UPCYCLING BIOWASTE INTO SUSTAINABLE COMPOSITES FOR ADDITIVE MANUFACTURING AT TU DELFT CAMPUS

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ABSTRACT

This paper reviews the applicability of a local conceptual model to upcycle biowaste material using Additive Manufacturing Technologies. By repurposing waste material and decentralizing manufacturing, circular economy principles can be implemented in various industries, specifically for construction and architecture. It is a thematic exploration on creating a sustainable alternative to locally manufacture context specifically designed architectural components by repurposing end of life resources on TU Delft campus. The paper consists of local waste stream analysis with the help of an interview to investigate possibilities on closing or narrowing down resource loops, followed by a comprehensive literature review to identify existing research in this field. The aim is to assess the viability of this model and derive important conclusions relevant to a future 3D printing setup on the TU Delft campus.

KEYWORDS

Additive Manufacturing, Closing Resource Loops, Upcycling Waste Materials, Biomass, Local Waste Streams

METHOD

This research paper employs a multi-method approach as assess how local waste materials can effectively be upcycled for architectural applications using Additive Manufacturing, addressing both theoretical and practical aspects of the research question.
Firstly, a semi-structured interview was conducted with a key stakeholder involved in waste collection, disposal, and classification at TU Delft. This in-person interview provided in-depth insights into the operational aspects of waste management. In addition to interviews, data from past reports and ongoing investigations was leveraged to justify material selection.
The research also included a comprehensive literature review focused on Additive Manufacturing, Sustainability and circular economy practices and upcycling waste streams such as biowaste. However, it was limited to peer reviews sources and excluded relevant industry reports for the sake of brevity, relying on findings of other researchers.
Finally based on individual interview and literature review findings, relevant setup and parameter considerations were outlined in the conclusion segment. This research paper is intended as preparation for the upcoming 3d printing and prototyping phase of design, which will take place in the Laboratory of Additive Manufacturing at the faculty of Architecture on TU Delft campus.

I. INTRODUCTION

In light of the climate crisis and mandated sustainability goals of governmental bodies, this mindset of mass production is gradually being replaced by critically thought and engineered, context-specific products (Müstecaplioglu, 2024). Up until the last decade the majority of the construction sector operated on a linear economic model, desensitizing us to the high amount of waste output. Within the circular economy model, the urgency of 'spending' raw materials and resources for capitalistic production and consumption habits of industries and individuals is being problematized (Müstecaplioglu, 2024).

Recent advancements in additive manufacturing (AM) have showcased its ability to repurposes various resources at the end of their lifecycle, ranging from electronic waste to thermoplastic polymers and materials from the construction sector (Romani et al., 2023).
AM offers an opportunity to alleviate the reliance on raw material by using biodegradable and edible crops as material inputs and reduce pollution associated with conventional manufacturing processes. Furthermore, the integration of AM with biowastes opens doors for ecofriendly design practices, emphasizing the upcycling and recycling of biowastes into functional 3D printing feedstock (Romani et al., 2023).

The potential of 3D printing to advance circular economy principles by reducing the consumption of new materials, promoting recycling, and fostering localized manufacturing is significant. The widespread availability of affordable 3D printers has standardized prototyping, enabling individuals to manufacture objects from the comfort of their homes(Hassan et al., 2024). However, the broader implementation of AM regarding sustainability and circular economy practices, especially at the local level, remains limited.

This paper explores the viability of upcycling local biowaste through AM technologies, presenting a conceptual model that demonstrates how local waste streams can be used as resources for sustainable 3D printing. The focus is on architectural development at the TU Delft campus. The research aims to answer the following main and sub question:

MQ: What is the viability of upcycling local biowaste into sustainable composite material to additively manufacture architectural components for TU Delft campus?

> RQ1: What is the current state of the academic field on additive manufacturing with waste materials, and what are the potential benefits aligned with sustainability practices?
>
> RQ2: Which waste materials can be locally harvested on the TU Delft campus and serve potential for preliminary material testing?
>
> RQ3: What considerations should be kept in mind while mixing materials out of biowaste composites?
>
> RQ4: What parameters and factors require optimizing during prototyping to enhance printing results through additive manufacturing with biowaste composites?

Each chapter is designed to address the sub question listed above, contributing to the overarching goal of answering the main research question. The paper begins by presenting the outcomes of an interview conducted to identify local waste streams on campus. Based on these findings, specific waste streams are selected for further investigation through literature. The literature review delves into the current state of research on additive manufacturing and waste materials, providing a comprehensive overview of prevalent knowledge in the field. Subsequently, the focus shifts to the technical aspects of 3D printing with biowaste, highlighting key considerations such as material characterization and material compositions to enhance or ensure the quality of mechanical properties. Finally, the paper outlines essential parameters for 3d printing technologies to ensure optimal conditions for high-quality printing.

