

Design and Development of Custom-Made 3D Printed Breast Prostheses: A Multidisciplinary Approach Integrating Material Science, 3D Scanning, Product Design and Production Process

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Design and Development of Custom-Made 3D Printed Breast Prostheses: A Multidisciplinary Approach Integrating Material Science, 3D Scanning, Product Design and Production Process

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Abstract □ This thesis explores how 3D printing can be used to design lightweight and personalized external breast prostheses for women who have undergone a mastectomy. Traditional prostheses are often heavy, uncomfortable and not well adapted to individual body shapes. Through benchmark analysis, cocreation with users and parametric modeling in Grasshopper, this research aimed to develop a new generation of prostheses that better meet user needs. A customizable digital model was created, using internal hole structures to reduce weight while keeping the prosthesis soft and stable. Several prototypes were printed in PLA, TPU and silicone. Due to technical limitations, full testing with patients was not possible, but expert feedback was collected. The study shows that 3D printing offers important advantages for comfort, fit and design flexibility. It also highlights the importance of involving users in the design process. The results provide a strong base for future research and clinical testing.

Keywords □ breast prosthesis, 3D printing, customization, cocreation, Grasshopper

I. INTRODUCTION

Breast cancer is the most commonly diagnosed cancer among women globally. In 2020, the World Health Organization's International Agency for Research on Cancer (IARC) reported 2.3 million new cases, accounting for 11.7% of all cancer diagnoses worldwide [1], [2]. Thanks to advances in early detection and treatment, the five-year survival rate for breast cancer now exceeds 80% [3], [4]. Despite improved prognosis, many survivors face long-term physical and emotional challenges, particularly following mastectomy—a surgical procedure involving the removal of one or both breasts. This intervention often leads to feelings of bodily imbalance and emotional disconnection [5], [6].

For individuals who choose not to pursue surgical breast reconstruction, external breast prostheses offer a non-invasive solution to restore body symmetry and confidence. However, current prosthetic products often lack in comfort, aesthetics and personalization. Most are mass-produced in standard sizes using materials like silicone that, although skin-like in texture, are often too heavy and poorly breathable. Standard prostheses typically weigh between 200 and 400 grams, which may be burdensome for users with smaller body frames. Moreover, the availability is limited, with most stores offering only 10 to 15 models [7].

Insights from a cocreation project conducted in 2024 with breast cancer survivors underscored the limitations of existing prostheses. Participants highlighted the lack of personalization and choice in current options. One participant poignantly remarked, “There are twice as many breasts on this earth as there are women,” reflecting the need for individualized solutions. Expert feedback from plastic surgeon Prof. Dr. Philip Blondeel further emphasized that conventional prostheses are especially uncomfortable for women with larger cup sizes, negatively affecting body image, self-esteem and emotional recovery [7].

Emerging technologies such as additive manufacturing (3D printing) open new pathways for innovation. This technology enables the development of highly customized prosthetic designs derived from 3D body scans and facilitates the creation of lightweight structures through techniques like Voronoi patterns and internal lattices [8], [9], [10]. Biocompatible materials such as medical-grade silicone and thermoplastic polyurethane (TPU) offer additional benefits, including softness, durability and washability. Despite their potential, these technologies are not yet widely implemented in external breast prosthetics. Companies like EVE and Hashtagtwo are pioneering the use of 3D scanning and printing in this field, but their solutions remain relatively inaccessible and expensive [11], [12], [13].

A benchmark study of six companies—Anita, Amoena, Trulife, ABC, EVE and Hashtagtwo—revealed that while each introduces unique design innovations, none fully address the combined need for personalization, lightness, breathability aesthetics and accessibility [7], [11], [12], [13]. This underscores a significant gap in the market and the need for a more integrated, user-centered design approach.

This thesis explores how 3D printing technology can be used to optimize the design of external breast prostheses that are lightweight, personalized and meet medical safety standards. A set of seven sub-questions guides the study:

1. Which materials can be used in 3D printing to ensure that breast prostheses remain lightweight, durable, safe and comfortable for users?

2. What infill percentage, layer height, print speed, bed/chamber temperature and curing time should be used to ensure that the prostheses are safe, comfortable, lightweight and durable for users?
3. What design innovations, such as hole structures or lattice designs, can reduce the weight of 3D printed prostheses?
4. What types of personal preferences (e.g., shape, weight, texture) can be incorporated into 3D printed prostheses?
5. How can user feedback (e.g., from breast cancer survivors) be integrated into the design optimization process?
6. What insights can be drawn from the characteristics of breast prostheses from benchmarks to optimize the design of 3D printed breast prostheses?
7. How can a Grasshopper code be used to create a personalized prosthesis model?

