology using Grasshopper (García-Dominguez, Claver and Sebastián, 2020).

The workflow developed by García-Dominguez et al. (2020) can be extended in the field of Robotic additive manufacturing. This extension is demonstrated by Chacón et al. (2022) who have developed a workflow for generating CNC machine programs within the Grasshopper software. The generated program facilitates slicing tool path planning by using NURBS instead of STL files. The proposed methodology offers advantages in terms of manufacturing tolerance fidelity and utilization of G2 and G3 G-codes which provide more CNC motion-friendly arc and spline movements compared to linear G1 and G0 motions. This approach is particularly useful for Robotic systems where linear point-to-point movements require high acceleration and jerk control due to the machinery's inertia. Therefore, this methodology has the potential to significantly benefit the Robotic additive manufacturing process. (Chacón et al., 2022.) Figure 11 describes the workflow that has been used in this paper for slicing of the design and generating NC code for 3 axis motion system machinery.

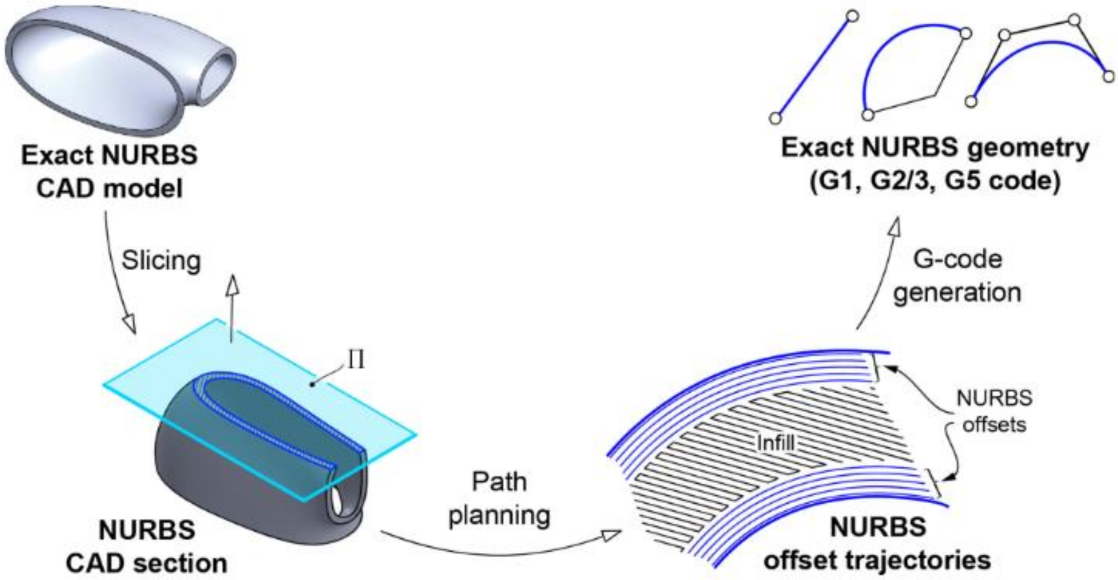


Figure 11. Workflow of NC/Gcode generation from NURBs in Grasshopper with 4 steps, 1- NURBS importing, 2- Planner contouring, 3- generation infill structure based on the offset from the contours, 4- Translating the movements to Gcodes of linear, circular and spline commands (Chacón et al., 2022).

Ashrafi et al. (2022) devised a concrete extrusion additive manufacturing workflow within Rhino's Grasshopper platform to model material deformation during construction-scale concrete additive manufacturing. The objective was to counteract deformation during toolpath design via innovative mathematical compensation algorithms. The workflow incorporates a 3D slicer, specifically for concrete 3D printing, which is integrated into Grasshopper, a Rhino plugin. Similarly, Chien et al. (2016) developed a workflow that employs a voxelization algorithm implemented through Python in Grasshopper. The algorithm matches raster information extracted from analyses to three-dimensional geometrical models consisting of voxels, each represented by a box with a side length equal to the material's thickness upon extrusion. (Gardner et al., 2021.)

As the conclusion of the literature review undertaken for this thesis, the information has yielded insights indicating that Grasshopper is an ideal platform for implementing a robotic additive manufacturing workflow. Such a platform holds immense potential for further research and industrial applications. Accordingly, the thesis advances a method that serves as a gateway to both experimental and theoretical research, with the primary objective of enhancing the quality of Large-Scale Additive Manufacturing (LSAM). It is notable that this technology is still in its nascent stages, and as such, demands significant development and research efforts from the academic and industrial communities alike. This thesis aims to provide a straightforward platform for fostering research and development in areas such as design for LSAM, design optimization, slicing and path planning, integrated machinery and tool change, robotic programming optimization, additive manufacturing process parameter optimization, adaptive real-time process control, Generative AI based design, Structural analysis, among others.

3 Developments Process

This chapter elucidates the developmental process, encompassing the equipment, necessary requirements, and software employed. Additionally, it delves into the design of the experiments. It is important to note that all the equipment and licenses utilized in this thesis were legitimate and in compliance with research purposes, being the property of Savonia University of Applied Sciences.

3.1 Equipment and Facilities Used for Laboratory Testing

The research for this thesis was carried out as a part of a technology development project funded by the European Union in Finland. The research was conducted at the 3DROBO Laboratory, located in the Savonia University of Applied Sciences. The laboratory is equipped with a KUKA KR120 RKUKA KR 120 R2700-1/FLR robotic arm that is controlled by a KR C4 controller. Additionally, a CEAD E25 robot extruder is As a tool for polymer additive manufacturing, the robot is equipped with a CEAD E25 pellet screw extruder. This robotic additive manufacturing system is capable of printing in the volume of more than 1.5 cubic meter. And the extruder is capable of extruding up to roughly 12 kg of material.

The material has been used in for the tests is UPM FORMI 3D40, a biobased recyclable compostable cellulose fibre and native polylactide acid composite pellets. The UPM Formi 3D product is fabricated utilizing cellulose fibers that are derived from renewable sources. Material can be recycled or burned for energy. Table 1 shows the material properties of the UPM FORMI 3D40. (UPMformi)

Table 1. Physical and Mechanical properties of UPM FORMI 3D40 (UPMFormi (2022)).

Property	Test Method	3D 40
Density, g/cm^3	EN ISO 1183	1.2
Tensile Strength, N/mm^2	ISO 527	48
Tensile modulus, N/mm^2	ISO 527	5400
Strain (tensile), %	ISO 527	2
Impact Strength, Charpy, kJ/m^2	ISO 179/1eU	14
Peak melt temperature, °C	ISO 11357	135-180
Glass melt temperature, °C	ISO 11357	60
Melt flow index (190°C/10kg)	ISO 1133	7
Fiber content		40
Mechanical properties measured from injection mouled test specimens		

3.2 Creating a Workflow for Robotic Additive Manufacturing in Grasshopper

In the context of this thesis, the Rihnoserous 7 software was utilized, along with the Grasshopper plugin, which is equipped with a licensed version dedicated to scientific purposes at the Savonia University of Applied Sciences. The Rhinoceros CAD modeling environment served as the primary tool for the design of the experiment models. The KUKA PRC plugin, serving as a post processor for KUKA robotic programming, was also employed with the university's dedicated license. In addition, the script development process made use of several open-source Grasshopper plugins, including IronPython 2.7, ROBOTS, Lunchbox, Weaverbird, Parametric Zoo: KUKA PRC toolpath optimizer, as well as Droid. The Rhinoceros CAD modeling environment was the main tool for designing of the experiment models.

3.3 Laboratory tests

The main aim of the laboratory experiments conducted in this research was to evaluate the efficacy of the RhinoSerous Grasshopper workflow in enhancing the caliber of printed results. In order to attain the objective, a sequence of empirical examinations were carried out to assess the efficacy of software and hardware constituents and scrutinize the functioning of the system. The results section presents a detailed record of the test outcomes, which could serve as a foundation for future research and the development of design principles for additive manufacturing on a large scale.

The tests conducted in this study comprised an analysis of layer width formation and the assessment of the ratio between layer width and nozzle size. Furthermore, tests were conducted to evaluate the quality of print in angled printing at varying layer heights, analyze tolerances with different slicing orientations, evaluate overhangs in angled slicing, test ramps and bridges in angled slicing, and adapt speed based on layer path length.

4 Results and Discussion

The present investigation presents its findings in the results section, which commences with a detailed account of the workflow that was developed utilizing Rhino/Grasshopper software for robotic additive manufacturing. The first subsection of this section provides an elaboration on the specifics of the workflow, including its design and process parameters, along with any challenges encountered in the utilization of robotic techniques. The challenges that were encountered are further discussed in the following subsection. Subsequently, the second subsection elucidates the tests that were conducted to evaluate the software's operational efficacy, including the results obtained from these tests.

4.1 Workflow of Robotic Additive/Hybrid Manufacturing in Grasshopper

As stated in the introduction, the principal aim of utilizing the parametric visual coding platform of Grasshopper was to integrate the complete software workflow of robotic additive manufacturing into a unified software environment. This workflow comprises several stages, including CAD modeling, tool path generation, and post-processing for robotic programming, all of which are conducted within the Rihnoserous software.

4.1.1 CAD modelling

The workflow entails CAD modelling, which is conducted within the CAD modelling interface of Rhinoceros. In numerous cases, the CAD modelling process can be harmoniously integrated with the Parametric Interface of the Grasshopper plugin, which enables the parametrization of design functions such as lofts, sweeps, extrusions, diameters, offsets, thicknesses, among others. The models generated can range from simple box-like structures to intricate geometries, such as parametric wall patterns, support structures, and end-use applications, including molds. The figure 12 illustrates three samples of designs in Rhinoceros from simple designs to complex parametric designs and figure 13 illustrates a generative design with mathematical calculations in Grasshopper which script is shown in figure 14.

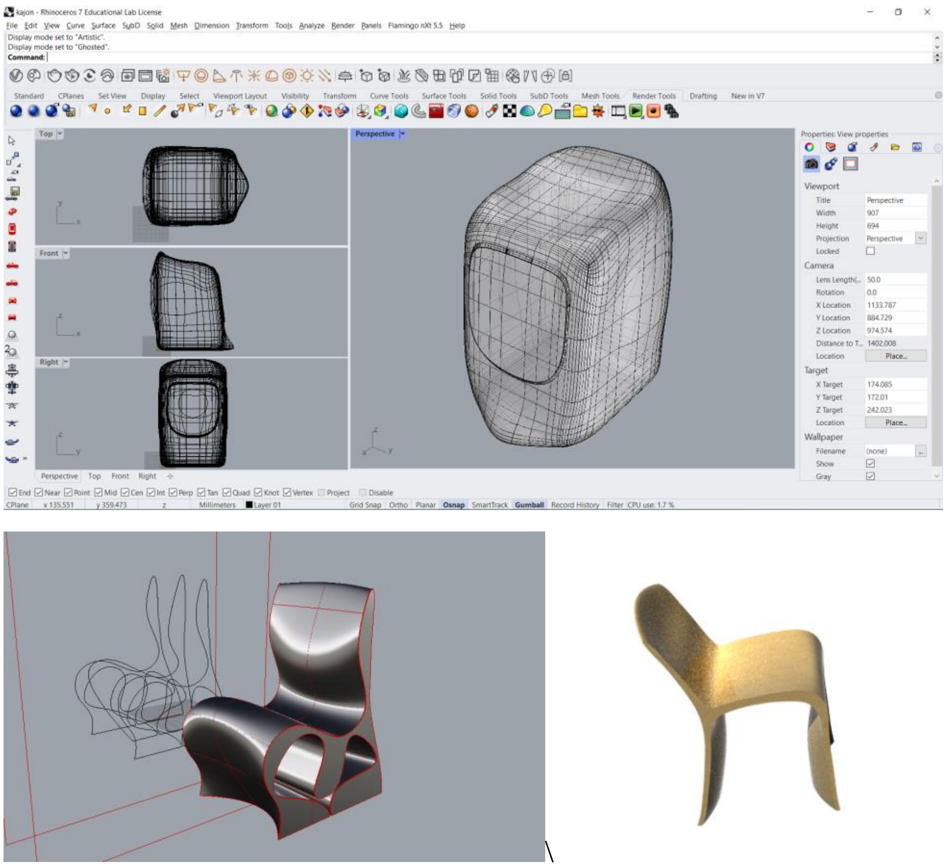


Figure 12. Nonparametric design done in Rihnoserous using NURBS and Solid tools

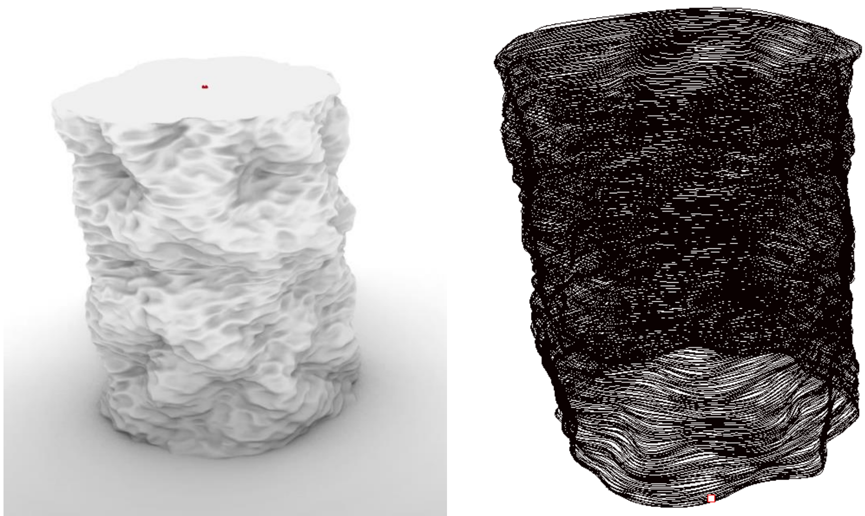


Figure 13. Parametric Design in Rhinoceros Grasshopper with the visual scripting (adopted from the YouTube tutorial of How to: 3D spinalization technique for diagrams and 3D printing (GH + Silkworm Tutorial) (2022)).