II. INTERVIEW WASTE STREAMS ON TU DELFT CAMPUS

Preliminary research on waste materials at the Technical University of Delft (TU Delft) campus revealed a lack of substantial public documents regarding waste management. After attempting to contact Campus Real Estate Management, the request was referred to the Facility Management department. This led to an interview with Michiel Faber, Coordinator of Logistics and Environment at TU Delft. The semi-structured interview provided valuable insights and data about waste management and the disposal and collection of various waste streams on campus. This chapter is based on the verbal conversation during the interview and reports and data sourced by Michiel Faber. The full transcript of the conversation is available in Appendix A.

The logistics department is responsible for the safe collection and disposal of the waste produced daily on campus. In public facilities, waste is separated into three main streams: paper, plastics, and residual. The waste generated is collected per faculty in preordered containers and transported safely by an external company to appropriate facilities.

Since early 2024, TU Delft has employed PreZero, a company that shares its sustainability ideals. PreZero separates waste streams into several categories, including glass, wood, coffee grounds, plastic, metal, paper and cardboard, PD, Styrofoam, confidential paper and products, foil, e-waste, hazardous waste, and construction and demolition waste. The company aims to see waste as a potential resource, aiming to close the loop without depleting natural resources (PreZero, n.d.).

Data from the interview with Michiel Faber indicated that 64% to 70% of the residual waste on campus could have been sorted into other waste stream categories before disposal and collection. This was evident from PreZero's investigations, detailed in Appendix C. This was evident from PreZero's investigations, detailed in Appendix C. This percentage is notably high and when overlapped with the annual waste report of TU Delft campus in 2023 can present missed opportunities. The annual waste report for TU Delft campus in 2023 was conducted by the former waste disposal company, Renewi and can be found in Appendix B.

Key findings include,

- *Incorrect waste disposal:* According to registered waste weights in 2023, 38% of the total waste was categorized as residual waste. When overlapped with PreZero's investigation, this suggests that roughly 25% of total campus waste could be avoided with proper sorting.
- *Cost Implications:* Residual waste disposal currently accounts for 50% of TU Delft's waste management costs. Correct sorting could potentially reduce these costs by 35%. However, this might also increase costs for other waste stream disposals, making overall cost reduction uncertain.

This means that TU Delft could reduce its impact on Landfills and co2 emissions caused by transportation and incineration of waste by 1/4th with the correct disposal of waste streams, merely by managing the residual waste disposal accordingly, with a possibly reduced budget.

By reintroducing certain waste streams as feedstock material for additive manufacturing, TU Delft could form or narrow a closed resource loop, reducing costs, CO_2 emissions, and pollution.

Appendix C shows that biowaste is the largest waste stream category in sample bins from both the Echo (50%) and TBM (25%) buildings. Other significant waste residues include plastic, glass, and paper. These initial findings justify the selection of materials that could potentially be looped back as resources. Further investigations with larger sample sizes and additional campus facilities are recommended for more conclusive results.