The outcome is a proof-of-concept prosthesis that incorporates user feedback, 3D scans and parametric design to create breathable, lightweight and customizable prostheses. Through an interdisciplinary, cocreative process, this work aims to improve the physical and emotional quality of life for breast cancer survivors by restoring confidence, comfort and dignity.

II. STATE OF THE ART

This chapter reviews the current landscape of external breast prostheses, highlighting the limitations of traditional products and exploring emerging innovations. Although external prostheses have long supported women after mastectomy, they continue to present significant challenges related to comfort, aesthetics, personalization and accessibility. Based on benchmark analysis, industry visits and digital technology exploration—including 3D scanning, 3D printing and parametric modeling—this section identifies key gaps in the market and promising directions for improvement.

Traditional external breast prostheses are typically made of silicone or foam and are worn inside a bra. While these products help restore body symmetry and confidence after surgery, many users report discomfort due to their weight, heat buildup and lack of breathability. Most prostheses weigh between 200 to 400 grams and often do not conform well to the individual's body shape. These problems are especially noticeable during extended wear, physical activity or in warm climates. Furthermore, the prostheses are usually produced in fixed sizes and shapes, making it difficult for many women to find a model that fits their unique anatomy. Most shops only offer 10 to 15 models, resulting in limited options and low user satisfaction [7].

Partial prostheses are becoming more important due to the rise in breast-conserving surgeries, yet the market for these remains underdeveloped. Current options for partial forms are often unstable, unnatural in shape and poorly fitted, which causes both physical discomfort and emotional dissatisfaction [14]. Many women feel that the available prostheses do not reflect their body type or personal identity, especially in cases

of asymmetry or non-standard chest contours. The lack of diversity in shape, skin tone and softness adds to the feeling of emotional disconnect from one's own body.

Customization is a major unmet need. While some companies offer custom-made solutions, these are typically expensive and difficult to access. This creates inequality in prosthesis availability, as many women cannot afford personalized care [7]. Additionally, traditional manufacturing methods such as mold-making are time-consuming and inflexible. These processes also generate more waste and require more manual steps, further increasing production costs.

To better understand what is currently offered on the market, a benchmark study was conducted. It included 32 products from four leading companies—Anita, Amoena, Trulife and ABC—representing a range of standard, partial, sport-specific and swim prostheses. Each company shows unique strengths: Anita focuses on simplicity, lightweight materials and reliable comfort; Amoena is known for innovative features like air chambers and temperature-regulating Comfort+ layers; Trulife incorporates advanced silicone and gel technologies with enhanced breathability; and ABC offers functional diversity and extra comfort-focused solutions. While each brand contributes valuable design elements, none fully address all user needs at once.

In addition to traditional products, this study examined innovative companies applying 3D printing to breast prostheses. Two such companies—EVE and Hashtagtwo—are based in the Netherlands and provide highly personalized prosthetic solutions. EVE uses a network of 20 cameras to scan the user's torso and 3D print a mold that is later filled with silicone and hand-finished [32]. Hashtagtwo, by contrast, uses direct silicone 3D printing (via ARBURG Freeformer technology) to fabricate prostheses from medical-grade, recyclable silicone. They also apply a circular subscription model that allows prostheses to be returned and recycled, adding an element of sustainability to their service [11], [12].

Company visits to Anita's headquarters further deepened the understanding of current production techniques and industry challenges. Observing their manufacturing process revealed the high level of precision and care involved in producing silicone prostheses [15]. However, even with this professionalism, there remains room for improvement—especially in terms of personalization and integration of digital technologies. During the visit, 3D scanning of breast model was conducted using Artec 3D devices, demonstrating the technical possibilities for digital modelling. The feedback from Anita's development team showed a strong interest in parametric design and lightweight prototypes made using silicone 3D printing, such as those developed in this research.

This thesis also investigates the use of Grasshopper, a visual programming tool for parametric design, to create prostheses tailored to individual users. Grasshopper allows for fast and flexible modifications of 3D models, integration of 3D scans and the addition of advanced features like internal hole structures. These designs can reduce weight, improve grip and enhance breathability without compromising durability. When combined with self-scanning technologies—such as mobile apps like Polycam, xOne AI or DECAL—the workflow

becomes more accessible, enabling users to scan their bodies from home and participate in the design process.