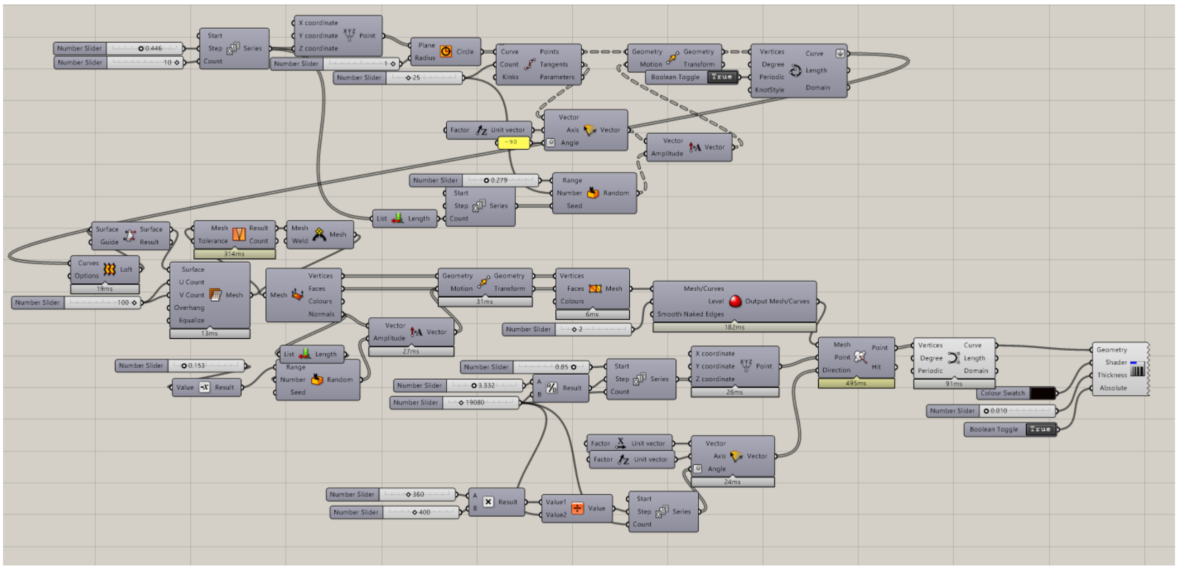


Figure 14. The script for the design of the parametric design shown in the figure 13

4.1.2 Tool path generation

The development of algorithms for tool path generation, also known as Slicing, posed the greatest challenge in this thesis work. Given the need to consider retraction for robotic pellet extrusion and overhangs, one of the most crucial slicing strategies for robotic additive manufacturing is vertical and angled planner slicing. Spiralizing this tool path would be preferable, as it would eliminate seam lines in the printed object and minimize visible signs of layer changes. As highlighted in the introduction, it is imperative for the design, slicing, and manufacturing processes to be integrated seamlessly, such that the design can be sliced and printed accurately. The utilization of Grasshopper has the added advantage of eliminating the requirement for the translation of NURB CAD models to STL format for slicing based on reduced geometry.

This thesis work introduces a workflow for slicing that is based on the original NURB of the model, resulting in improved dimensional accuracy of the printed part and enhanced robotic manufacturing performance. Figures 15 depict the planner slicing workflow developed for the design, which is applicable to a single perimeter shell printing and represents the most significant path planning strategy for Robotic AM. The visualization of the workflow shown is depicted in figure 16. In addition, this work includes a demonstration of tool path generation for a milling process performed on the same platform which is shown in the Figure 17 and its visualization is shown figure 18.

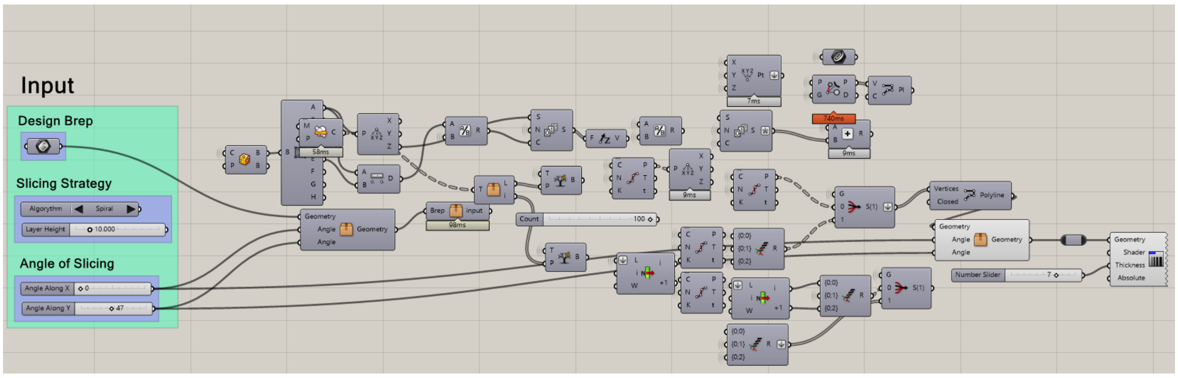


Figure 15. Script of angled slicning in grasshopper

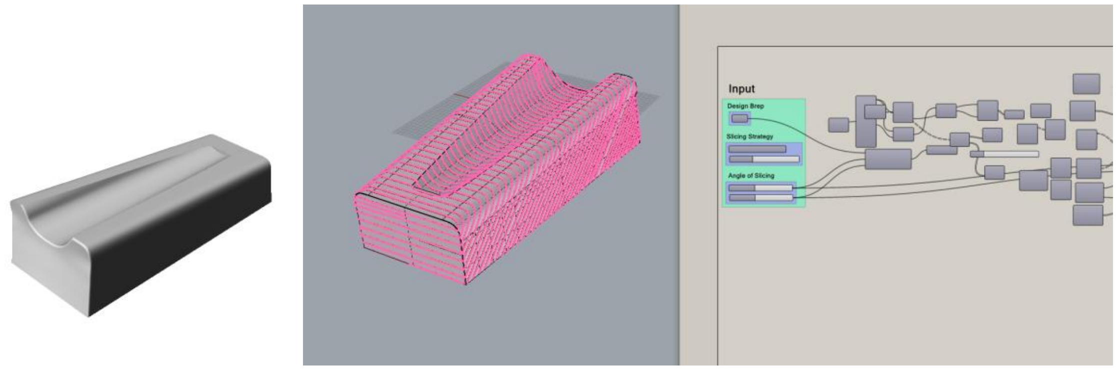


Figure 16. Visualization of angled sclicing in made in grasshopper

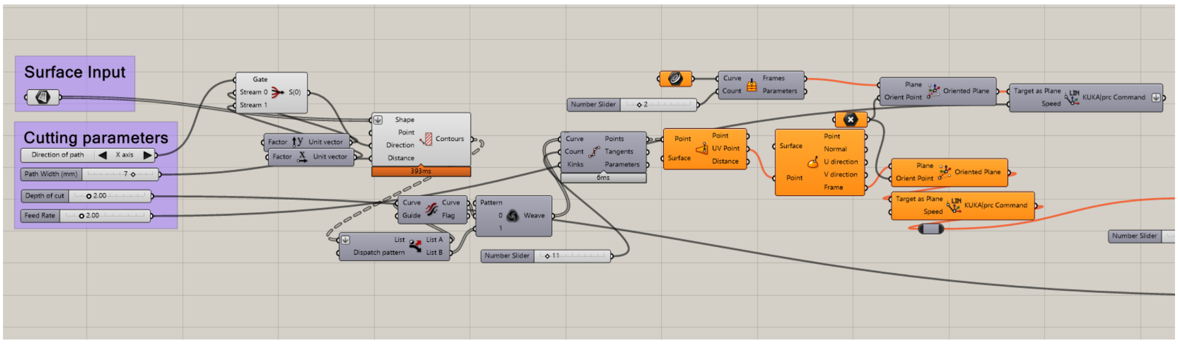


Figure 17. The script of parametric path planning Surface milling in grasshopper

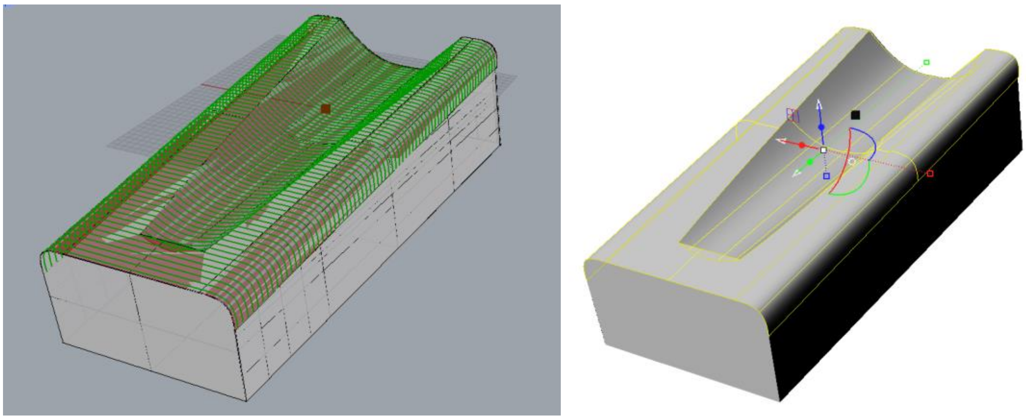


Figure 18. Visualization of surface milling parametric path planning in Grasshopper

4.1.3 Robotic programming Postprocessor

The availability of plugins for robotic programming in the Grasshopper platform has enabled the execution of robotic programming within this environment. To this end, several postprocessing plugins, such as ROBOTS, Robots components, and Kuka-PRC, have been developed. Given that the robotic arm utilized in this thesis work was a KUKA robot, the KUKA-PRC plugin was employed for this project. By utilizing the plugin's scripting component within Grasshopper, a script for the robotic work cell of Savonia 3DRobo was developed. This postprocessor was then utilized to translate the tool path generated in the previous section and generate KRL code that can be compiled by the KUKA controller. Figure 19 provides a visual representation of the Grasshopper script developed for this purpose. The script created facilitates the straightforward adjustment of processing parameters, tool changes, as well as the export and merging of programs.

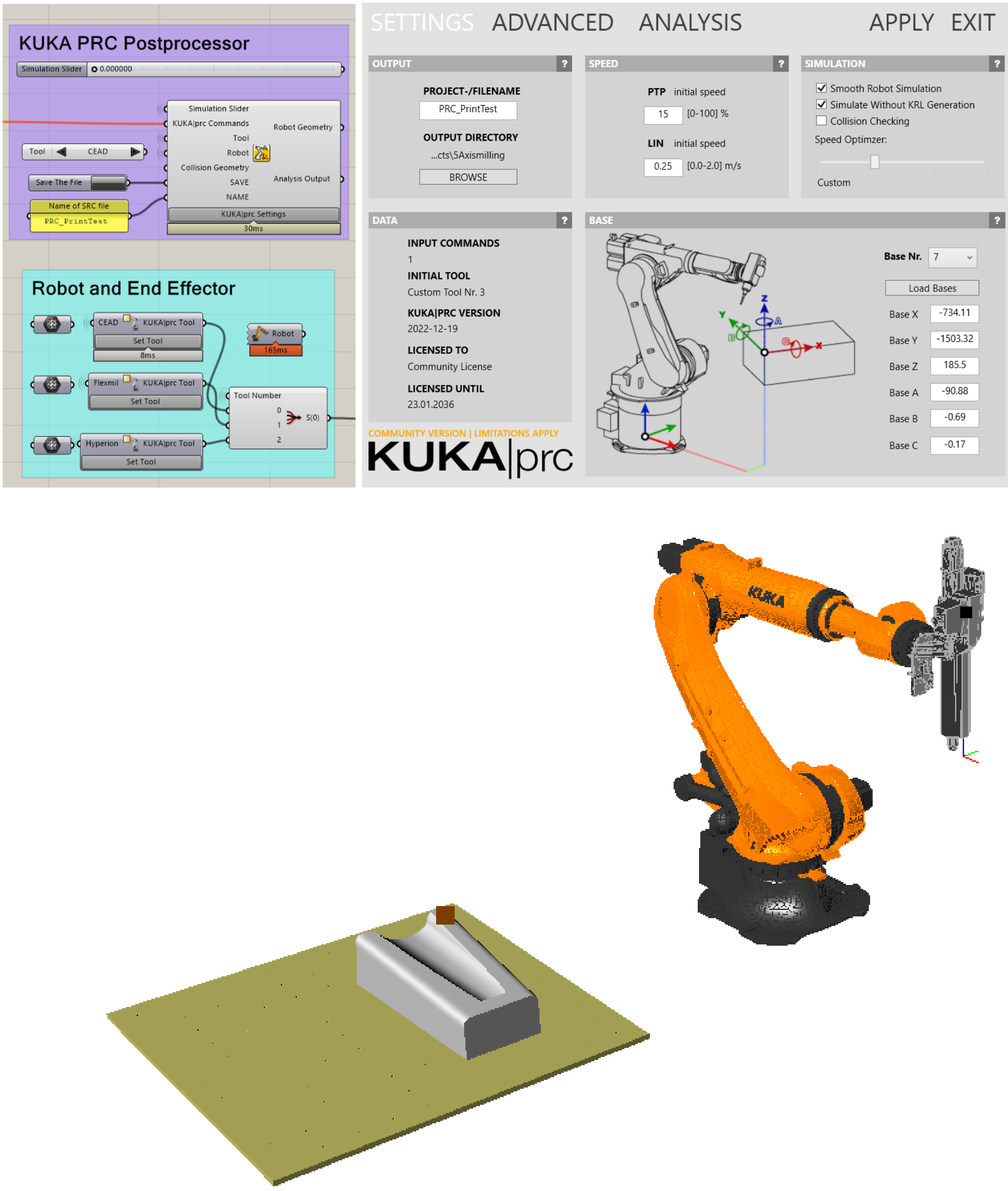


Figure 19. Script and Simulation results in Grasshopper for the printing work cell

The present study involves the integration of three stages within the workflow. Firstly, a design is created, followed by the definition of tool path for additive manufacturing and machining. Finally, programming is performed using the Grasshopper platform. The outcome of this integration is depicted in Figure 20, which showcases the simulation results and the generation of a robotic program using the KUKA PRC postprocessor.