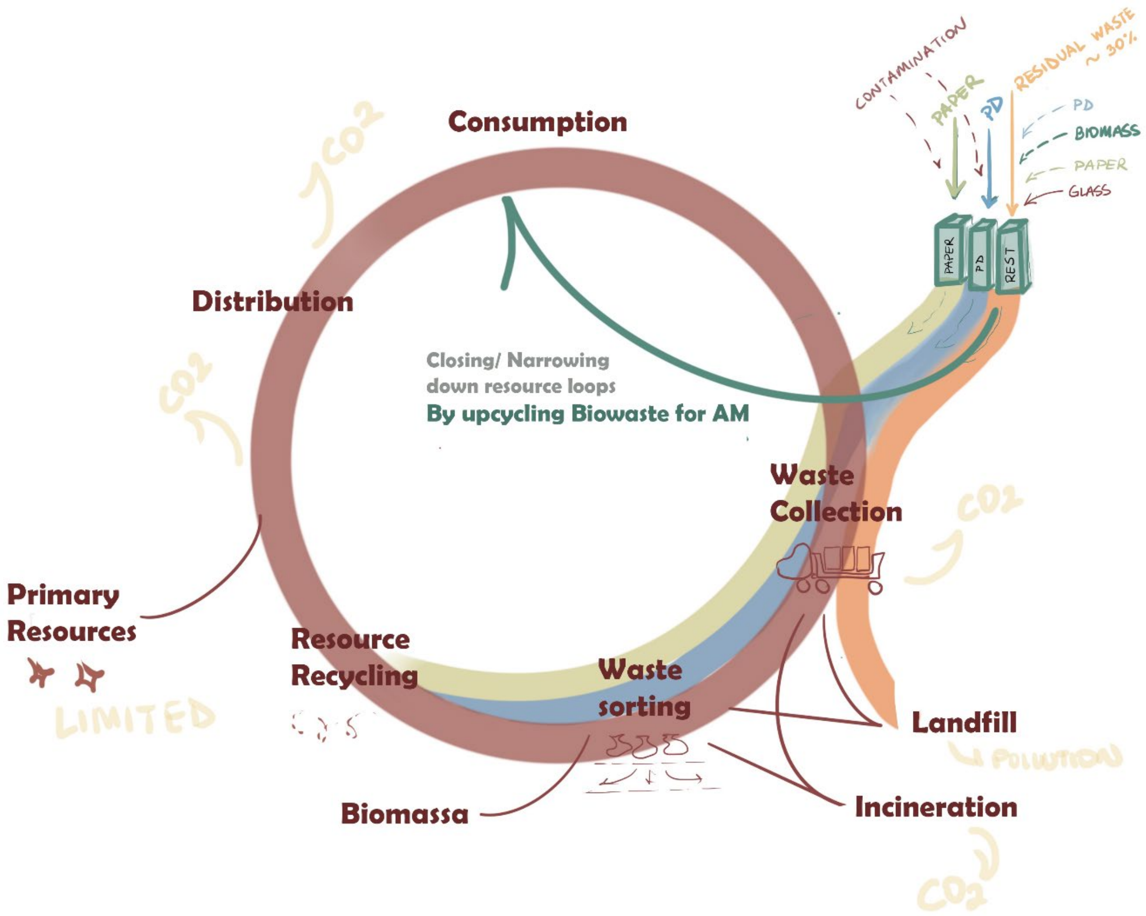

Figure 1:Waste Diagram including conceptual model of research paper.

Recommendations and Future Plans

A critical issue is the lack of bins for alternative waste streams, as currently, TU Delft only provides three types of waste disposal bins in public spaces. This initiative started in March 2020 but was low-profile due to COVID-19 restrictions. Another challenge is the lack of public knowledge about waste separation, leading to contamination of designated waste bins. Michiel Faber mentioned the need for informational pamphlets on bins to guide proper waste disposal.

Campus Facility Management plans to enhance campus sustainability by conducting surveys and residual waste data analysis, aiming to create accurate waste streams and improve waste sorting efficiency. Michiel Faber also mentioned companies like Circ.Energy, which convert biomass waste into sustainable energy, reducing CO2 emissions, reliance on fossil fuels, waste transport, and improving soil quality. Future plans may include biomass incineration for energy, though this method still emits CO2 and requires significant space and management.

Alternatively, upcycling biomass and other waste into 3D printing materials aligns with campus and governmental sustainability goals, potentially reducing waste transport and landfill use. Additive manufacturing can help close local resource loops. Surplus and under-sorted products like biomass, paper, and glass can be upcycled into new forms, such as façade components or interior objects. The concept of this research has been illustrated in Figure 1. The next chapter will explore how additive manufacturing can provide potential solutions for improving waste management.

III. ADDITIVE MANUFACTURING WITH WASTE STREAMS

This Chapter aims to convey why Additive Manufacturing technologies serve the potential to transform waste materials into functional printing feedstock. As a result of interview in chapter 2, the focus has been set on biomass waste which includes residual organic byproducts as well as agricultural and forestry residues.

Circular economy and bioeconomy models are increasingly being implemented as means to develop sustainability strategies such as reusing and recycling. A systematic review on the publications focused on new materials from biomass waste or by-products for extrusion-based additive manufacturing processes (Romani et al., 2023). This review starts by introducing Circular economy model as a sustainable alternative as opposed to the previous/current linear model.

'True circularity' can be reached by combining Circular Economy practices with sustainable supply chain (Nascimento et al., 2019). Closing supply-chain loops can provide feasible solutions for sustainable manufacturing when it comes to the conservation of raw materials and environmental concern (Müstecaplioglu, 2024). A closed loop supply chain usually consists of recycling, remanufacturing, or reuse chains as end-of-life management strategies (Nascimento et al., 2019).

Aligned with the circular economy model, waste management has a big role in maximizing resource recovery through end of life management strategies such as reusing, recycling, upcycling (Romani et al., 2023).

Additive Manufacturing a.k.a. 3d printing, displays potential to support sustainability goals through reducing the consumption of raw materials, saving time and energy etc.(Li et al., 2023). This technology can be seen as a cleaner manufacturing method due to its compatibility with end-of-life management strategies such as reusing and recycling. These strategies can both be applied to waste material as well as material that has lost its primary use.

Hassan et al (2024) provides an excessive description on terminologies such as upcycling, primary -, secondary -, tertiary – and quaternary recycling (main technique used by the municipal waste management systems to recover energy through producing thermal energy by incineration). The review explores the potential of additive manufacturing in sustainable waste management specifically through upcycling waste plastics and biomass. It aims to display the creation of a sustainable composite in which recycled plastics serve as matrix combined with biomass acting as fillers (Hassan et al., 2024).

Allesio Romani (2023) has published a paper on new materials from biomass waste or by-products for extrusion based additive manufacturing processes and has systematically classified existing literature. Due to the preliminary nature of studies on printable biomass materials, insufficient practical applications in form of case studies, Romani et al (2023) mentions the lack of LCA studies.

Biomass products can potentially offer significant benefits when used as 3d printing feedstock. Feedstock is a terminology referred to as material input for 3d printing. These predominantly include resins, ceramics, metals and food materials (Hassan et al., 2024). By using food waste, forest residues and other agricultural residues which form the general term of Biomass, Additive Manufacturing technologies may provide a cleaner alternative, decreasing overall all reliance on traditional nonrenewable petroleum based plastics (Hassan et al., 2024).

