INTEGRATING LARGE-SCALE ADDITIVE MANUFACTURING AND BIOPLASTIC COMPOUNDS FOR ARCHITECTURAL ACOUSTIC PERFORMANCE

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Abstract. Emerging regulations in the context of sustainability have placed renewed attention on construction protocols, including consideration of end-of-life, waste reduction and a shift to bioplastics. However, much research is required on the integration and compatibility of bioplastic materials and their performance concerning construction industry standards. Parallel to the material perspective, increased efforts are placed on additive manufacturing (AM) processes in architectural design and their potential contribution to sustainability through experimentation with new materials, enhanced performance prototyping and reduction in material use. Within this context, the following paper develops a framework towards large-scale additive manufacturing examining bioplastic compounds for architectural components with acoustic performance. A design workflow outlines the component geometry and micro-structuring for both scattering and absorption. It explores the ability to expand on the acoustic behaviour of the chosen materials through printing techniques such as pull printing, fiber printing and dynamic structure printing, within a robotic FDM setup utilizing non-planar tool path design. The robotic workflow developed, outlines a material-informed calibration of bioplastic compounds, their predicted acoustic compatibility to the construction industry, and highlights the potential of such AM workflows to align with current sustainability goals.

Keywords. Bioplastic Compounds, Robotic Fabrication, Large Scale Additive Manufacturing, Non-planar Tool Path Design, Acoustic Performance.

1. Introduction

Architecture has persistently shown a growing interest in the technological progress of innovative materials and materials as a source for design. Such tendencies have been reinforced in recent years by the emphasis placed on developing sustainable materials for design and construction due to the contribution of construction materials to greenhouse gasses and industrial waste [Agusti-Juan and Habert, 2016]. Such is the case with plastic compounds that are in high demand within the construction industry and originate from derivatives of the petrochemical industries, i.e., Polycarbonate (PC), Polyvinyl chloride (PVC), and Polypropylene (PP) [European Commission, 2015]. New processes and techniques should therefore be developed in order to enable design to overcome inefficiencies and waste production within standard plastic applications in the construction field [Burlow et al. 2018]. Within additive manufacturing (AM), research into large-scale printing is beginning to reveal potential applications in architecture that enable new computer-aided design (CAD) to computer aided manufacturing (CAM) workflows supporting the fabrication with new materials. These workflows can contribute to achieving significant environmental benefits and help prioritize architectural processes that support sustainability [Ferreira-Filipe et al. 2021, Verhoef et al. 2018]. In this paper, we 1) explore bioplastic compounds suitable for potential building applications. 2) integrate two compounds in an AM workflow adapted towards large scale printing 3) demonstrate the potential integration of acoustic performance by utilizing AM non-planar tool path design for both scattering and absorption. It is our aim to demonstrate that the adoption of such workflows can lead to advantages in both architectural and environmental performance.

2. Bioplastic Compounds for Additive Manufacturing

Modern polymers are mainly based on petrochemical derivatives. In contrast, "bioplastics" refers to polymers that are either bio-based, biodegradable, or both [Wijk and Van Wijk, 2015]. Biobased plastics are produced free from fossil fuel, are sourced from biomass, and are considered promising in the context of sustainable materials [Wijk and Van Wijk, 2015]. However, bio-based does not guarantee biodegradability, which describes a plastic's ability to decompose by biological microorganisms in natural environments [Chen and Yan, 2020]. Supported by European policy, renewed attention has been placed on material standards within industrial processes, pursuing considerations of end-of-life, recyclability and promoting a shift to bioplastics [Mikula et al. 2020]. As a result, bioplastics are being developed to match the material properties of petrochemical plastics currently used in industrial processes. Furthermore, with the increase in demand for renewable materials in the additive manufacturing field, a wide range of biomass-derived compounds for 3D printing have been reviewed [Ji et al. 2020, Wijk and Van Wijk, 2015]. In our research, we first identified commonly used plastics in the production of construction elements, i.e. Polycarbonate (PC) and Polyvinyl Chloride (PVC) [Bahar et al., 2022, Lewandowski and Skórczewska, 2022]. Both PC and PVC (as a foam form) are used for scattering and absorption performance in acoustic products [Hushcity, 2022, Palram, 2022]. Understanding the applications of PC and PVC as derived from industry requirements served as a reference for the examination of potential bioplastics as alternatives. Identified alternatives for an initial case-study experimentation included Bio Polyethylene Terephthalate Glycol (Bio-PETG) and a Polypropylene compound with bio-based Q additive reinforced with carbon fibers (PPQCF). A wider material scope will be examined in future steps based on the preliminary results.