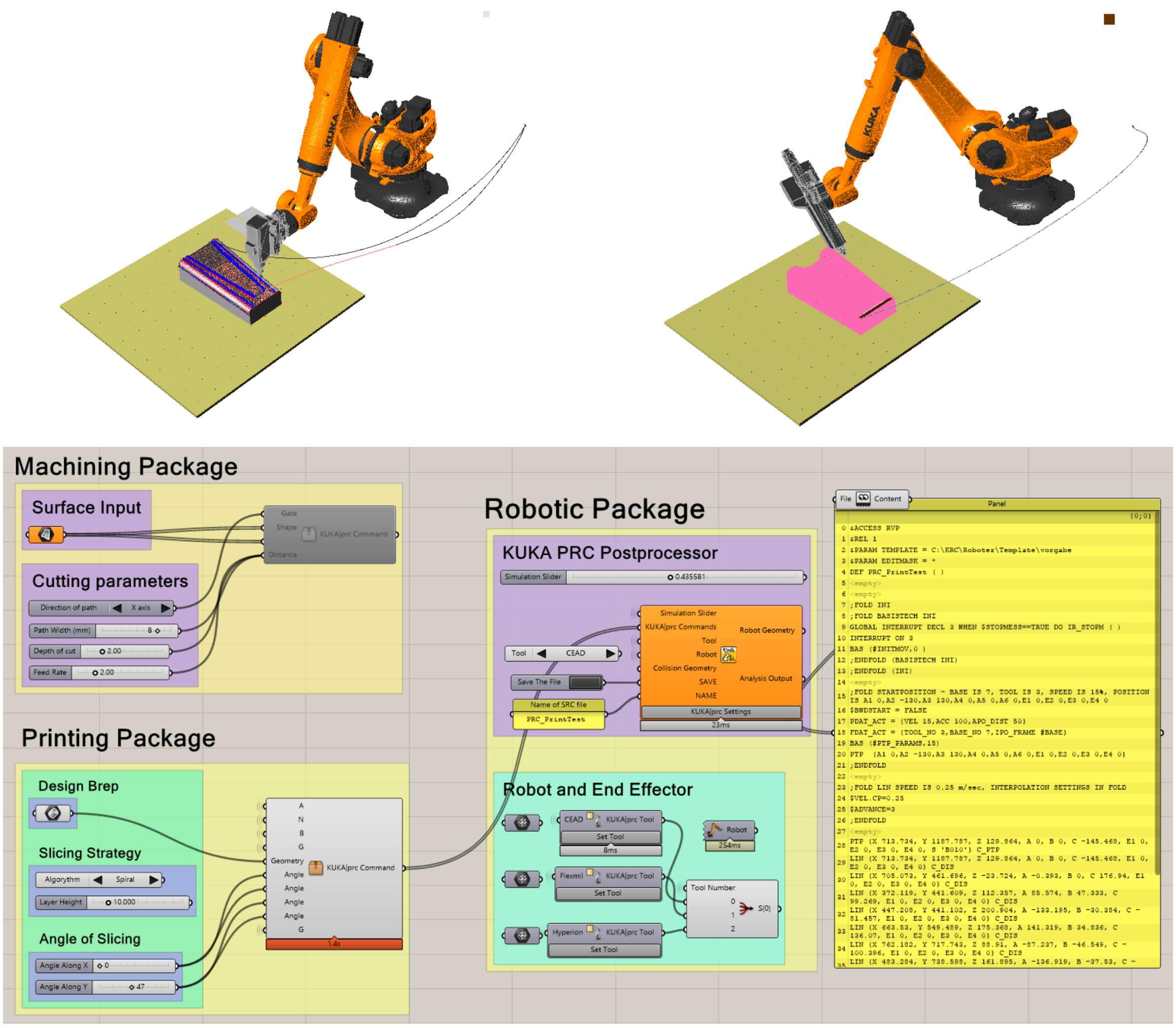


Figure 20. Compacted interface of Additive/ Hybrid Manufacturing workflow

4.2 Printing tests and gained knowhow

This thesis presents initial exploratory trials of robotic additive manufacturing undertaken by the author, in a project that was new to the university. As such, the thesis reports on rudimentary quality tests that were conducted to gain knowledge about the system and explore the challenges involved. The tests included both additive manufacturing and machining, but the main focus of the thesis is on the additive manufacturing side, with only one example of a machining test presented. During the tests, several programming workflow issues were discovered, and design considerations related to angled slicing were also understood. However, the tests were not systematically designed, as the main focus of the thesis was to establish a parametric workflow for future scientific experiments. Nonetheless, some of the results presented in this thesis are novel, particularly with respect to design considerations for large scale additive manufacturing, at least within the existing literature.

4.2.1 Layer hight printing tests and quality of surface

In a sequence of experiments, a uniform cubic shape with dimensions of 15×25×15 cm was manufactured through a nozzle diameter of 5 mm, utilizing a constant printing speed of 30 mm/s, which is a relatively slow rate. The cooling process was accomplished through the generation of a qualitatively high flow by an industrial fan. The geometries were sliced through 45 degree angled slicing, and the boxes were printed with layer heights of 1 and 2 millimetres. Surface quality was examined, and the final diameter of the box was measured using a calliper meter. Table 2 below depicts the collected data regarding the test and processing parameters of the prints. In general, the experiment was successful in verifying the feasibility of the software workflow. Notably, the angled printing technique demonstrated the ability to print roofs without supporting structures, which is the primary advantage of angled slicing. Generally, it is widely acknowledged that a reduced layer height leads to better surface quality, albeit at the expense of increased printing time. Furthermore, it is recognized that when printing at an angle, the print speed should be decreased compared to that of vertical printing, as the force of gravity can result in deformation of the printed object's roof. The result of the test is shown in Figure 21.

Further investigations pertaining to the correlation between fidelity of tolerance and layer height are recommended for future research and development.

Table 2. 45 degree angled sliced boxes with different layer heights

Test	Layer height (mm)	Flow rate multiplier on controller	Layer width (mm)	Final diameter (cm)	Pritning time (minute)	Surface quality
A	1	0.87	~7	15.16×25.04×15.22	53	Good
B	2	1.12	~7	15.08×24.88×15.03	27	Fair

Figure 21. Test print of a boxes with 1 and 2 mm layer heights in 45-degree angle with 6 mm nozzle and 10 mm layer width

4.2.2 Wall thickness in angled printing and material flow behaviour

Based on the results of the previous and additional printing tests, it was ascertained that wall thickness may differ due to the misalignment of layers in relation to one another. This observation holds particular significance for design and machining processes, as variations in wall thickness may result in different orientations. In addition, upon close examination of material deposition, it was noted that the deposition of layers in areas such as roofs or overhangs may be subjected to gravity, leading to deformation of the material flow and layer deposition. This can contribute to differences in tolerance when compared to nominal tolerances and is believed to be mitigated by reducing the layer height. Further research is recommended to explore tolerance-related issues in greater depth. The schematic representation of this finding is depicted in Figure 22. Figure 23 thereafter is an example of the phenomenon that is explained.

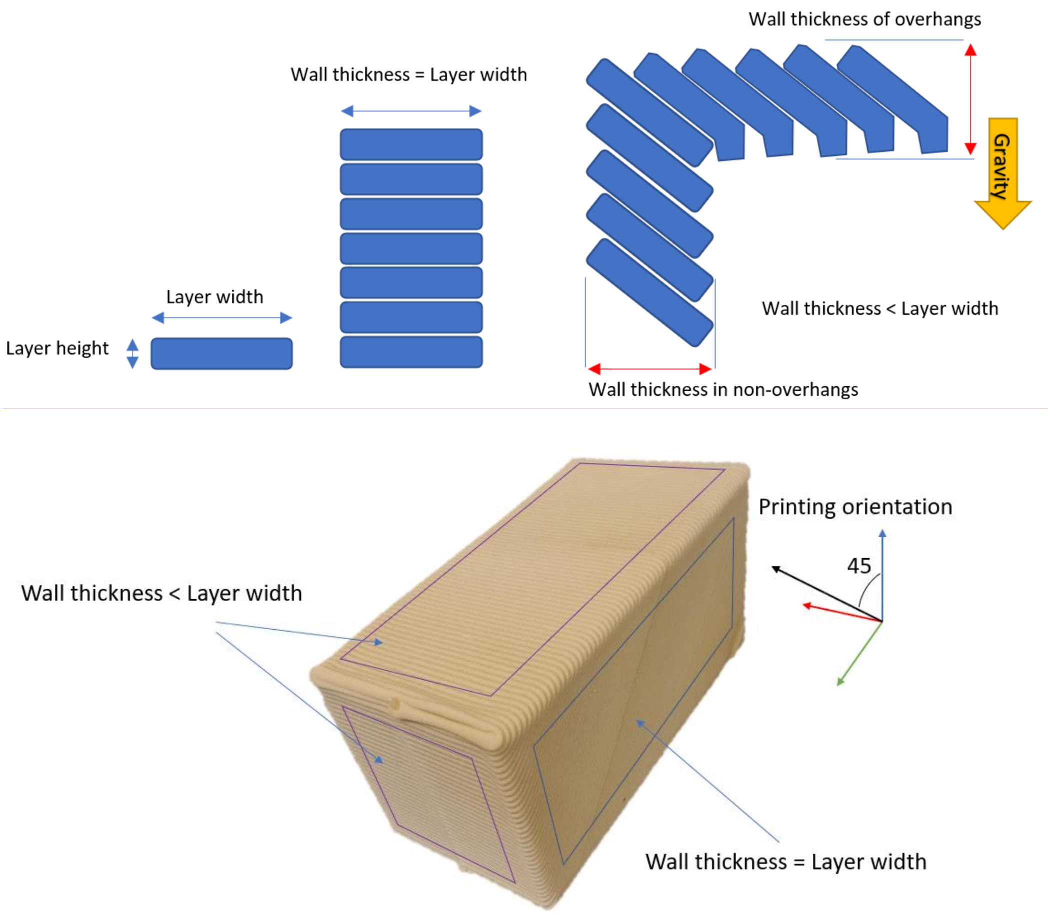


Figure 22. Wall thickness variation due to layer shift and asymmetric deposition

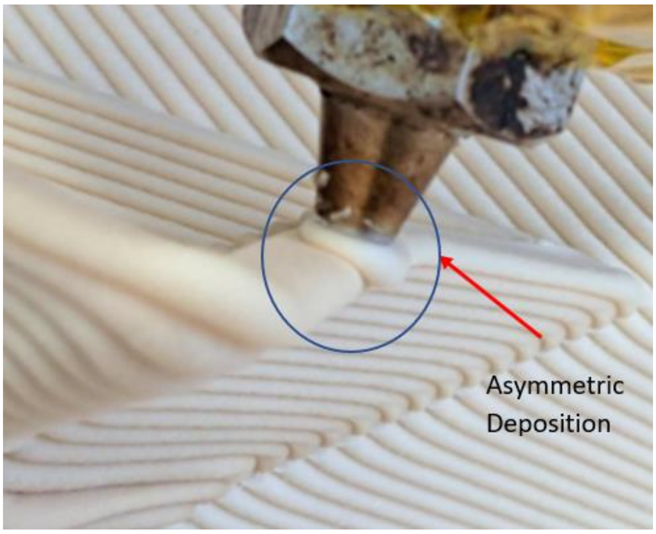


Figure 23. The captured picture of the asymmetric deposition due to overhang angled printing.

4.2.3 Bridging over hangs and printing orientation

The term "bridging" in additive manufacturing pertains to the process of printing without the need for support structures. Through various print tests, it has been observed that this method may result in certain deformation patterns, such as curvy roofs, when printing overhangs and roofs. The results of these tests suggest that aligning shorter lengths of overhangs with the printing orientation is preferable, as it minimizes the amount of bridging required. This finding is depicted in Figure 24, which illustrates three levels of severity of deformation in angled printing. Consequently, this result can be used as a design guideline for largescale additive manufacturing when employing angled printing. Figure 25 illustrate the concept of this rule in pictures.

Figure 24. An example of failure due to long bridging in angled sliced print

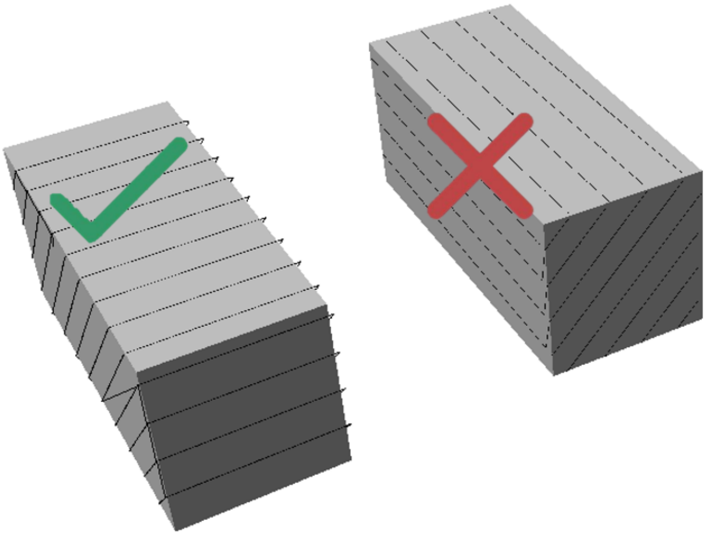


Figure 25. Orientation of slicing along shorter length of the part as angled printing guideline suggestion

An alternative approach involves angling the orientation of slicing around two axes, which enhances the feasibility of printing edges. Nonetheless, this technique results in diverse cross-sectional tool paths from the onset of printing until the conclusion of the component. The subsequent section will expound on a design methodology that facilitates the printing of such instances.

4.2.4 Starting and ending ramps for angled slicing

When attempting to slice a component for angled printing along two axes, it may occur that the tool path's introduction and conclusion become excessively short, resulting in minimal printing time in these regions. This can lead to issues with adhesion at the beginning of the print, potentially causing printing failure. Furthermore, insufficient solidification of the material due to the short printing time at both the start and end of the component may result in deformation. Designers can address this problem by incorporating supplementary ramps in the computer-aided design (CAD) file via Boolean operations, which can subsequently be removed following the completion of the printing task. This design methodology is depicted in Figure 26. The printed example of this rule is depicted in the Figure 27.

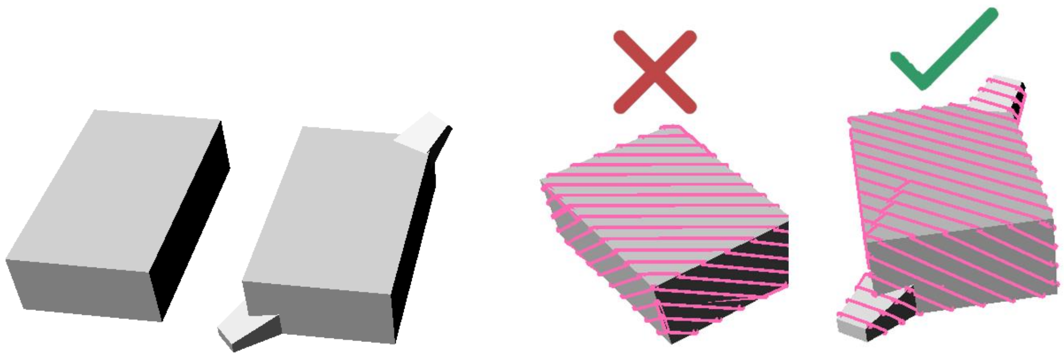


Figure 26. Creating additional ramps in design of the printing for better starting and ending of the print with angled printing in multi direction

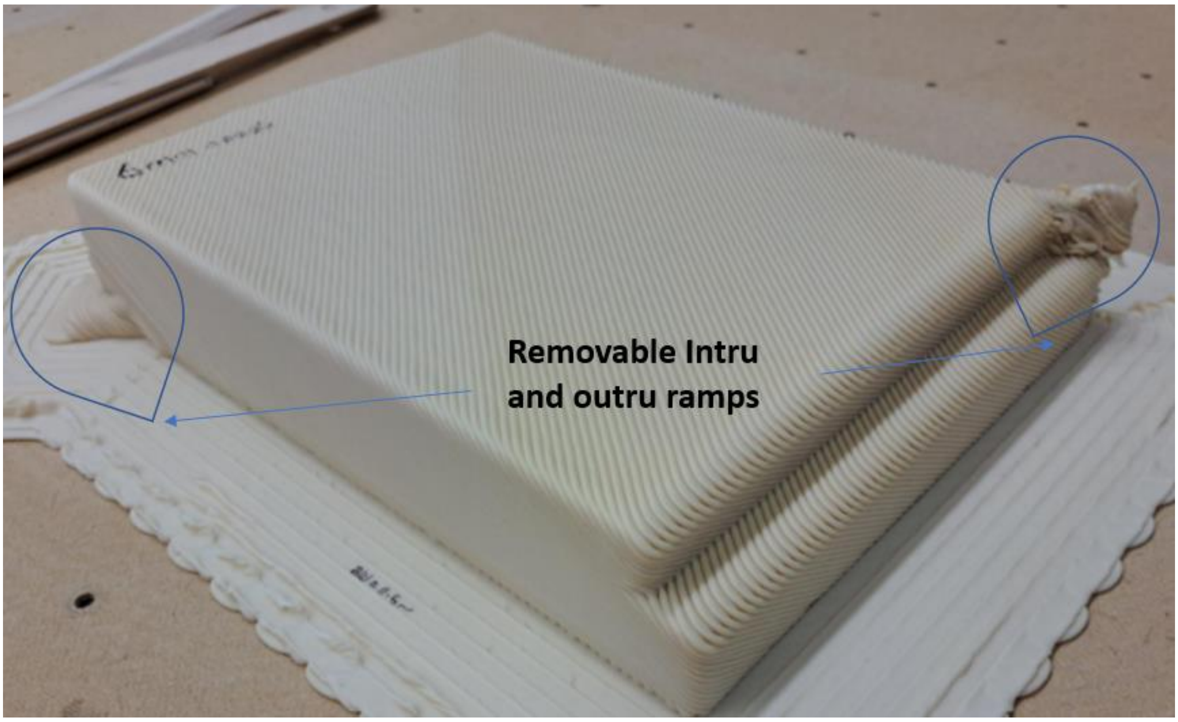


Figure 27. Example ramps for multi axis angled sliced print. These ramps will be mechanically removed in postprocessing

4.2.5 Connecting between slicing islands to create a continuous toolpath

The retraction process, which entails the cessation and resumption of extrusion in pellet extruders, is challenging to control due to the pressure associated with the extrusion process. Consequently, printing layers with dissimilar discontinuous contours may result in material oozing, leading to a decline in printing quality. Therefore, during the design phase, it is critical to minimize separate geometries that lead to distinct slicing contours, or "slicing islands." One approach, which has been tested, involves designing additional walls between the islands to connect the contours. These walls are subsequently eliminated via machining, thereby improving the printability of the design. The concept is depicted in Figure 28 and serves as a design guideline for large-scale additive manufacturing.