Despite promising developments in internal implants and bioprinting, external breast prostheses have not benefited equally from technological innovation. There remains a lack of research and commercial products using 3D printing to create realistic, lightweight, breathable and affordable external prostheses [8], [9], [16], [17]. Integrating 3D printing with scanning and parametric modelling offers the chance to overcome limitations in fit, comfort and customization. Furthermore, digital workflows reduce production costs and can expand access to high-quality prostheses.

III. METHODS

To answer the main research question, this thesis used a structured, multidisciplinary and user-centered design approach. The thesis was guided by seven sub-questions, each focusing on a specific topic. These sub-questions helped to shape the research methodology and informed each phase of the design process. Although not all research steps could be completed due to time and technical limitations, each sub-question was addressed to the best extent possible within the scope of this master's thesis.

The first sub-question focused on selecting appropriate materials for 3D printing breast prostheses. A literature study was conducted to identify materials that are biocompatible, lightweight, skin-friendly and durable. Special attention was paid to medical-grade silicones and flexible thermoplastic materials, such as TPU. These materials also had to be compatible with 3D printing equipment [18], [19], [20], [21], [22]. Although hands-on material testing was planned, it could not be completed due to delays with the silicone printer. Nevertheless, this study formed a strong foundation for future testing.

The second sub-question aimed to define optimal printing parameters (e.g., infill percentage, layer height, print speed, curing time) for safe, comfortable and durable prostheses. The original idea was to experiment with slicer software settings (Simplify3D), but due to complexity and time restrictions, this task was outsourced to Yannick Christiaens, lecturer at Ghent University with experience in 3D printing. Therefore, print parameters were not tested independently in this thesis but will be explored in future work.

The third sub-question investigated design strategies that reduce prosthesis weight, such as using internal hole structures. These designs were tested through physical prototyping with FDM printers using PLA and TPU. Voronoi and lattice geometries were applied to minimize weight while preserving structural stability [23], [24]. Results showed that such structures can significantly improve breathability and reduce material use, pointing to an effective design strategy for comfort and sustainability.

The fourth sub-question explored how individual user preferences (shape, weight, texture, ...) can be integrated into the prosthesis design. A MoSCoW analysis was performed using interview data from previous cocreation sessions and feedback from Anita representatives. This prioritization helped define which features were essential, optional or unnecessary,

and it formed the basis for the user-centered Program of Requirements (PoR).

The fifth sub-question focused on integrating user feedback into the design process. Although one-on-one user interviews and scenario testing were planned, these could not be executed due to development delays in the Grasshopper model. Instead, qualitative feedback was collected from design experts, medical professionals and Anita's development team. Their insights helped refine the design direction, especially in terms of feel, usability and aesthetics. Full user testing remains a recommended step for future development.

The sixth sub-question involved a detailed benchmark analysis of 32 existing breast prostheses from companies like Anita, Amoena, Trulife and ABC. Products were evaluated based on comfort, fit, material, aesthetics, weight and use cases (e.g., swimming, sports, post-operative). This analysis revealed gaps in personalization, comfort and diversity, and helped shape the design criteria for the 3D printed alternative. The study also included innovations from two companies (EVE and Hashtagtwo) using 3D printing in prosthesis development.

The seventh sub-question addressed how to use Grasshopper—a visual programming tool in Rhino—to create a customizable prosthesis model. A parametric script was developed to generate models based on 3D scan data, allowing adaptation to individual body shapes. Although the final silicone prototype could not be printed on time, the digital model is functional and forms the basis for future mass customization and rapid prototyping.

The overall design process followed a research-through-design approach, integrating user feedback, iteration and prototyping. It was supported by methods from user-centered design, codesign and participatory design. Breast cancer survivors were treated as cocreators, not just participants. While full cocreation was limited by time, user perspectives strongly influenced the direction and requirements of the thesis.

To ensure structure, the Pahl and Beitz engineering design method was used alongside the Biodesign principles. These frameworks helped guide the thesis from need identification to early prototype testing [25], [26]. In parallel, research into medical device regulations (MDR and ISO 13485) ensured that safety, documentation and quality were considered [27], [28], [29]. Regulatory classification indicated that the prosthesis is a Class I medical device, allowing development within a manageable scope. Risks were analysed across health, technical, user and planning domains and documented in a central file about the medical device regulations.