PETG is a common translucent thermoplastic polyester. Two types of PETG have been developed that can be classified as bioplastic; Bio-Based PETG, which is derived from natural biomass [Lee and Lee, 2018], and Bio-PETG which is petrochemical-based but is biodegradable [Gokhale, 2020]. In comparison to PC, it provides significant chemical resistance, durability, excellent formability and low shrinkage which makes it suitable for large scale printing. However, PETG is UV sensitive; therefore, when used outdoors (for roof and wall panels), it needs to be UVstabilized to maintain its properties.

PPQCF integrates; Polypropylene (PP), biobased thermoplastic Q additive and carbon fibers (CF). It is a new compound developed by UBQ Materials based on PP which is a fossil-based polymer. While PPQCF cannot be classified completely as bioplastic, the compound can include up to 50% biobased Q additive. A main benefit of the additive is the ability to neutralize the carbon footprint of the manufactured product when used above 15% [UBQ, 2022] which is directly aligned with UN SDG's. Although the additive reduces the mechanical properties of the compound, carbon fibers is used for compensation and enables the compound application towards large scale printing.

3. Additive Manufacturing for enhanced performance

The development of AM technologies has enabled the integration of new materials within performance-oriented CAD to CAM workflows in design research [Gao and Kiendl, 2020]. In the context of bioplastics, such workflows allow efficiency in material use by complex material distribution in order to achieve enhanced properties and performance (i.e. strength, reduced weight, acoustics etc.) [Agusti-Juan and Habert, 2016]. There are fundamental effects that have been demonstrated with AM and are directly linked to sustainability [Agusti-Juan and Habert, 2016, Verhoef et al., 2018]; Shorter supply chain, energy saving, waste reduction, and the integration of new materials such as bio-based and biodegradable materials that can change the current standards of plastics in construction. Designing with AM workflows can be separated into two main phases; 1) the digital model design, and 2) the manufacturing process [Aljassmi et al., 2018]. The digital model design allows for the creation of complex and elaborated digital geometries. The manufacturing process enables the design of material distribution and the generation of instructions for printing. Recently, robotic manufacturing is expanding the scope of design methods for large-scale printing and enabling the fabrication of complex forms with 5 axis that cannot be done in standard fused deposition material (FDM) 3d printing. The CAD to CAM workflow presented in this paper initially followed five main phases for robotic additive manufacturing [Ahlers et al., 2019, Aljassmi et al., 2018, Garcia and Retsin, 2015]:1) Model design - developing a parametric model in the Rhino Grasshopper3d environment. 2)Performance simulation and optimization - The base design model runs through simulation tools for the relevant performance and the design geometry parameter values are optimized for the chosen performance. 3) Selection of the final computational model for the CAM workflow. 4) Printing program and toolpath simulation - creating the relationship between the CAD model, the material properties, and the robotic arm printing process. 5). Robotic fabrication - following the GCODE commands, the robotic arm distributes the material through the designed toolpath. As a case study to test the CAD to CAM workflow with the selected bioplastic compounds Bio-PETG and PPQCF, the research focused on designing an acoustic component as a potential replacement for current PC and PVC products.

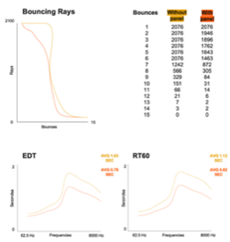
3.1. THE DESIGN TO MANUFACTURING OF AN ACOUSTIC COMPONENT - A CASE STUDY.

Nowadays, most acoustic treatment happens after the initial space planning and design process. However, there are few design tools that enable architects to improve the acoustic performance of their design through analyses and simulation, such as Pachyderm Odeon, Acou, and Comsol. Pechyderm differs from most tools as it is integrated directly with the Rhino3D CAD workflow of the design model. Moreover, most of the existing solutions on the market today focus on shortening the reverberation time by absorbing sound energy [Vomhof et al., 2014]. Reverberation time (RT) is the time it takes for reflected sound to decrease by 60db from the source of the original signal (RT60). Reflected sounds tend to build up to a level louder than the original directional signal and creates what we define as an echo. The existing solutions today for reverberation are mainly separated to two methods; scattering by design of geometry and absorption by use of material that has high coefficient absorption [Vomhof et al., 2014]. Such solutions to sound energy absorption lead to products that are made from complex materials and manufacturing processes, and rely on the material properties and thickness. Most of the time, such products cannot be customized by specific performance and cannot be designed for a specific space [Vomhof et al., 2014]. Solutions to scattering (diffusing surfaces) are based on particular rules that rely on highly articulated geometry. The surface's texture and depth are directly related to the frequency of the sound that should be scattered, and it's possible to predict the acoustic scattering behaviour by “acoustic shooting simulation” [Cox and D'Antonio, 2009]. This information can be applied in the design and create a wide range of unique geometries that are acoustically effective in scattering. In recent years, research has focused on printing geometries that enhance the acoustic performance by designing a scattering form. In our research, we applied three fundamental rules from existing scattering experiments in order to enhance acoustic performance through customized geometry [Cox and D'Antonio, 2009, Foged and Walker, 2018, Vomhof et al., 2014]: importance of division in-depth (minimum 20cm) , importance of division in width (maximum step size of 10cm) , Avoiding periodic repetition for effective scattering or reflecting sound waves.