Although biowaste can serve as an alternative green energy as mentioned in the chapter above through bio-transformers, additive manufacturing with biomass can also provide an alternative to mitigate waste management issues, reducing greenhouse gas emissions and diverting organic materials from landfills and incineration processes (Hassan et al., 2024).

By combining the urgency of the inclusion of another waste stream at the campus of TU Delft, this segment has demonstrated the possibility of waste biomass in participating in the circular economy practice. Specifically, by closing a resource loop on a local scale and upcycling biomass such as food waste and coffee grounds, composites can be created as new material for 3d printing. In the following chapter, the paper will dive in further on 3d biomass printing and technicalities that should be considered based on previous research and literature reviews.

IV. TECHNICALITIES OF WASTE BIOMASS 3D PRINTING

Biomass materials consist of dominantly degradable materials composed from woody, herbaceous gramineous and vine plants as well as processed iterations of residues and wastes by biological, chemical, and physical means. Currently the Technology regarding 3d printing with biomass concentrates around compositional materials as opposed to manufacturing of raw material or materials entirely derived from biomass (Li et al., 2023).

Integrating the use of biowaste as printable materials for additive manufacturing in forms such as pastes, gels, inks and powders can reduce costs and enhance sustainability and biodegradability (Rahman et al., 2023). Conceptually, the inclusion of biowaste materials seems like a self-evident solution for sustainability practices. However, practical considerations regarding certain challenges and difficulties should not be disregarded. Processing will likely alter material properties and affect the thermal and mechanical characteristics of filaments, ultimately impacting printing quality, impairing dimensional stability, reducing strength, and increasing brittleness (Rahman et al., 2023).

Substantial literature reviews by Romani et al. (2023), analyzing 69 selected works, and Hassan et al. (2024), analyzing 57 publications, provide a comprehensive overview of this topic. While there is potential overlap between these reviews, several forthcoming experiments on different material composites, 3D printers, and parameter settings have been analyzed to identify useful considerations for optimizing material mixing, material printing, and pre- and post-processing.

In the first phase, it is imperative to focus on optimal material compositions consisting of biomass materials to prevent decreased mechanical and thermal properties of the 3D-printed product. According to the data collected by the studies, 30% of biowastes were mainly integrated into the material mixture as bio-fillers for developing 3D-printed filaments for FDM (Fused Deposition Modeling; see Appendix D for further explanation). For this specific technology type, a higher rate of biowaste inclusion in the matrix could negatively impact the mechanical properties of 3D-printed products (Rahman et al., 2023). Other technologies, such as LDM (Liquid Deposition Modeling; see Appendix D for further explanation), have been analyzed. Results show that up to 90% of the paste, inks, and gels can consist of biowaste materials. Most matrix materials are included in the process to enhance the rheological[1] behavior of the material mixes, ensuring optimal consistency for printable gels/pastes (Rahman et al., 2023).

When using biomass as fillers for mixed materials, specific challenges have been identified concerning thermal stability and low heat resistance above 180 degrees Celsius (Hassan et al., 2024). The specific temperatures during extrusion are individually reliant on material tolerances and depend on the degradation temperatures of specific waste materials (Romani et al., 2023). Considering these potential mechanical, chemical, and thermal degradations, optimizing material consistencies is crucial during the creation of a print with high quality and accurate material properties. Composites are especially useful in these cases, as adding certain materials, such as recycled PLA, can enhance strength and improve the overall quality of the end product. Even certain types of biomasses can be added to improve the functional properties of biowaste material mixtures. For example, mixing walnut shell powder with additional fillers or increasing the content of plant waste in the bio-filler can increase the tensile strength of composite materials. Another study showed that PLA (polylactic acid) served as reinforcement in flexural and impact tests for certain materials (Rahman et al., 2023).

Additional challenges include the particle sizes of biowaste materials, which can impact mechanical and thermal properties and factors such as elasticity and tensile strength. Due to biodegradation and decay from microbial growth and moisture absorption, biowastes can have a narrow printing window, compromising the durability and stability of 3D-printed parts. This information highlights the importance of mechanical characterization of materials to ensure a comprehensive understanding of material properties such as tensile strength, elasticity, and thermal behavior (Rahman et al., 2023).

[1] Rheology is a science dealing with the deformation and flow of matter source: https://www.merriam-webster.com/dictionary/rheology

Once the material in use is properly understood by identifying challenges and possibilities, printing settings can be properly adjusted and optimized to ensure effective quality and performance of products.

A subject this paper has not yet addressed is the scale of production and manufacturing with biowaste materials. Large-scale additive manufacturing (AM) presents several challenges, including increased energy consumption due to pre- and post-processing of this manufacturing method (Rahman et al., 2023). However, the concept of this study focuses on local manufacturing of components that utilize context-specific design solutions, rather than mass manufacturing of products. For this reason, the scope of this research does not extend to the topic of scale and economic feasibility.