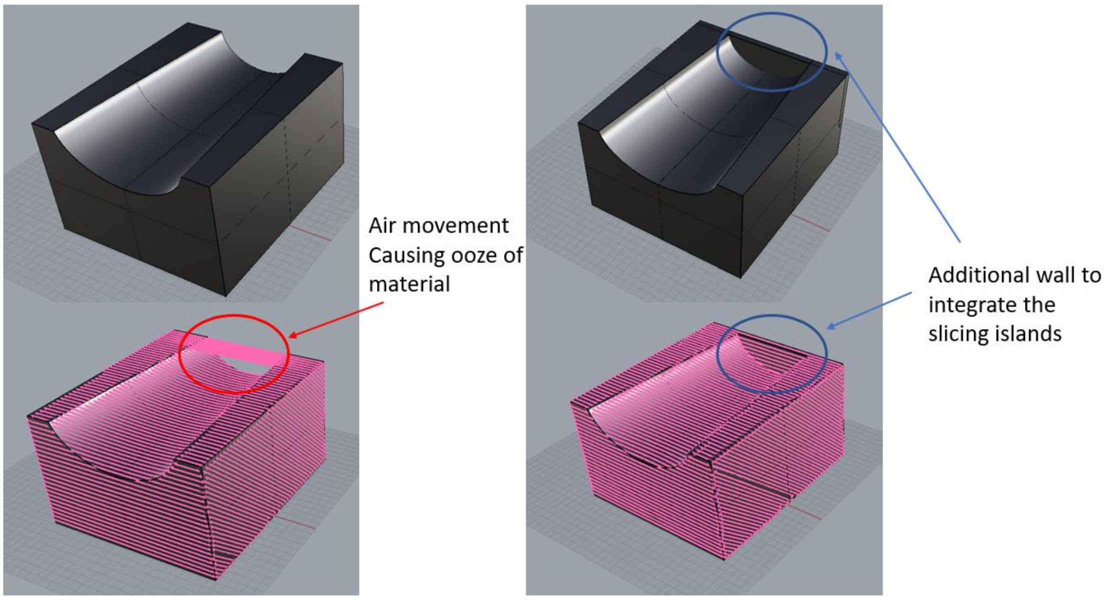


Figure 28. Adding extra removable wall for integration of island to eliminate air movements

4.2.6 Adhesion of material and part to printing bed

Ensuring printing adhesion is critical as thermal deformation-induced delamination is a common failure in printing processes. In a series of printing tests, three bed printing materials, namely glass, aluminium, and wooden sheets, were evaluated for their adhesion properties. The results demonstrated that the material UPMFORMI40 exhibited the strongest adhesion to a wooden-based bed without requiring any additional adhesion media, such as glue. Furthermore, adhesion was found to improve even more when using uncoated rough-surfaced medium-density fibreboard (MDF) sheets, which have wood fibers and a perforated surface to enhance material bonding to the bed. This rough-surface MDF sheet proved to be convenient as it eliminated the need for a heated bed or glue, thereby reducing printing preparation lead time.

While using a wooden bed eliminated delamination of the part from the bed, this level of adhesion was inadequate for subsequent machining processes. To overcome this, a raft was designed to be added to the part design and clamped to the printing bed via clamping fixtures. This innovative approach serves as an additional design guideline presented in this thesis based on the outcomes of the test series. Figure 29 provides an illustration of the concept and successful clamping of the printed part. Figure 30 depicts the design of the clamping raft in the Software.

Figure 29. The integrated raft to be used of clamping of the printed part on the bed

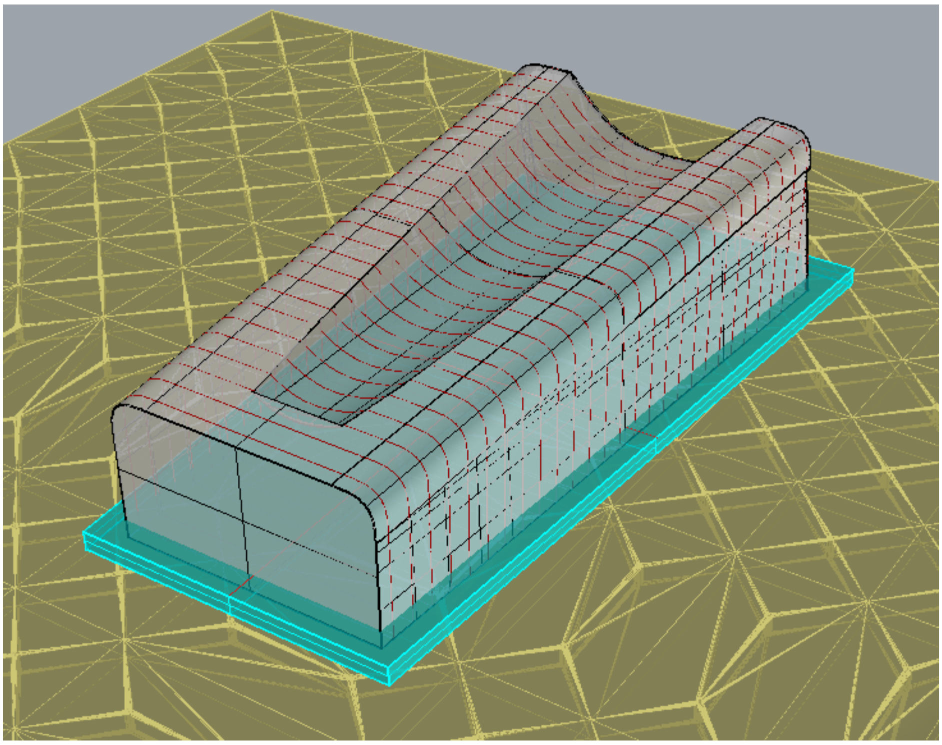


Figure 30. Integrated removable raft on the design of the part in the Software atmosphere

4.2.7 Layer width, nozzle diameters and surface roughness

In small-scale additive manufacturing of polymers, it has been recommended that the layer width should range from 50 to 200% of the nozzle size, as reported by Polak, Sedlacek, and Raz (2017). However, this thesis work conducted experiments that revealed a slight modification to this ratio, suggesting that a suitable layer width should fall within the range of 120 to 180% of the nozzle size. The results showed that a smaller layer width caused a rough, stretched shark-skin texture, while a layer width greater than 180% of the nozzle size produced a bloopy texture on the surface due to the non-flat nature of the bead. This phenomenon is influenced by several factors such as material properties, printing temperature, printing speed, nozzle geometry, and layer height, among others (Lutz, 3D printer nozzle comparison guide). Nevertheless, the stretching of the material was found to play a more significant role than the adhesion of layers in large-scale printing. Thus, a low ratio of printing speed to extrusion rate resulted in a stretched bead with cracks on its surface, while increasing the extrusion rate improved the print surface quality. In conclusion, design guidelines should take into account the nozzle size and a relative bead diameter of 150% of the nozzle size for adjusting the design accordingly. Figure 31 and 32 depicts the examples of failure and successful surface quality with a identical nozzle (8 mm) with 8 and 14 mm layer width. Figure 33 depict this design rule for ratio between layer width and nozzle size.

Figure 31. Cracks in beads due to under extrusion caused by material dragging with nozzle

Figure 32. Acceptable surface quality with increasing the flow ratio and bead width

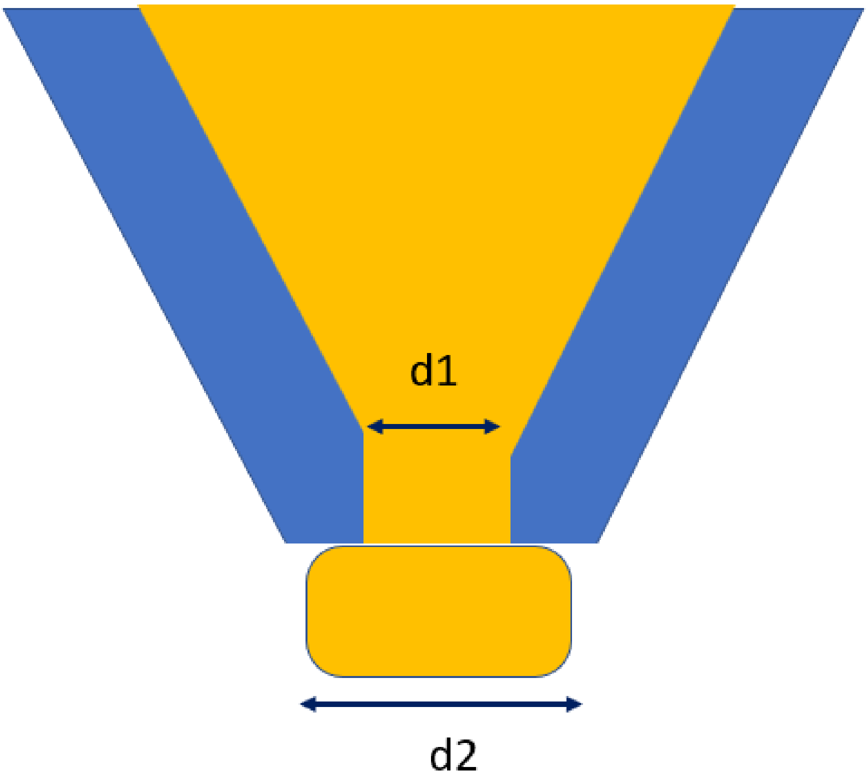


Figure 33. A successful ration of extrusion width in LSAM according to the finding of this thesis. Nozzle diameter 150% (d1) < Layer width (d2) < 180% (d1)

4.2.8 Tolerances of double walls and wall overlaps

In the context of designing double wall perimeters in many manufacturing processes, it is crucial to carefully consider the geometry of the wall design in order to ensure proper bead fusion and prevent material extrusion shift during printing. Due to the semi-oval shape of the beads deposited during extrusion, there may be a void in between the bead configuration which can lead to anisotropic properties of the wall. However, the amount of bead overlap can be adjusted to decrease the volume of voids, thus increasing the contact area between layers and perimeters.

This thesis conducted a test on double wall design with different wall thicknesses while maintaining a constant nozzle and extrusion rate. The results indicated that the best performance was achieved when there was a 5 to 20 percent overlap between the walls, and the best quality with 15 percent overlap, meaning that the geometry of the wall should be 5 to 20 percent less than double the width of the bead. Two nozzles were used in the test, each with two different extrusion rates, to print a multiple size double geometry. The conditions of the test were described in Table 3, and the results were visually depicted in Figure 34, the concept of porosity migration using layer overlap is shown. Figure 35 depicts the design geometry and actual print example that has been used for this design of experiment. Figure 36 illustrates the failures and successful results of the test which is projected in the table 3 and 4.

Although the results of this experiment were evaluated based on visual inspection, future studies are recommended to use more scientific and precise methods to verify the findings. The outcomes of this investigation were evaluated through visual observation, and further research is recommended to conduct more scientific and precise testing.

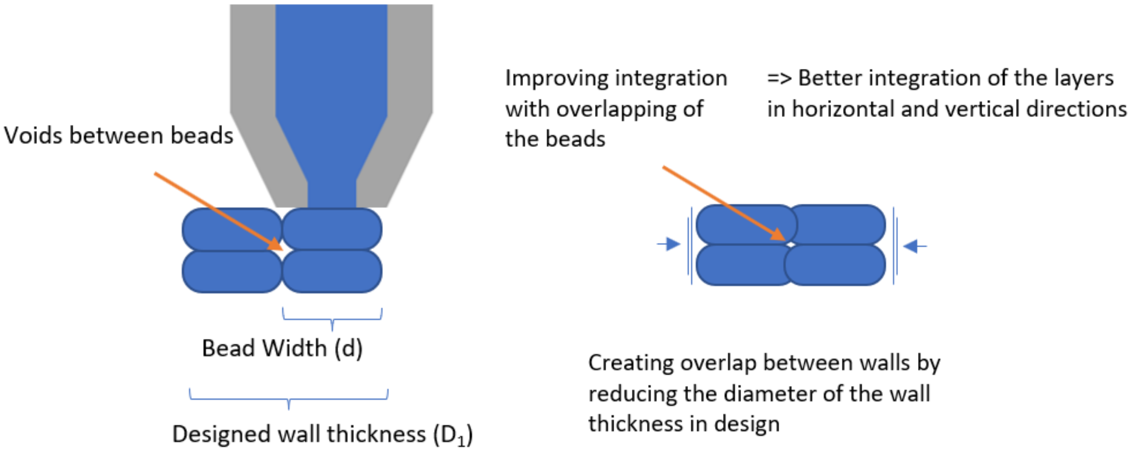


Figure 34. The concept of layer overlap technique to mitigate the porosity between the layers and increasing the layer adhesion