3.2. ACOUSTIC SCATTERING DESIGN

An existing interior classroom wall (500x300x30cm) was selected for the case study. The CAD model was developed in Rhino with the Pachyderm plugin [Orase] to obtain the scattering acoustic performance. The Pachyderm tool simulates an acoustic behaviour of given soundwaves frequencies in each space according to the coefficient absorption of the chosen material and geometrical form (Fig. 1). Results considered were 1) RT60. 2) early decay time (EDT); the time it takes to lose 10db from the source. 3) bouncing rays - the number of living sound particles after each bouncing (Fig. 1). Such results enable us to understand and evaluate the acoustic performance of each iteration and extract the iterations with the best potential to reduce the reverberation time. The frequency range selected for testing (65hz to 8000hz) was based on tube impedance test range cover that will be used as our evaluation method in future empirical tests. The room without the acoustic treatment achieved the result of 1.2

seconds average of RT60 (average of the frequency range). A thousand iterations were generated to reach the minimum RT60 time in the room. Each iteration changed by the number of sections that define the whole geometry and the sections geometrical form. The optimal iteration reached an average of 0.82 seconds, an improvement of 26.6% from the initial result (Fig. 2). In addition, the results show that there is an improvement in EDT, and that living rays die faster after each bounce. This indicates fewer chances of echoing sounds in the room. Based on the optimized results, the highest performing iteration was selected as a base model for the additive manufacturing process with the chosen materials.



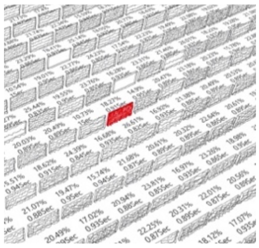


Fig. 1. Pachyderm results (bouncing rays, EDT, RT60) for design iteration.[author] Fig. 2. Iterations RT60 results and the best iteration(red).[author]

3.3. ADDITIVE MANUFACTURING FOR ACOUSTIC ABSORPTION THROUGH MICROS-STRUCTURES

In addition to the scattering behaviour, sound absorption materials are utilized for the improvement of room acoustics. In recent years acoustic absorption has been explored (mostly in engineering fields) through the utilization of polymer micro-structure printing [Zieliński et al., 2022]. This opens new possibilities for the integration of both scattering and absorption through a combined AM workflow [Foged and Walker, 2018, Vomhof et al., 2014]. Micro-structures enhance the sound absorption behaviour while enabling improved properties to the whole element, such as stiffness [Johnston and Sharma, 2021]. Developing such structures with customization of form targeting both scattering and absorption with micro-structures, opens the potential for new kinds of acoustic solutions emerging from printing capabilities. Different approaches of printing micro-structures have been researched, including micro-perforated panels, micro complex pattern structures, periodic foam structure, micro lattice and its rotation, printed fibrous material, and the combination between them [Johnston and Sharma, 2021 , Liu et al.,2017 , Zieliński et al., 2022]. Besides the material itself, the absorption characteristics of the printed model highly depend on the printing parameters (i.e., speed, extrusion factor, bridging method) and can be improved by 3d-printed geometries [Johnston and Sharma, 2021]. An additional challenge for acoustic performance that can be addressed through micro-structure printing relates to the layered texture (also known as stair-stepping) in standard printing that has negative effects on the acoustic properties of the surface [Zieliński et al., 2022]. Currently research on printing micro-structures for acoustics does not address construction standards and has yet to be implemented in large-scale printing. Experiments conducted in parallel fields (mechanical and aerospace engineering) used SLA (Stereolithography) or Polyjet printing methods to achieve high resolution textures that are difficult to achieved in printing methods such as FDM or robotic fabrication for large scale artifacts. However, novel experiments with FDM have introduced new techniques such as pull printing, fiber printing, dynamic structure, and taking advantage of the imperfection of printing [Johnston and Sharma, 2021, Zieliński et al., 2022] that potentially can help achieve improved sound absorption for large-scale printing structures. In our ongoing research, we aim to address both acoustic solutions (scattering and absorption) through an integrated FDM workflow: the scattering performance through component geometry and a new absorption performance by printing the geometry as a micro-structure. The scattering method will be imparted in the CAD development phase as part of the general geometry design. In the CAM phase, the material distribution and the toolpath design will impart the potential sound absorption printing techniques.