V. SETUP CONSIDERATIONS

This chapter will specifically focus on optimizing Additive Manufacturing Technologies to enhance the properties of 3D printed products. Firstly, it will provide an overview of current 3D printing technologies and specify the categories of interest. Further, the prevalent 3D printing technologies of the Architecture Faculty will be outlined. Lastly, specific parameters and optimization considerations will be discussed as preparation work for an optimal printing setup.

Additive Manufacturing operates on layer-by-layer stacking principles and can be categorized into seven categories: binder jetting, directed energy deposition, material extrusion, vat photopolymerization, material jetting, sheet lamination, and powder bed fusion (Hassan et al., 2024). For the scope of this research paper and upcoming design task, the focus will be on extrusion-based 3D printing technology, including Fused Filament Fabrication (FFF), Direct Ink Writing (DIW), and Liquid Deposition Molding (LDM). Further individual explanations and illustrations of these specific categories of technology have been included in Appendix D to maintain the flow of the chapter.

Future experimentations in material mixing, testing, and prototyping will take place at the Architecture Faculty of TU Delft, specifically at the Laboratory for Additive Manufacturing in Architecture (LAMA), where extrusion-based 3D printers are available. Predominantly, the experimentation will be conducted with the WASP 3D ceramic printer and possibly the UR5 robot. Depending on the scale of the products, upgrading to the KUKA robot for 1:1 scale prototyping will be possible. For this initial phase of testing material mixes, the use of a mechanical gun will be sufficient.

In the previous chapters entailing literature reviews, studies aimed to achieve quality enhancement of mechanical properties through optimization of 3D printing parameters. A specific example was using recycled plastics. These parameters, identified as extrusion temperature, feed rate, nozzle diameter, nozzle size, nozzle temperature, raster angle, orientation, infill ratio, layer height, and printing speed, require intricate examination and balance (Hassan et al., 2024). This typically translates into various design experiments and prototypes (Rahman et al., 2023).

Adjustments in properties can result in improvements in mechanical properties such as an increase in tensile strength, bending strength, ductility, and impact resistance. When it comes to biowaste materials, specific factors such as particle size may affect the printability of the material mix/paste/gel. Such inputs can cause decreased printing resolution, uneven material homogeneity, and impact surface roughness and mechanical properties of printed parts. It may even cause clogging and blockage in the nozzle (Rahman et al., 2023). As the quality of the printed products is highly influenced by the characteristics of biowaste material itself as well as proportions and compatibility of the composite materials (Li et al., 2023), using material grinders and mixers as preprocessing tools is highly recommended.

Post-processing is a crucial step that enhances the properties of 3D printed objects made from biomass. Common post-processing techniques include drying, curing, heat treatment, and surface modification (Li et al., 2023).

VI. CONCLUSION

This paper has explored the viability of upcycling local biowaste through additive manufacturing (AM) technologies, presenting a conceptual model that demonstrates how local waste streams can be used as resources for sustainable 3D printing. By mixing waste materials into composites suitable for 3D printer feedstock, products can be manufactured with a focus on architectural development at the TU Delft campus.

The initial steps involved mapping the current waste streams and identifying points of improvement for waste management on campus to reduce waste ending up in landfills or oceans, as well as lowering carbon from waste transporting and incineration processes. The interview with Michiel Faber, the coordinator of logistics and environment at TU Delft, helped identify potential materials for upcycling. The most significant improvement identified is the separation of biowaste from residual waste stream, where it is currently combined. Specifically, segregating biomass waste in public facilities could substantially reduce the amount of residual waste ending up in landfills, thereby creating a closed resource loop on campus. This biowaste can be upcycled into sustainable composites for additive manufacturing, supporting campus development through the production of architectural components.

A comprehensive literature review was conducted on the technicalities of 3D printing with biomass waste composites. The review highlighted the potential of AM to support circular economy and bioeconomy models by upcycling biomass waste into functional 3D printing feedstock. This approach can reduce reliance on traditional, nonrenewable materials and contribute to environmental sustainability. However, several technical challenges must be addressed, including the impact of biowaste properties on mechanical and thermal characteristics, the narrow printability window, and the potential for biodegradation over time. Effective material characterization and optimization of printing parameters are crucial to ensure the quality and durability of 3D printed parts. Post-processing techniques such as drying, curing, and surface modification can further enhance the properties of these products. While the focus of this research is on local-scale production at TU Delft, further exploration into material compositions and printing technologies is essential for advancing the application of biowastes in additive manufacturing.

Lastly, the research involves preparations and considerations for the prototyping phase of the design project. This included listing crucial printing parameters and identifying potential challenges when printing with biomass. The insights gathered from this research are intended to inform the upcoming prototyping phase, focusing on the development of architectural products such as facade components.