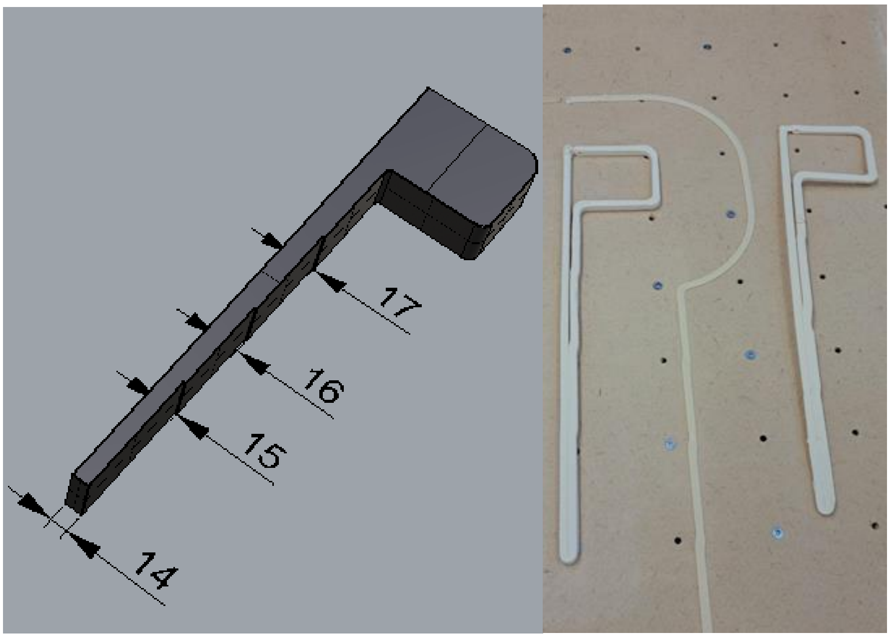


Figure 35. 2) Parametric design for the geometry of the test and sample of the print on the printing bed

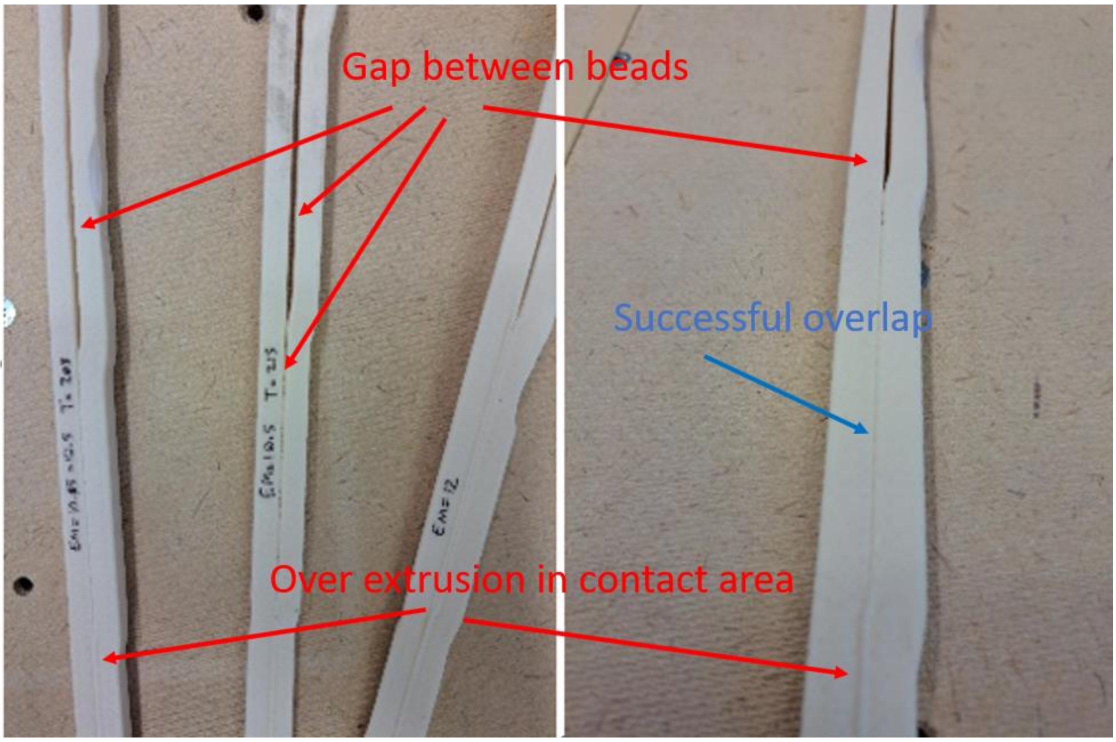


Figure 36. Examples of gaps, successful overlap, and over extrusion in the overlap contact area. Below, the design of experiment is projected in the table 3 and 4 where the parameters for two test cases are shown

Table 3. Design of experiment for tolerances of double walls for 6mm nozzle with 10 mm layer width

Nozzle size = 6 mm & layer width = ~10 mm				
Test	Designed Wall thickness (mm)	Overlap between (%)	Measured wall Thickness (mm)	Result of visual observation
1	14	30	18.3	Over extrusion, extrusion shifting, inflate contact area, slight material oozing.
2	15	25	18.7	Slight Over extrusion, extrusion shifting, inflate contact area
3	16	20	19.4	Acceptable double wall quality, slight extrusion shifting, slight inflate contact area, good integration between layers vertically and horizontally. Final tolerance of the wall is less than design.
4	17	15	19.9	Best quality, flat double bead, near zero void, close tolerance outcome.
5	18	10	20.2	Flat double bead, Slight voids in the round corners, close tolerance outcome.
6	19	5	20.2	Improved flatness of beads contact area, improved contact between beads, disconnection between beads in round corners.
7	20	0	20.3	Void between horizontal and vertical layers. Disconnection between beads in some spots.
8	21	-5	21.1	Unconnected beads, considerable void between bead.

Table 4. Design of experiment for tolerances of double walls with 8 mm nozzle and 12 mm layer width

Nozzle size = 8 mm & layer width = ~12 mm				
1	16.8	30	22.6	Over extrusion, extrusion shifting, inflate contact area
2	18	25	23.2	Slight Over extrusion, extrusion shifting, inflate contact area, slight material oozing.
3	19.2	20	23.7	Acceptable double wall quality, slight extrusion shifting, slight inflate contact area, good integration between layers vertically and horizontally. Final tolerance of the wall is less than design.
4	20.4	15	24.1	Best quality, flat double bead, near zero void, close tolerance outcome.
5	21.6	10	24.2	Flat double bead, Slight voids in the round corners, close tolerance outcome.
6	22.8	5	24.3	Improved flatness of beads contact area, improved contact between beads, disconnection between beads in round corners.
7	24	0	24.3	Void between horizontal and vertical layers. Disconnection between beads in some spots.
8	25.2	-5	25.3	Unconnected beads, considerable void between bead.

4.2.9 Custom support structure and clearance tolerances

As previously noted, angled slicing and printing offer the advantage of producing overhangs without requiring support structures. However, when printing large surfaces, the roofs may be printed but the use of plastic material and its inherent flexibility may not satisfy the strength requirements for certain end-uses such as molding purposes. Additionally, unsupported roofs may vibrate during the milling process, thus necessitating the need for support structures to increase structural strength. Nonetheless, in Large Scale Additive Manufacturing (LSAM), the contours of the part should be continuous closed loops, precluding the use of traditional algorithmic support generation methods provided by conventional slicers. In this study, a technique involving the creation of grooves in the bottom surface of the part at a certain offset from the top surface was employed to address this issue. Consequently, when the part is sliced, a cross-section of the part is half cut up to the surface, thereby generating a double-walled support structure for the roofs. This approach was adapted from the article by Roschli et al. (2019) and may serve as a design guideline for custom-made support structures for LSAM parts. Further research could algorithmize this technique to reduce the lead time of the design process. Figure 37 illustrates this concept. The tolerances of the implementation of this technique will be discussed later in the result section.

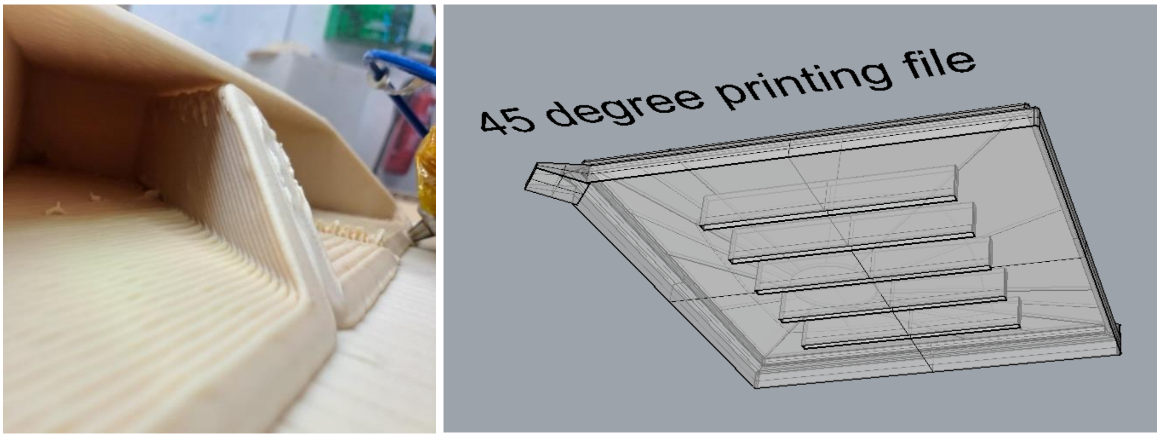


Figure 37. A perspective bottom view of groves made to create custom made support structure for the roofs

4.2.10 Printing on printed parts

Robotic systems offer advantages for large-scale additive manufacturing due to their capacity for rotation and configuration flexibility. The combination of these capabilities with angled slicing allows for parts to be printed on top of each other, resulting in an assembly of geometries in a single build process. This approach was utilized during the research presented in this thesis, which involved trials with various geometries. The concept of printing parts on top of one another was inspired by Wu et al. (2017), who implemented a similar approach. This method can also be used to raise parts that require machining on all surfaces. To achieve this, a box-shaped raiser support structure is designed and printed beneath the actual print, after which the part is machined. This technique prevents collisions with the bed and clamping units according to the hindsight derived from the work of the author.

In future research, another idea to be considered for further development is the possibility of using cladding on tool path generation methods. However, since there is a time gap between the printing of different assemblies on top of each other, preheating of the previous part will facilitate better fusion between the molten material and the cooled surface (Compton et al., 2017). Figure 38 illustrates the result of a printing test involving the production of multi-boxes printed on top of each other using angled slicing. The top surface was subsequently machined. Notably, all parts had zero infill content.

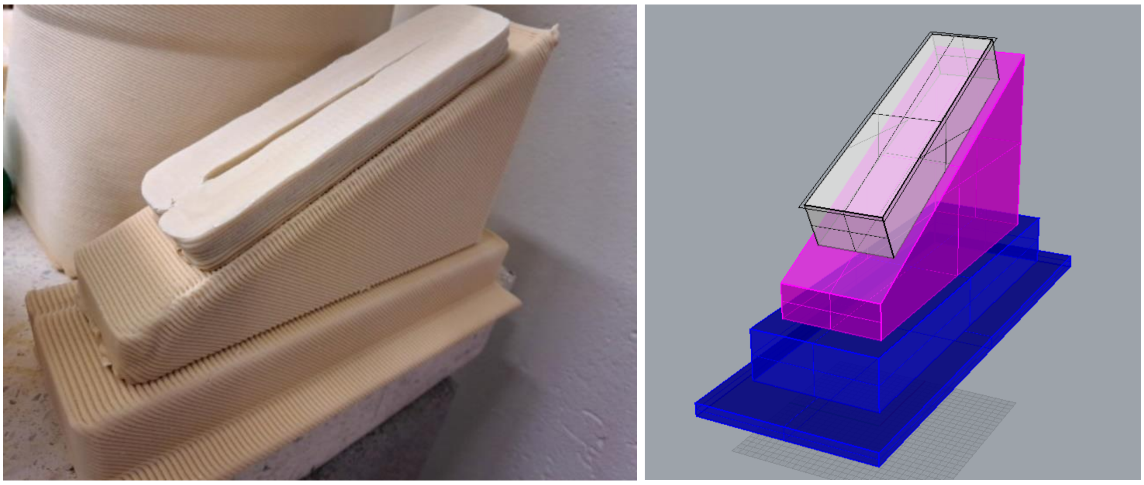


Figure 38. Printing of assemblies of parts in one printing run

4.2.11 Colouring of the material

The material denoted as UPMFORMI40 exhibits a creamy to white hue. In the process of extrusion, it is plausible to incorporate coloring PLA-based pellets, termed Masterbatch, into the material. The recommended ratio of mixture entails 2 to 10 percent of the weight of Masterbatch in proportion to the weight of the base material. Nevertheless, it is imperative that the blending of the material is conducted cohesively. A practical examination of this technique was conducted during the printing test implemented for the purpose of this thesis. A design was produced through a mixture consisting of 8 percent colouring agent and 92 percent base material. The outcome of this test is portrayed in Figure 39 where the extruded pellets are shown. Figure 40 is a result of a printed part which was coloured in the process. However, the test was not deemed successful due to the development of delamination and cracks during the printing process. The subsequent topic shall expound on this matter.

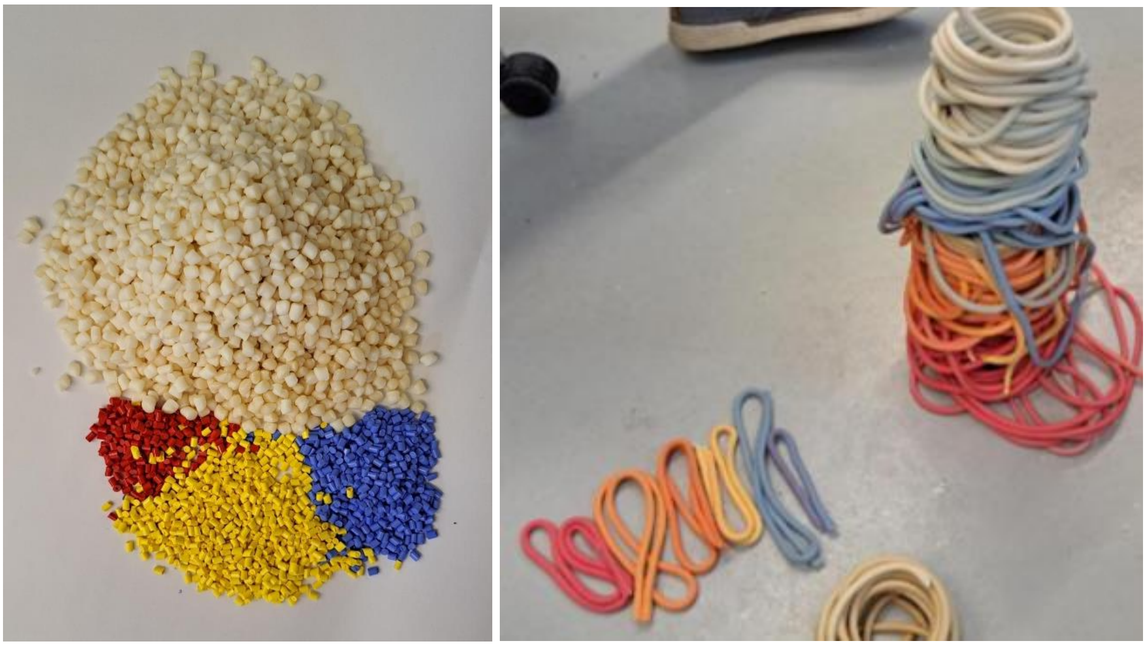


Figure 39. Mixing masterbatch and UPMFormi40 (left picture) and extruding spectrum of coloured bead (right picture)