4. Robotic Fabrication Workflow for Scattering and Absorption Acoustic Performance

In recent years with the increased presence of robotic arms, robots have also been adopted to perform FDM-like printing processes and enable architects and designers the possibility to investigate design methods for large-scale printing [Garcia and Retsin, 2015]. The common method for 3d printing today is the linear method, which is actually 2.5d printing [Ahlers et al., 2019]. The printer extrudes the planner path (X and Y motors), and moves to the layer above (Z motor). It means that in most cases the three motors do not work simultaneously. This method has shortcomings such as poor geometrical accuracy due to the stair-stepping, weakness of the model, and the difference between the virtual design to the fabricated application [Jin et al., 2017]. On the other hand, toolpath design strategies enable higher geometrical accuracy and patterning, increased printing strength, and bridging the gap between the virtual model to the fabricated by manipulation of the tool path [Breseghello et al., 2021]. Therefore, most robotic fabrication workflows involve custom tool path design through parametric CAD software. The tool path design not only self-organizes according to geometry but also needs to react to the structure and performance of the model [Ahlers et al., 2019, Garcia and Retsin, 2015]. In recent years a new method has been proposed, using curved layers (three-dimensional) to create the tool path. These curves follow the model surface curvature and create three-dimensional lines (mostly non-horizontal) instead of planners. The method is known as curve layer fused deposition (CLFD) or as form responsive method (FRM) [Ahlers et al., 2019, Jin et al., 2017, Molloy and Miller, 2018] and is based on the motion that moves all three motors simultaneously to print the desired layer. The geometry now is defined by curves that are utilized for toolpath and not by surfaces that define the three-dimensional form [Molloy and Miller, 2018]. This method brings opportunities to enhance the functionality of the print, and create alternative articulation for printing beyond stair-stepping. For acoustic performance, CLFD may be preferable in relation to scattering performance by bridging the stair-stepping challenge. CLFD has also demonstrated that parts with non-planar layers can be stronger and stiffer due to the fiber continuity along the extrusion path [Ahlers et al., 2019, Jin et al., 2017]. The path is generated opposite from the linear method, from the top to the bottom of the geometry. The top layers have more curvature and build upon linear layers at the bottom. This enables a transition from planner to non-planar curves through the process of printing the form. [Ahlers et al., 2019] Besides the advantages of non-planar printing, it is challenging to design the tool path and takes many constraints to consider: The machinery form (the way the printer is built) is considered to prevent collisions and guarantee safe printing. The nozzle and its tip form are critical for the calculation of collisions and curvature possibilities of the print [Ahlers et al., 2019]. In our research, similar to the CAD process, the CAM process is designed in the Rhino- Grasshopper environment to enable workflow continuity. Also, an expansion on the earlier outlined five phased workflow was proposed adding two additional phases (3 and 4): 1) Model Design, 2) Simulation and Optimization of the model geometry 3) Tool path design – based on model geometry and material distribution 4) Simulation and optimization of tool path (currently under development) 5) Final tool path model 6) Printing program and simulation, 7) Robotic fabrication.

In our workflow phase 2 is conducted before the tool path design and phase 4 will be conducted directly on the toolpath to corelate gaps between the CAD to CAM models. The tool path conversion to robotic instruction is done with HAL framework plugin. The HAL framework plugin enables simulation and feedback considering machinery constraints and collisions and sets the printing parameters for the robotic arm procedures.

5. Results

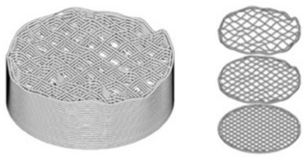
The implementation of bioplastic compounds through a customized non-planar tool path within an AM robotic workflow resulted in several meaningful findings:

1. Integration of bioplastic compounds in AM workflows: based on the printed experiments we were able to print both Bio-PETG and PPQCF under large scale printing parameters and achieve the targeted geometry resolution.

2. Custom non-planar tool path: achieving a tool path that corresponds accurately to the designed form. This bridges the gap between the CAD model to the CAM and creates a continuous workflow. Also, as discussed in chapter 3, the linear method can negatively affect the acoustic behaviour due to its stair-stepping. Therefore, the non-planar path can bridge this phenomenon and create a complex form that can additionally enhance the absorption of the model.