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TABLE OF FIGURES

APPENDIX A: INTERVIEW WITH MICHIEL FABER

Date: 22/05/2024
Location: Heertjeslaan 5, Building 69 TU Delft Campus
Interviewee: Michiel Faber
Interviewer: Su Müstecaplioglu
GitHub link: https://github.com/guzinmust/Upcycling-local-waste-materials-for--additive-manufacturing-at-TU-Delft-Campus

This appendix will include the semi-structured interview questions which highlight the main conversational topics discussed with Michiel de Faber. The interview audio content was 54 minutes, which results in transcription records of 50 pages. For this reason, a GitHub link has been included to enable access to the full extent of the interview for interested parties. The audio has been transcribed by the dictate tool in word.

Short Description of project goal:
Su Müstecaplıoğlu, Architecture master student in Architectural Engineering Studio.
My graduation project focuses on a sustainable campus development using existing resources on the campus. Specifically, there was very little knowledge accessible for me about the waste on campus and what happens after it exists consumers. I am fascinated in creating 3d printed products that can enhance circular economy principles and integrating waste material as feedstock will reduce co2 transport costs as well as provide a new life cycle for end-of-life products. My goal with this interview is to obtain valuable information about types and quantities of waste as well as the TU Delft and global aims for sustainability. Potentially this interview will provide me with a selection of waste products such as specific biomass or plastics or metals that can be upcycled into building components.

Introduction to Campus Waste Management

1. Global recycling day initiative:
    - You mention that waste management is happening mainly behind closed doors. Have there been initiatives to change that?
    - Is recycle cafe still in function?

Data and Waste Categories

1. Waste Quantities and Data:
    - What are the main categories of waste produced on campus?
    - Are there any available statistics or data on the quantities of each waste category? Where can this data be found?

Disposal and Collection Processes

1. Waste Disposal Practices:
    - How do students, faculty, and staff dispose of their waste on campus?
    - How is waste predicted per faculty and does it differ per building?
2. Collection and Storage:
    - How is waste collected and where is it stored on campus?
    - What is the process for managing waste once it is collected?

Recycling and Sustainability Initiatives

1. Recycling Infrastructure:
    - Is there a recycling facility on campus, and what types of materials are processed there?

- How well is the sorting before it arrives to the facilities? And how does it funciton afterwards?

2. Sustainability Goals:
   - What sustainability initiatives are in place at the organizational level to manage waste effectively?
   - How do these initiatives support the campus's overall sustainability goals?

Enhancing Waste Management

1. Closing the Loop:
   - Considering the R-hiararchy can specific waste materials be recycled to close the resource loop on campus?
   - How can recycling streams be integrated with materials like organic waste, plastics, and metals?
2. Supply Chain and Material Flow:
   - How does the supply chain and material flow change throughout the academic year?
   - What strategies are used to manage these fluctuations?

Upcycling and Innovation

1. Local Upcycling Systems:
   - Is it feasible to develop a system for upcycling materials locally on campus?
   - What steps are needed to implement and systematize upcycling processes on campus?
2. Innovative Solutions:
   - Are there any innovative waste management solutions being explored at TU Delft?
   - How can additive manufacturing technologies be utilized to recycle waste into new materials, such as architectural components?

APPENDIX B: DATA ON WASTE STREAMS TU DELFT 2023

Four screenshots from the 2023 waste report by previous company 'renewi' have been included, obtained after the meeting with Michiel Faber, Coordinator of Logistics. These screenshots provide insights into the weight and costs associated with waste streams across the TU Delft campus. It's important to note that the report does not disclose financial details for privacy reasons.

Afvalstroom	Som van Gewicht	Percentage
Afval/Restafval	648.884	38,45%
Bouw & sloop	154.140	9,13%
Elektr(on)isch afval	3.141	0,19%
Gevaarlijk afval	76.481	4,53%
GFT	194.460	11,52%
Glas	15.024	0,89%
Grond	32.960	1,95%
Hout	51.460	3,05%
Koffiebekers	20.748	1,23%
Overig	0	0,00%
Papier/Karton	248.772	14,74%
PMD	15.690	0,93%
Puin	195.260	11,57%
Swill	8.234	0,49%
Vertrouwelijk papier	22.330	1,32%
Gesamtergebnis	**1.687.584**	**100,00%**

Figure 4: weight per waste stream and percentage.

Afvalstroom	Percentage
Afval/Restafval	49,46%
Bouw & sloop	7,11%
Elektr(on)isch afval	0,32%
Gevaarlijk afval	16,41%
GFT	2,59%
Glas	1,10%
Grond	0,42%
Hout	2,62%
Koffiebekers	3,44%
Overig	1,45%
Papier/Karton	11,03%
PMD	0,60%
Puin	0,89%
Swill	0,49%
Vertrouwelijk papier	2,06%
Gesamtergebnis	**100,00%**

Figure 3: Cost percentage per waste stream.