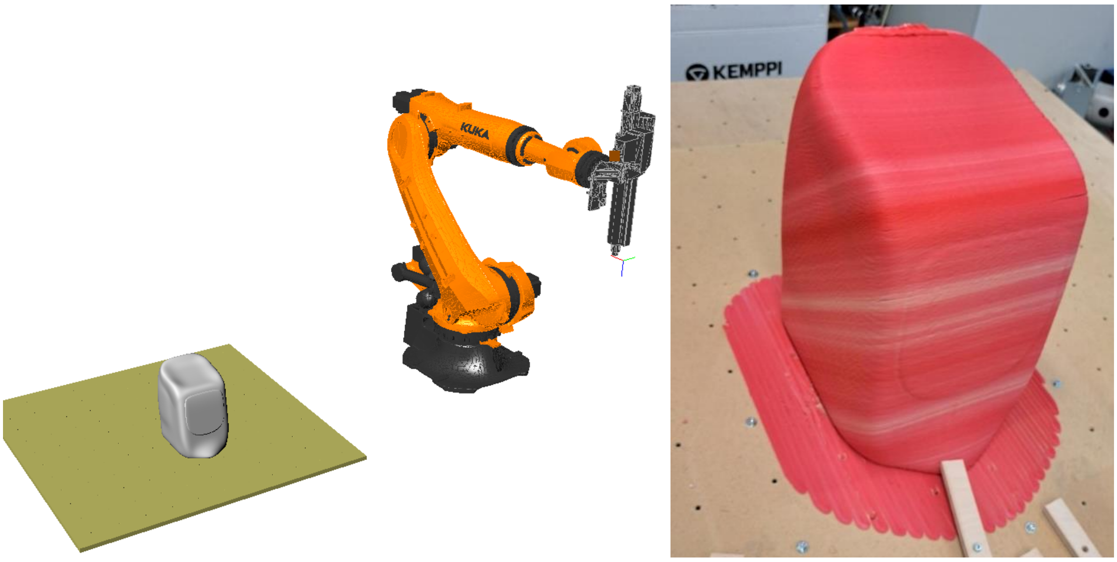


Figure 40. Manufacturing of a part with in-process colouring technique. Simulation is shown in the left picture and the printed part in the right picture

4.2.12 Cracks in layers during print process

Additive manufacturing of polymers is susceptible to thermal stress due to the differences in temperature between the melted material and the solidified material. Thermal shrinkage occurs during the printing process, and the flexibility of the material allows some of this stress to be absorbed in the part's structure. However, if the bonding of the layers is not sufficient, cracks may occur during or after the printing process. In addition to cracks, good mechanical properties require precise thermal control of the printing process. A balance between cooling and printing speed is necessary, as insufficient cooling can lead to collapse and deformation of the part, while excessive cooling can result in weak layer adhesion and cracks under thermal or other stresses during the part's application.

Several approaches have been proposed to address this issue. One effective method is to control the printing speed to allow the material to cool and solidify adequately without becoming too cold, resulting in weak layer adhesion. Borish et al. in the series of research in 2019, 2020, and 2021 found that the ideal temperature range for the previous layer is between 100 and 120 degrees Celsius for the material CF20%ABS, and the cooling rate is

0.5 degrees per second (Borish, 2021). These findings highlight the importance of thermal analysis and control of the printing process.

During testing for this thesis work, a large object printed at a slow speed of 30 mm/s with a layer adhesion of 2 mm experienced thermal cracking. Some of the cracks occurred during the printing process, while others developed after the part detached from the build plate. This outcome prompted the development team to focus on thermal control practices to ensure good mechanical quality of future prints. Finite element method simulation of the printing process's thermal behaviour can also be used to program the printing speed without adaptive speed control. Another approach suggested in the literature is to conduct real-time thermal analysis of the layers and create a closed-loop speed control for the robot.

Fortunately, another advantageous feature of the KUKA PRC plugin for Grasshopper is its compatibility with the MX-Automation software of the KUKA PLC computer. This capability enables direct communication between a computer and the real-time execution of streaming data. As a result, an external computer can be connected to a robot and a thermal camera, which can then adapt the robot's motion while analysing the data obtained from the camera. However, these topics are beyond the scope of this thesis and will be referred to in future research and developments. Figure 41 illustrates this failure, emphasizing the importance of considering this issue for designers, robot programmers, and operators.

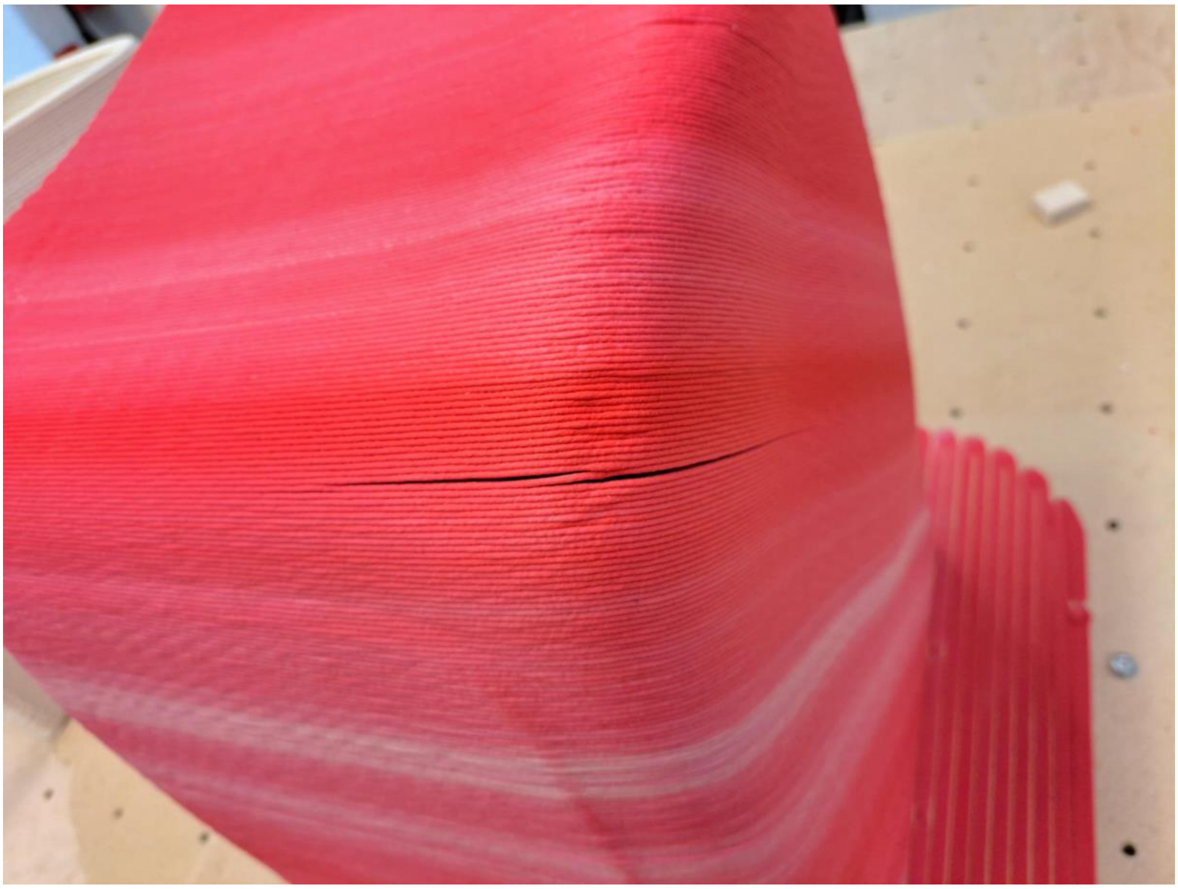


Figure 41. The occurrence of cracks during the printing process was attributed to thermal stresses and inadequate bonding between the layers

4.2.13 Program excution buffer length on robot

The robotic system employed in this study had a limitation of three advanced points, whereby the robot could only perceive the next three points ahead and would compute the required kinematics for the fourth point upon reaching the third point. However, each of these computations in the robot's computer took a small amount of time. In cases where the kinematics of the robot movement was faster than the speed of the movement's calculation, the robot would halt at a point, waiting for the calculation to be completed. This phenomenon is referred to as buffer lag, and it occurs when the time between two points is less than a specific time for calculation. Buffer lags occur when the distance between two points is too short or the printing speed is high.

During the printing process, buffer lags cause the robot to stop for brief periods, resulting in artifacts of over extrusion due to material oozing. The concentration of points on a tool path can occur in various cases. To address this issue, several solutions were developed in this study. Splicing can be done for STL and NURB models. When slicing is performed on STL files, a series of planner or non-planner surfaces with a defined trajectory would cut the part, and their cross-sections with the design would be utilized to extract the outer contour for tool path generation. However, the cross-sections of the contours often intersect a concentrated area where the triangles' edges meet at a common point since the SLT format defines the design's geometry with triangular or rectangular surfaces. A polyline with a concentrated number of points in a small area is then generated, leading to concentrated short moves for the tool path that result in buffer lags.

To mitigate this problem, the mesh size configuration of the model can be reduced, but this comes at the expense of geometry fidelity. This would, however, increase print quality since the robot's movement would be at a constant speed. The mesh fixing method would have a better result, even when the new mesh is generated with a quadrangulate configuration along with the slicing planes. This reduces the likelihood of slicing contours crossing near concentrated junctures edges. According to our testing practices, this method performed best, but with the highest sacrifice in geometry fidelity loss. Figure 42 depicts the buffer lag failure and figure 43 is the illustration of different meshes as well as their contouring results.

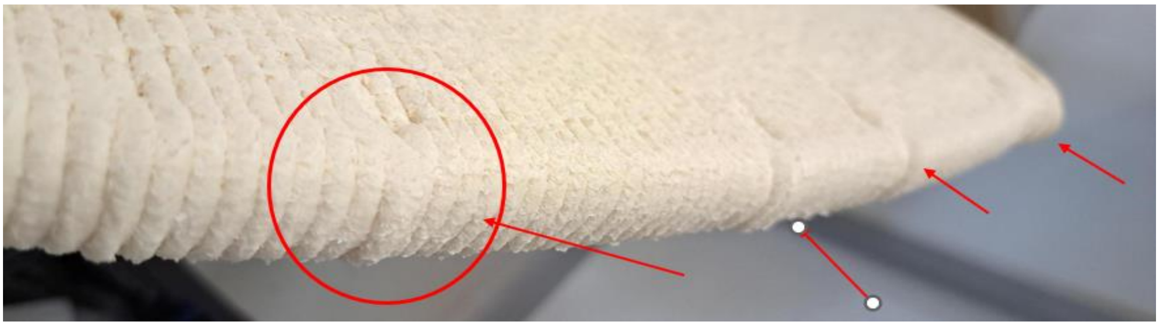


Figure 42. Buffer lag in movement of robot causing print quality failure

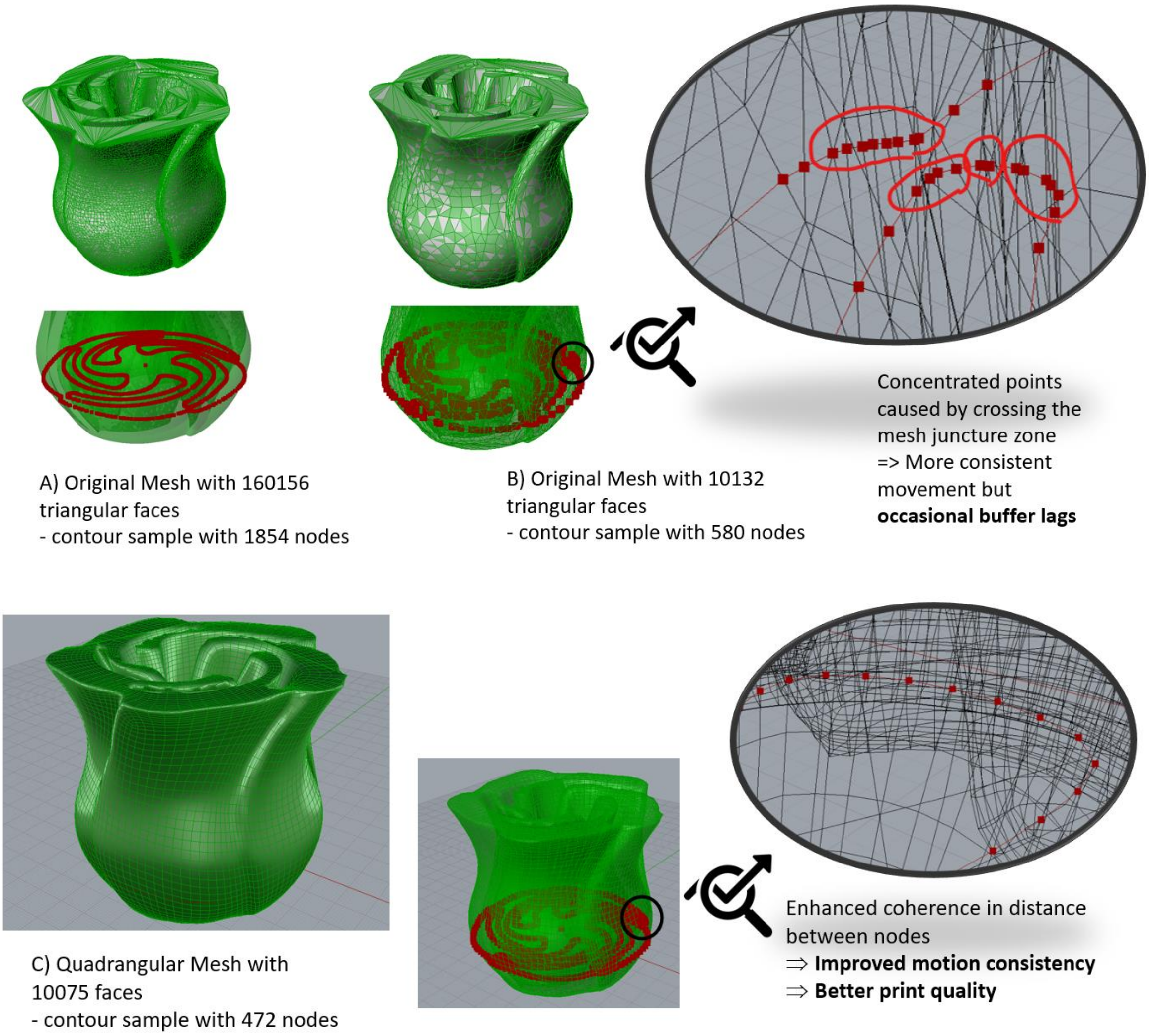


Figure 43. Mesh modification for improvement of robot speed consistency and enhanced print quality

An alternative method for reducing the number of nodes in a polyline generated as a tool path involves post-processing the polyline by detecting concentration areas, identifying short distances between nodes, and removing the node in between to create longer moving commands. This approach can be implemented through different algorithms within various platforms, such as the Arcwelder plugin in the Cura slicing software. However, this thesis work utilizes the advantage of Grasshopper in compiling Python scripts to implement a node reduction post-processing of polylines within the workflow. The implemented Python code examines the list of distance nodes in the polyline of a contour and removes all distances less than 1 mm. Figure 44 shows the script of the node reduction workflow.