3. Micro-structure printing to enhance acoustic absorption: variations of structure patterning were explored in order to expand absorption performance beyond the coefficient of the selected material. This method is advantageous when using polymers to compensate for their lower intrinsic coefficient absorption.

The suggested workflow developed a custom non-planar tool path design. The form of the geometry was generated and then optimized by Pachyderm to achieve scattering results, while the non-planar infill based on grid pattern was defined in order to structure the form. The grid infill pattern changes its curvature from bottom to top (linear to nonlinear) to achieve better surface scattering results avoiding stair-stepping [fig 3]. Its density changes from 4mm to 10mm and creates a non-consisted grid infill based on Johnston and Sharma's experiment [Johnston and Sharma, 2021] to achieve better acoustic absorption. One of the main challenges in non-planar printing is the design of the travel (i.e. the movement of the extruder without extruding material). In standard printing, the travel is a linear straight movement that can go through the inner part of the geometry without damaging the infill. However, in non- planar, there is a chance of collision through travel since the infill part can be higher than the perimeter. Therefore, a method was designed to avoid collisions and suggests a travel that will also be efficient on printing time by traveling the shortest path of the perimeter curve [fig. 4].



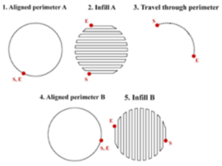
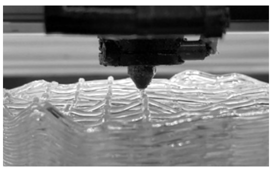
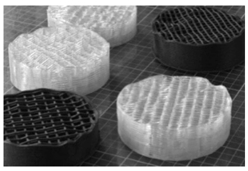


Fig. 3. (left) Grid infill changes its density and curvature from bottom to top. [author] Fig. 4. (right) Suggested non-planar travel scheme, [author]

Although 3D printing with PETG is already common, non-planar robotic printing of Bio-PETG for acoustic performance is yet to be done to the best of our knowledge. Based on the initial experiments, a material-informed toolpath for large scale printing was developed with the following properties: 2mm nozzle diameter (a minimal diameter for robotic print), Bio PETG printed with 225 degrees, bed temperature of 85, extrusion factor of multiple 4 and around 15mm/s printing speed. PPQCF also printed with the same nozzle and printing properties defined as: 205 degrees printing temperature, bed temperature 105, extrusion factor of 4.5 and 10mm/s printing speed. Due to material behaviour PPQCF required two fans to accelerate the cooling, at least a 20mm brim and an adhesive to hold the first layer to the bed. Both compounds Bio-PETG and PPQCF, achieved the targeted combined geometric form for scattering and absorption. The next step will be empirical testing of the disc experiments in an impedance tube to validate the acoustic performance of the geometry and create a correlation between the digital simulation results and the physical results.





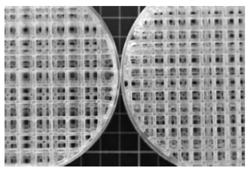


Fig. 5. (left) Non-planar printing with bio-PETG examines the printability of the custom tool path [author] Fig. 6. (Middle) Non-planar testing discs printing both materials examining printability of different curvatures and grid patterns. [author]. Fig.7. (Right) Different grid densities.[author]

6. Conclusion

The paper introduces a robotic additive manufacturing workflow that integrates two types of bioplastic compounds towards large-scale printing of acoustic components. Such integration can steer construction industry standards towards better environmental impact, reduce waste, and achieve enhanced performance through geometrical customization. Most acoustic solutions today address absorption mainly through the absorption coefficient of the material and scattering through geometrical form. The suggested workflow integrates existing acoustic knowledge and simulation tools that involve acoustic scattering with advanced AM. Through the design of a non-planar custom tool path we address acoustic absorption as part of a micro-structuring technique while eliminating the stair-stepping phenomena that can affects the scattering behaviour. Non-planar custom tool path design experiments were conducted on PPQCF and Bio-PETG utilizing large scale printing properties (i.e printing speed, extrusion factor etc.).The experiments proved the feasibility of designing a tool path and printing the articulated geometries combining both acoustic solutions (scattering and absorption) within an integrated form. The next step will be validating the acoustic result by empirical tests. Following such validations, it will be interesting to check different infill patterns and their absorption effect, different infill orders, and customize different zones of the model for acoustic performances. Understanding acoustics as a case study that demonstrates the value of AM techniques in advancing towards more sustainable and customized solutions, we see great potential in developing such methods for additional architectural performances (i.e. light transmission, weight reduction, thermal performance, etc.) in future applications.

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