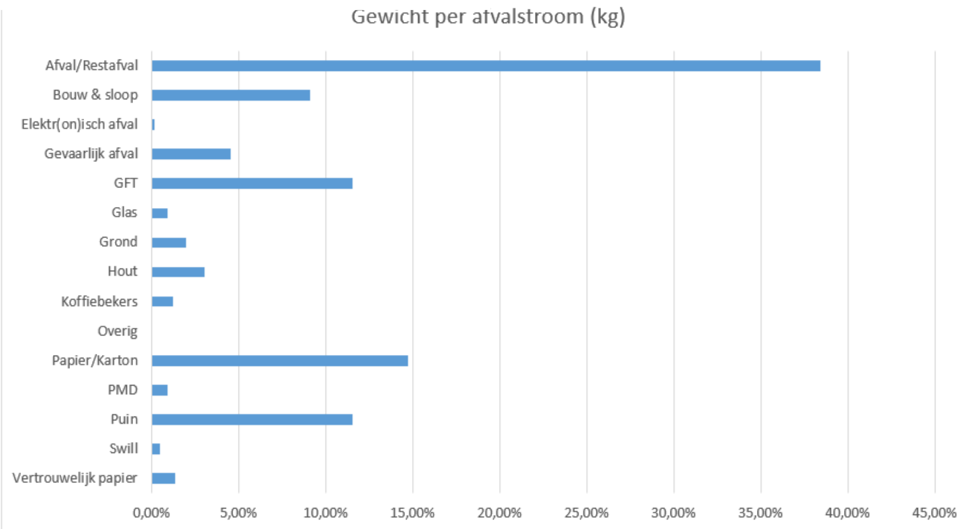

Figure 4: weight percentage graph per waste stream

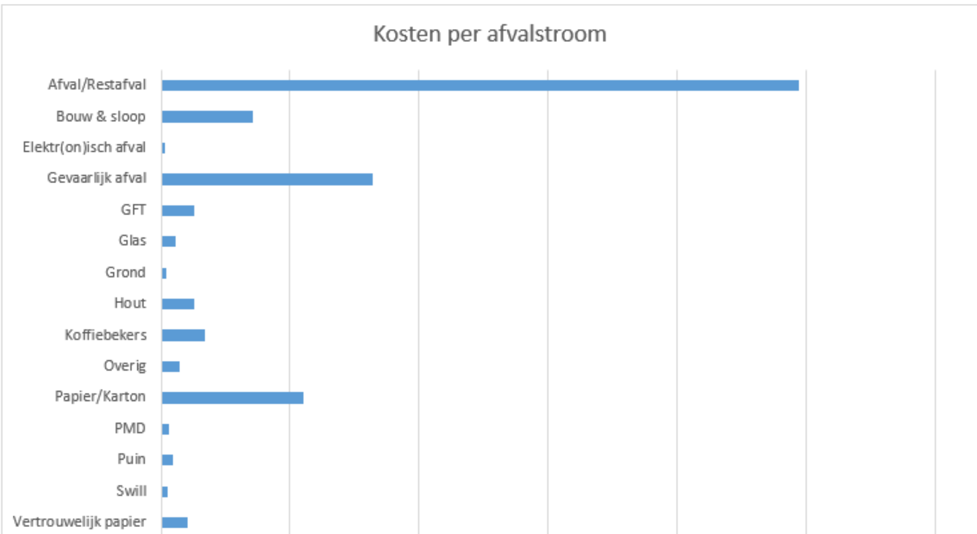

Figure 2: Cost percentage graph per waste stream

APPENDIX C: CONTENT INVESTIGATION ON SAMPLE RESIDUAL WASTE BINS 2024

Below, two tables have been included to display the results of a preliminary investigation into residual waste content. This investigation is being conducted by the new waste collection company, 'PreZero'. The sample datasets from the Echo building and TBM faculty show waste content analysis in percentages. This analysis aids in identifying waste streams that can be separated from the residual waste stream, ultimately reducing landfill waste.

Grondstoffenanalyse TU Delft

Klant naam **TU Delft**
Locatie: **Echo**
Hoeveelheid **13,27 kg**
Datum: **20 maart 2024**

#	Geconstateerde fracties	Vuilruimte	Restaurant	Totaal	Percentage	Opmerking
1	Groente, Fruit en Etensresten	4,08	2,35	6,43	48,5%	
2	Koffiedik	0,00	0,00	0,00	0,0%	
3	Plastic verpakkingen en Drankenkartons	0,74	1,46	2,20	16,6%	
4	Glas	0,16	0,33	0,49	3,7%	
5	Papier/Karton	0,07	0,09	0,16	1,2%	
6	Papieren Koffiebekers	0,00	0,00	0,00	0,0%	
7	Papieren Handdoekjes	0,05	0,21	0,26	2,0%	Vervuild
8	Handschoenen	0,00	0,00	0,00	0,0%	
9	Overig	0,00	0,00	0,00	0,0%	
10	Restafval	1,85	1,88	3,73	28,1%	
Totaal (kg)		6,95	6,32	13,27	100,0%	

Figure 6: Sample residual waste stream analysis of Echo building

Grondstoffenanalyse TU Delft

Klant: **TU Delft**
Gebouw: **TBM**
Hoeveelheid: **10,84 kg**
Datum: **8 mei 2024**

#	Geconstateerde fracties	Vuilruimte	Totaal	Percentage	Opmerking
1	Groente, Fruit en Etensresten	2,64	2,64	24,4%	
2	Koffiedik	0,00	0,00	0,0%	
3	Plastic verpakkingen en Drankenkartons	1,51	1,51	13,9%	
4	Glas	2,06	2,06	19,0%	
5	Hout	0,00	0,00	0,0%	
6	Papier/Karton	0,73	0,73	6,7%	
7	Papieren Koffiebekers	0,00	0,00	0,0%	
8	Papieren Handdoekjes	0,00	0,00	0,0%	
9	Handschoenen	0,00	0,00	0,0%	
10	Overig	0,00	0,00	0,0%	
11	Restafval	3,90	3,90	36,0%	
Totaal (kg)		10,84	10,84	100,0%	

Figure 7: sample residual waste stream analysis of TBM building.