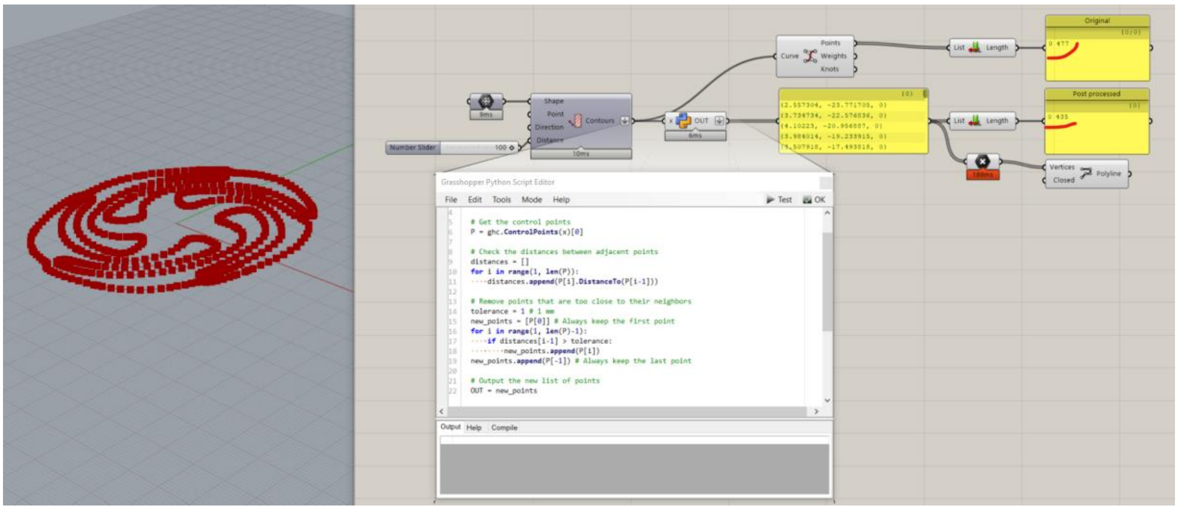


Figure 44. Node reduction postprocessing with python in Grasshopper

However, it is important to note that this node reduction method may not be suitable for simple algorithms, such as the one introduced earlier. The reason being that while reducing the nodes in the slicing plan, the alignment of the nodes in the Z direction (in the case of planar slicing) may be altered, resulting in misalignment of the tool path and local shifting of the layers. To overcome this issue, more complex mathematical algorithms are required that can align the points in the Z direction and for post-processing, which is beyond the scope of this thesis work and will be referred to as future developments. Nonetheless, this issue was detected during one of the test prints and further simulation of the tool path. Figure 45 illustrates the simulation and printing failure of this issue.

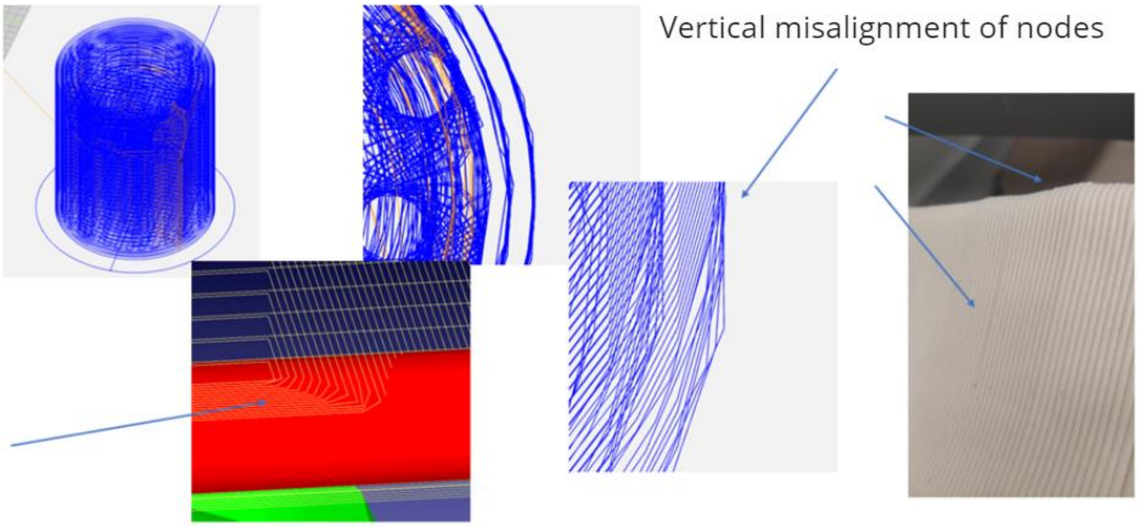


Figure 45. Problem with misalignment of the nodes in Z direction and layer shifting

An alternative and efficacious approach to generating a slicing tool path is available in only a limited number of slicer software programs and can also be accomplished using Grasshopper. This method involves generating the slicing tool path directly from the NURB model and offers several advantages. The alignment of the tool tolerances with the geometry boundaries is highly precise, and the slicing contours can be segregated into three distinct types of interpolations: linear movement, circular movement, and spline curves. These three types of NURB curves can be easily translated to robot movements as the KUKA krl language features four types of movement commands: point-to-point (PTP), linear (LIN), circular (CIR), and spline (SPL) movements. This approach reduces the size of the robot program and significantly improves robot movement.

Grasshopper provides highly beneficial interpolation components that allow for mass customization and optimal results. Among the interpolation methods, the 'Curvetopolyline' component is the most optimum one that enables the interpolation of any type of curve with defined tolerances, angle tolerance, and minimum and maximum distance between nodes. Additionally, two other useful components are available for interpolating curves into a series of splines or circular curves, which can simplify the robot programming process.

Table 5 and 6 illustrates the curve division and interpolation methods in Grasshopper that could be used in path planning for robotic additive manufacturing. Designers of large-scale additive manufacturing processes should possess a comprehensive understanding of the technology's limitations and capabilities, including the methods and algorithms used for slicing.

Table 5. Curve division methods in Grasshopper

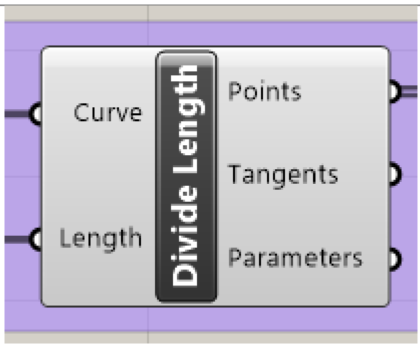
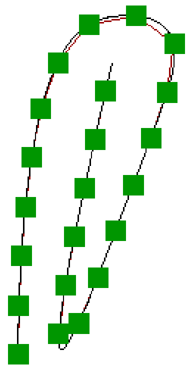
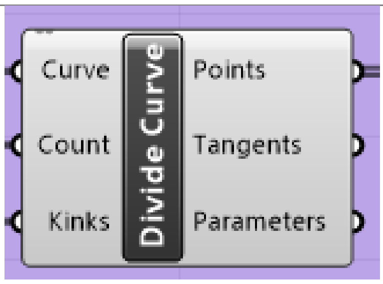
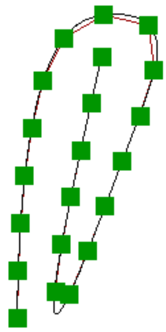
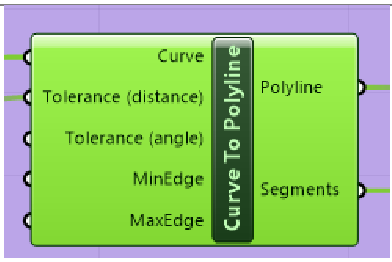
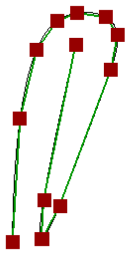
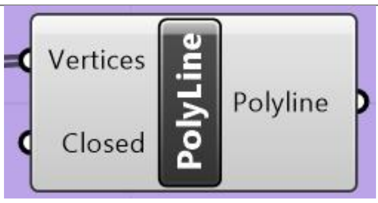
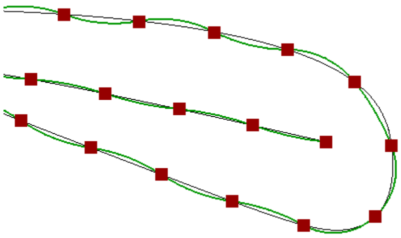
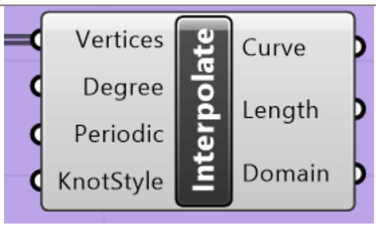
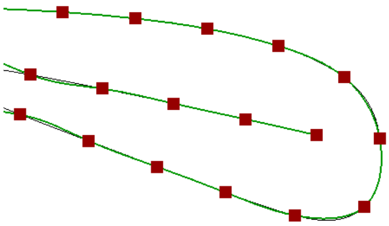
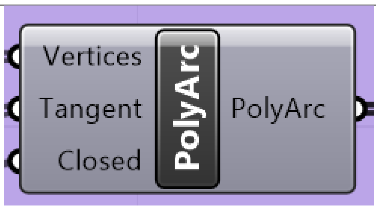
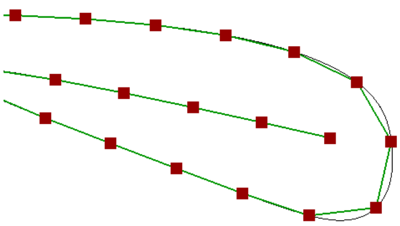
Method	Component	Result	Parameters
Equal length division			Distance along the curve between two nodes
Equal distance by counts			Number of nodes on the curve in total
Multi parameter division			Tolerances and distance definitions

Table 6. The interpolation methods in Grasshopper

<table>
<tr><th>Method</th><th>Component</th><th>Results with equal curve division</th></tr>
<tr><td>Polyline</td><td>
</td><td></td></tr>
<tr><td>Spline</td><td>
</td><td></td></tr>
<tr><td>Circular</td><td>
</td><td></td></tr>
</table>

One of the curve division methods that has been found to be highly efficient is the multiparameter division method, which is particularly suited to linear and spline interpolation methods. However, it is important to note that each of the aforementioned methods has its own advantages and specific applications. For example, circular interpolation is particularly useful when dealing with designs featuring blended edges that require equal distance division curves. On the other hand, spline interpolation may not be well-suited to designs with sharp edges, but is highly effective for general curvy surfaces. Similarly, the polyline interpolation of equal distance by number of curves can greatly facilitate node alignment workflows.

Moreover, these various interpolations and curve divisions can be employed to create patterns that possess both aesthetic and structural benefits. For example, as demonstrated in Figure 46, a circular wall may be constructed in a zigzag pattern to achieve greater structural stability. These possibilities provide large-scale additive manufacturing designers with the ability to seamlessly integrate their design skills with technology that is both manufacturable and of high quality.

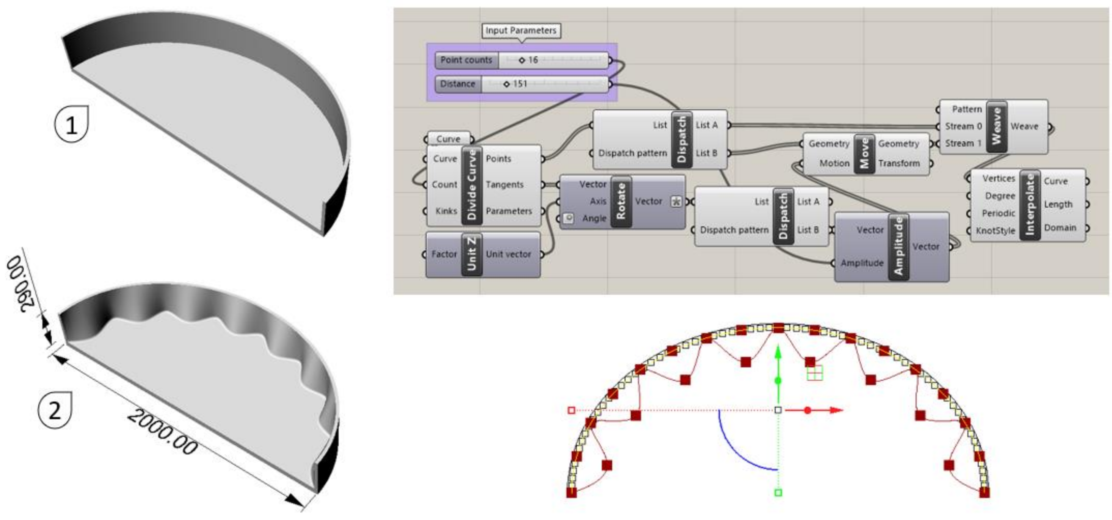


Figure 46. Creating self supporting walls with equal distance curve division: 1- original model 2- parametric modified version with curve division and interpolation

5 Conclusions

Large scale additive manufacturing is an innovative technology that not only enables the production of large parts but also encourages new approaches to product design and fast production of new products. One of the most significant benefits of this technology is its potential for sustainable manufacturing. Pellet extruders designed for large scale additive manufacturing make it possible to extrude different types of materials, from high performance to environmentally friendly and recycled materials, leading to circularity in the economy, which is much needed in today's world.

Despite the wide capabilities and promises of using robotic systems for LSAM pellet extrusion, there are still significant challenges faced by this new technology. Two of the most important challenges are the lack of design guidelines and integrated software solutions for robotic additive manufacturing. This thesis aims to address these challenges by investigating the obstacles in this technology and developing a software workflow for robotic additive manufacturing that integrates all the stages software needs for this technology. The workflow for robotic additive manufacturing was built using the Rhino serious grasshopper platform, and its effectiveness was validated during a series of test prints. Thirteen design guidelines were extracted from the thesis tests, which is the second goal of this thesis work. Altogether, the research questions are answered as below:

1) What are the gaps in the current workflow of additive manufacturing using robotic pellet extrusion, and how can they be addressed through a comprehensive software solution?

Currently, there are a limited number of software solutions available for large scale additive manufacturing. However, these options have limitations and do not encompass the entire workflow, resulting in the need for multiple licenses and difficulties integrating different software. These incompatibilities may also hinder the ability to use all available options within a single software program. This leads to time-consuming efforts in learning and troubleshooting software integration. As a result, there is a pressing need for a customizable and integrated software solution for robotic additive manufacturing. Based on the findings of this thesis work, the Rihnoserous Grasshopper platform was identified as a promising solution for building a comprehensive workflow for large scale additive manufacturing in a single platform.

2) How can the development of an angled slicing technique improve the toolpath generation process for large-scale additive manufacturing using robotic pellet extrusion?

The utilization of angled slicing technique in the context of robotic additive manufacturing offers several advantages. The most significant benefit is the ability to print overhangs, such as roofs, without requiring support structures. This capability reduces material consumption, printing time, and manufacturing costs. Additionally, since pellet extruders lack the capacity to retract material, printing complex geometries using vertical conventional slicing is often impractical. Angled slicing offers designers greater flexibility to design complex geometries that might not be manufacturable otherwise. Nevertheless, angled slicing poses its own challenges and limitations, which should be considered. It should only be used for relevant designs and not as a default option. Tolerance issues and mechanical properties of the resulting parts can be inferior to those manufactured using vertical slicing. Despite these limitations, the utilization of angled slicing can be an attractive option when employing robotic arms for large-scale additive manufacturing.