APPENDIX 4: OVERVIEW 3D PRINTING TECHNOLOGIES

This segment has been extracted from Li et al.'s research paper from 2023, offering a detailed overview of current Additive Manufacturing (AM) methods. Each method is thoroughly explained and visually depicted for clarity. While this paper doesn't extensively cover AM technologies, including these descriptions can benefit readers unfamiliar with the field by providing basic concepts, terminologies, and processes.

Fused Filament Fabrication (FFF) utilizes material extrusion, where filamentous material is melted and precisely deposited through a CNC nozzle along a predetermined path, as illustrated in Figure a. The deposited filament cools and bonds to form a two-dimensional plane, with subsequent layers stacked to create three-dimensional objects.

Direct Ink Writing (DIW) employs computer-controlled pneumatic pressure or screw extrusion to deposit high-viscosity paste, forming a two-dimensional plane along a programmed path, as shown in Figure b. Layers are then stacked to construct three-dimensional models.

Stereolithography (SLA) involves UV light irradiation of photosensitive resin to cross-link and cure a two-dimensional plane, with the printing platform moving vertically to build a three-dimensional object, as depicted in Figure c.

Selective Laser Sintering (SLS) utilizes laser sintering to fuse materials into a two-dimensional plane when the melting point of the powder exceeds a set temperature, illustrated in Figure d. Layers are then stacked in the Z-axis direction to form the final object.

Laminated Object Manufacturing (LOM) is an established AM technology patented by Michael Feygin in 1985, involving the layer-by-layer bonding of sheets coated with hot melt glue using a carbon dioxide laser beam, as shown in Figure e.

Liquid Deposition Modeling (LDM) is a novel technology based on extrusion molding, employing wood chips or flour mixed with methyl cellulose and water or wood binders as raw materials, deposited and molded under computer control, as depicted in Figure f.

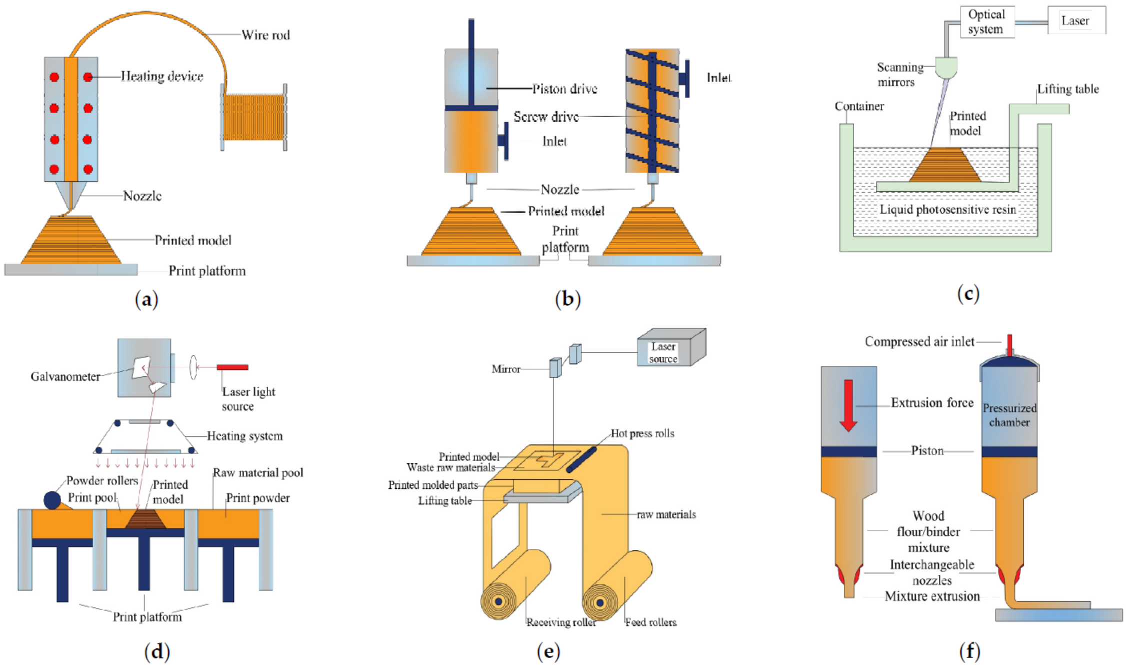

Figure 8: Overview of 3d printing Technologies according to Li et al. (2023)