3) How can post-processing tools be used to optimize the generated toolpaths for KUKA robotic arms?

In the field of robotic additive manufacturing, there exist various software tools for generating robotic programs. However, the software solutions that cater to this specific application are few, and their corresponding postprocessors for KUKA robots are typically written on an individual basis. It is common for end-users to take it upon themselves to modify postprocessors to suit their specific needs, as well as to verify their reliability, all while bearing the associated risks. This thesis work reveals that the KUKA PRC plugin, integrated within the Grasshopper environment, is a relatively reliable postprocessor with mass customization capabilities that can cater to individual needs. Moreover, compared to the use of mere codes, this plugin is considerably more user-friendly. The development of reliable postprocessors for robotic programming is critical to ensuring the safety and quality of LSAM processes. With the aid of KUKA PRC, this can be achieved effectively and reliably.

4) Is the proposed software solution workable for large-scale additive manufacturing using robotic pellet extrusion? Is integration of the workflows make the robot programming more efficient?

The software proposed in this thesis, although still in its early stage of development, has demonstrated its feasibility and workability. While the workflow may require certain skills and a learning curve to be developed, it has the potential to be simplified for use by operators and non-coding technicians in the future. At this point, since the workflow is not as developed as readymade software on the market, implementation of it, although all is done in one software, requires modification percase, therefore more time consuming. However, one of the major advantages of this workflow is that it only requires two sets of licenses, one for Rhinoceros and one for KUKA PRC, which are comparably inexpensive compared to other software solutions. Furthermore, this software enables the creation of parametric designs with potential for innovative structural designs to be manufactured. Overall, the software solution workability has been validated through a series of tests and shows potential for future works.

5) What are the design considerations related to large scale additive manufacturing with robotic pellet extrusion?

In the realm of large-scale additive manufacturing, there are a multitude of design considerations that must be taken into account. Among these are the specific machinery and materials to be used, as well as embedding conditions, intended mechanical properties, geometric requirements for the part, and post-processing methods. The selection of appropriate slicing software and program post-processing is also crucial, as is the overall safety of the process. To fully grasp the implications of these factors, it is necessary to apply the technology in practice. In this thesis, 13 key design considerations were investigated and introduced as a means of mitigating challenges in the manufacturing process. While this list is by no means exhaustive, it can serve as a starting point for the development of a comprehensive guideline for designers. Further research in this area may help to expand upon these considerations and provide additional insight into the unique demands of large-scale additive manufacturing.

6 Future research and developments

The results of this thesis work are the starting point for further research to improve the workflow and design guidelines for large scale additive manufacturing. The workflow developed in this thesis will initiate further research to explore the parametrical optimization of process parameters for robotic additive manufacturing since all of the workflows in Grasshopper are parametric. The success in the quality of the prints is related to the use of the right process parameters. The results of the design guidelines are useful for initiating more investigation of the design guidelines as well as educating designers for large scale additive manufacturing and students. In summary, the results of this thesis contribute to the realization of sustainable manufacturing.

During the literature review, workflow development, and laboratory tests of this thesis, several subjects were found to be influencing the process of large-scale additive manufacturing and referred to future research. Among all of them, further development of toolpath generation for additive manufacturing, as well as robotic milling, will be the main focus. The development of tool path generation will involve conformal, cladding, non-planner, sweeping, branching, and rotary slicing. The author also aims to investigate the development of the workflow to handle the robot in real-time control so that it can use the real-time sensing options for maximizing the quality of the printing. The author plans to perform a real-time thermal control of the additive manufacturing with thermal cameras.

In terms of material science, although it is not the author's area of expertise, testing of printing with different materials will be a new project. However, material development will not be the focus of the author's future work, as it requires different sets of skills and equipment. Nonetheless, material development for large scale additive manufacturing is essential, especially in the field of recyclable and high-performance materials. Another project that the author plans to pursue is finding a way to continuously mix the coloring material with the raw material, which could give the possibility to control the color of the extrusion.

In terms of design for large scale additive manufacturing, there is still a significant need for comprehensive design guidelines. The technology is new, and the equipment, materials, and software approaches are very different. Therefore, a comprehensive guideline for large scale additive manufacturing of polymers does not exist yet. However, for the need of the 3DROBO team and future career prospects of the author, the results of this thesis will be used to further investigate the design considerations with the current sets of equipment and software.

A prospective topic for the author's future research entails the advancement of large-scale additive manufacturing within the construction industry, specifically focusing on the utilization of concrete and alternative materials. This research area necessitates development akin to large-scale additive manufacturing utilizing pellet extruders, albeit with distinctive material characteristics and target geometries. The adoption of LSAM technology has the potential to reshape the construction sector, thereby necessitating the formulation of novel design guidelines, certifications, advancements in material development, and an enhanced understanding of manufacturing processes.

References

Adams, D. and Turner, C.J., 2018. An implicit slicing method for additive manufacturing processes. Virtual and Physical Prototyping, 13(1), pp.2-7.

Alhijaily, A., Kilic, Z.M. and Bartolo, A.P., 2023. Teams of robots in additive manufacturing: A review. Virtual and Physical Prototyping, 18(1), p.e2162929.

Borish, M. et al. (2019) 'Defect Identification and Mitigation Via Visual Inspection in Large-Scale Additive Manufacturing', JOM, 71(3), pp. 893–899. Available at: https://doi.org/10.1007/s11837-018-3220-6.

Braumann, J., Gollob, E. and Singline, K. (2022) 'Visual Programming for Interactive Robotic Fabrication Processes - Process flow definition in robotic fabrication', in. eCAADe 2022: Co-creating the Future - Inclusion in and through Design, Ghent, Belgium, pp. 427–434. Available at: https://doi.org/10.52842/conf.ecaade.2022.2.427.

Chacón, J.M. et al. (2022) 'G-code generation in a NURBS workflow for precise additive manufacturing', Rapid Prototyping Journal, 28(11), pp. 65–76. Available at: https://doi.org/10.1108/RPJ-09-2021-0254.

Chesser, P. et al. (2019) 'Extrusion control for high quality printing on Big Area Additive Manufacturing (BAAM) systems', Additive Manufacturing, 28, pp. 445–455. Available at: https://doi.org/10.1016/j.addma.2019.05.020.

Cleeman, J. et al. (2022) 'Scalable, flexible and resilient parallelization of fused filament fabrication: Breaking endemic tradeoffs in material extrusion additive manufacturing', Additive Manufacturing, 56, p. 102926. Available at: https://doi.org/10.1016/j.addma.2022.102926.

Dreifus, G.D., Jin, Y., Ally, N. and Post, B.K., 2016. Approaches to geometric data analysis on big area additively manufactured (BAAM) parts. In 2016 International Solid Freeform Fabrication Symposium. University of Texas at Austin. Duarte, J. et al. (2022) 'Curved layer path planning on a 5-axis 3D printer', Rapid Prototyping Journal, 28(4), pp. 629–636. Available at: https://doi.org/10.1108/RPJ-02-2021-0025.

Duty, C.E. et al. (2017) 'Structure and mechanical behavior of Big Area Additive Manufacturing (BAAM) materials', Rapid Prototyping Journal, 23(1), pp. 181–189. Available at: https://doi.org/10.1108/RPJ-12-2015-0183.

El youbi El idrissi, M.A. et al. (2022) 'Energy Consumption Prediction for Fused Deposition Modelling 3D Printing Using Machine Learning', Applied System Innovation, 5(4), p. 86. Available at: https://doi.org/10.3390/asi5040086.

Ford, S. and Despeisse, M. (2016) 'Additive manufacturing and sustainability: an exploratory study of the advantages and challenges', Journal of Cleaner Production, 137, pp. 1573–1587. Available at: https://doi.org/10.1016/j.jclepro.2016.04.150.

Fry, N.R., Richardson, R.C. and Boyle, J.H. (2020) 'Robotic additive manufacturing system for dynamic build orientations', Rapid Prototyping Journal, 26(4), pp. 659–667. Available at: https://doi.org/10.1108/RPJ-09-2019-0243.

García-Dominguez, A., Claver, J. and Sebastián, M.A. (2020) 'Integration of Additive Manufacturing, Parametric Design, and Optimization of Parts Obtained by Fused Deposition Modeling (FDM). A Methodological Approach', Polymers, 12(9), p. 1993. Available at: https://doi.org/10.3390/polym12091993.

Gardner, J.A., Nethercott-Garabet, T., Kaill, N., Campbell, R.I., Bingham, G.A., Engstrøm, D.S. and Balc, N.O., 2018. Aligning material extrusion direction with mechanical stress via 5-axis tool paths. In 2018 International Solid Freeform Fabrication Symposium. University of Texas at Austin. Gibson, I., Rosen, D. and Stucker, B. (2015) Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing. New York, NY: Springer New York. Available at: https://doi.org/10.1007/978-1-4939-2113-3.

Hong, F. et al. (2022) 'Open5x: Accessible 5-axis 3D printing and conformal slicing', in CHI Conference on Human Factors in Computing Systems Extended Abstracts. CHI '22: CHI Conference on Human Factors in Computing Systems, New Orleans LA USA: ACM, pp. 1–6. Available at: https://doi.org/10.1145/3491101.3519782.

Kampker, A. et al. (2019) 'Review on Machine Designs of Material Extrusion based Additive Manufacturing (AM) Systems - Status-Quo and Potential Analysis for Future AM

Systems', Procedia CIRP, 81, pp. 815–819. Available at: https://doi.org/10.1016/j.procir.2019.03.205.

Layher, M., Bliedtner, J., Schilling, M., Schmidt, L., Schricker, K.M., Pierre, J., Bergmann, U.K., Chodura, E. and Kramer, H., 2018. Conceptual development of a high-productive fabrication system for. Additive manufactured large-scale items from arbitrarily chosen plastics. In direct digital manufacturing conference. Berlin, Germany.

Meraz Trejo, E. et al. (2020) 'Compressive deformation analysis of large area pellet-fed material extrusion 3D printed parts in relation to in situ thermal imaging', Additive Manufacturing, 33, p. 101099. Available at: https://doi.org/10.1016/j.addma.2020.101099.

Murdy, P. et al. (2021) 'Leveraging the Advantages of Additive Manufacturing to Produce Advanced Hybrid Composite Structures for Marine Energy Systems', Applied Sciences, 11(3), p. 1336. Available at: https://doi.org/10.3390/app11031336.

Okur, S. and Altan, A. (2021) 'Grasshopper Optimization Algorithm-based Adaptive Control of Extruder Pendulum System in 3D Printer', in 2021 Innovations in Intelligent Systems and Applications Conference (ASYU). 2021 Innovations in Intelligent Systems and Applications Conference (ASYU), Elazig, Turkey: IEEE, pp. 1–6. Available at: https://doi.org/10.1109/ASYU52992.2021.9599025.

Post, B.K., Richardson, B., Lind, R., Love, L.J., Lloyd, P., Kune, V., Rhyne, B.J., Roschli, A., Hannan, J., Nolet, S. and Veloso, K., 2017. Big area additive manufacturing application in wind turbine molds. In 2017 International Solid Freeform Fabrication Symposium. University of Texas at Austin.

Post, B.K., Lind, R.F., Lloyd, P.D., Kunc, V., Linhal, J.M. and Love, L.J., 2016. The economics of big area additive manufacturing. In 2016 International Solid Freeform Fabrication Symposium. University of Texas at Austin.

Roschli, A. et al. (2019) 'Design for Slicing in Large Format Fused Filament Fabrication', in CAMX 2019. CAMX 2019, NA SAMPE. Available at: https://doi.org/10.33599/nasampe/c.19.0707.

Roschli, Alex et al. (2019) 'Designing for Big Area Additive Manufacturing', Additive Manufacturing, 25, pp. 275–285. Available at: https://doi.org/10.1016/j.addma.2018.11.006.

Roschli, A., Post, B., Chesser, P., Borish, M., Love, L. and Kim, S., 2019. Creating toolpaths without starts and stops for extrusion-based systems. In 2019 International Solid Freeform Fabrication Symposium. University of Texas at Austin.

Sampedro, G.A.R. et al. (2022) ‘Design of an In-Process Quality Monitoring Strategy for FDM-Type 3D Printer Using Deep Learning’, Applied Sciences, 12(17), p. 8753. Available at: https://doi.org/10.3390/app12178753.

Stock, T. and Seliger, G. (2016) ‘Opportunities of Sustainable Manufacturing in Industry 4.0’, Procedia CIRP, 40, pp. 536–541. Available at: https://doi.org/10.1016/j.procir.2016.01.129.

Urhal, P. et al. (2019) ‘Robot assisted additive manufacturing: A review’, Robotics and Computer-Integrated Manufacturing, 59, pp. 335–345. Available at: https://doi.org/10.1016/j.rcim.2019.05.005.

Vicente, C.M.S. et al. (2023) ‘Large-format additive manufacturing of polymer extrusion-based deposition systems: review and applications’, Progress in Additive Manufacturing [Preprint]. Available at: https://doi.org/10.1007/s40964-023-00397-9.

Wang, M. et al. (2019) ‘Research and implementation of a non-supporting 3D printing method based on 5-axis dynamic slice algorithm’, Robotics and Computer-Integrated Manufacturing, 57, pp. 496–505. Available at: https://doi.org/10.1016/j.rcim.2019.01.007.

Watson, N.D., Meisel, N.A., Bilén, S.G., Duarte, J. and Nazarian, S., 2019. Large-scale additive manufacturing of concrete using a 6-axis robotic arm for autonomous habitat construction. In 2019 International Solid Freeform Fabrication Symposium. University of Texas at Austin.

Wu, C. et al. (2017) ‘RoboFDM: A robotic system for support-free fabrication using FDM’, in 2017 IEEE International Conference on Robotics and Automation (ICRA). 2017 IEEE International Conference on Robotics and Automation (ICRA), Singapore, Singapore: IEEE, pp. 1175–1180. Available at: https://doi.org/10.1109/ICRA.2017.7989140.

Top 20: Best 3D printer Slicer Software (most are free) (2023) All3DP. Available at: https://all3dp.com/1/best-3d-slicer-software-3d-printer/ (Accessed: March 26, 2023).

Robotic Arm 3D printing – the ultimate guide (2023) All3DP Pro. Available at: https://all3dp.com/1/robotic-arm-3d-printing-platforms-software/ (Accessed: March 27, 2023).

Technical specification - upmformi.com (2021). Available at: https://www.upmformi.com/siteassets/datasheets/formi-3d/upm-formi-3d40-product-data-sheet-en.pdf (Accessed: April 5, 2023).

How to: 3D spiralization technique for diagrams and 3D printing (GH + Silkworm Tutorial) (2022) YouTube. YouTube. Available at: https://www.youtube.com/watch?v=U_k-fsKdQFg (Accessed: April 16, 2023).

Lutz, R. 3D printer nozzle comparison guide, MatterHackers. Available at: https://www.matterhackers.com/news/3d-printer-nozzle-comparison-guide (Accessed: April 20, 2023).

Additive Manufacturing Market Size Report, 2030. Available at: https://www.grandviewresearch.com/industry-analysis/additive-manufacturing-market