Figure 1: Medical device development cycle

Prototyping and early testing occurred in Phase 2 of the medical design development cycle (Figure 1). Functional prints in PLA, TPU and silicone were attempted. Silicone printing faced delays due to slicing and support structure issues and as a result, the final prototype could not be completed before the thesis deadline. Nevertheless, previous prototypes received

expert feedback from Anita and the research team, which helped refine the design.

A stakeholder mapping exercise categorized all involved parties—from core decision-makers to informed groups. This included patients, doctors, 3D printing experts, industry partners and ethics committees. To find participants, multiple channels were used: hospital flyers, social media and direct outreach. In total, 16 patients expressed interest in contributing to the research.

IV. RESULTS

This chapter presents the main technical and design results achieved during the development of a custom-made 3D printed breast prosthesis. The focus was on creating a parametric model in Grasshopper, developing and testing different internal hole structures, exploring 3D scanning workflows and integrating user feedback into the design process.

The initial Grasshopper file, developed by the previous cocreation team, served as the starting point. However, it contained several problems, including missing plugins (such as Parakeet), unused code blocks, errors and poor organization. Moreover, the script was too computationally heavy, often crashing on the student's laptop. After receiving advice from the supervisor, a more powerful university computer was used for some time, but because this was not available at home, the student decided to restart the modelling process in a new file. To simplify early development, a hemisphere was used as test geometry. This basic shape resembles a simplified breast form and allows efficient testing without overwhelming the software.

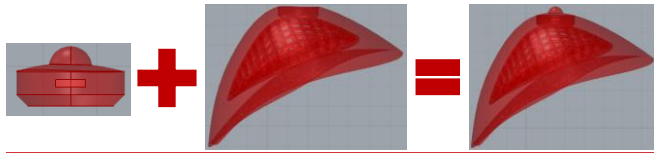


Figure 2: Final result of breast prosthesis

The final parametric model was structured as a modular Grasshopper script. It allowed step-by-step construction of the breast prosthesis geometry, including base shape generation, integration of hole structures and implementation of a removable nipple (Figure 2). To improve readability and functionality, the code was divided into groups. Each group served a specific purpose—for example, generating interpolated surfaces, selecting and filling unit cells, converting meshes and preparing geometries for export. The logic of the code followed a consistent and clear sequence, which made debugging and further development easier.

Five different internal structures were created and tested using hemispherical test samples. These included a lattice using Crystallon, three types of Voronoi patterns (surface, volume and offset) and a lattice skin. Each structure was programmed in Grasshopper and then applied to both test geometries and the final prosthesis model. The Dendro plugin was used to apply Boolean operations, merge geometries and create printable meshes. The lattice structure and the volumetric Voronoi model were especially promising in terms of weight reduction and structural integrity [23], [24].

An innovative feature in the final design was the removable nipple. This component provided both aesthetic value and a technical function—it allowed access to the prosthesis's interior for removing hydrogel support material after 3D printing. The nipple and corresponding opening were both modelled in Grasshopper using a stepwise logic of curve projection, Boolean operations and mesh refinement. Several prototypes were printed in PLA and TPU to evaluate the fit and usability of the nipple. Two design versions—one with a cylindrical shape and one with a filleted base—were tested and the latter was selected for better visual integration.

Physical testing played an important role in validating the hole structures. A total of ten hemispherical models and eight prosthesis-shaped models were printed using different materials: standard PLA (rigid), TPU 95A HF (flexible) and Lynxter SIL-001 (silicone) [22]. The goal was to evaluate printability, firmness, surface quality and weight. The PLA versions were easier to print but too rigid for use as prostheses. TPU samples had improved softness but required careful support removal. Silicone printing was more complex and only one complete print could be finished before the thesis deadline. Nevertheless, this print offered valuable insight into material performance and supported further development of the design.

Results showed that the solid PLA model weighed 66 g, while models with 15% infill or Voronoi structures weighed between 3 and 24 g. Thinner Voronoi designs were fragile, while gyroid and lattice structures offered a better balance between lightness and firmness. TPU samples performed well in terms of flexibility but were harder to clean due to internal supports. Silicone printing had the highest potential for realistic feel but also introduced new technical challenges in slicing, support generation and post-processing.

In terms of 3D scanning, the thesis aimed to allow self-scanning by patients using mobile apps. However, despite clear instructions and testing of four apps, the scans submitted by participants were not usable. Common issues included incorrect file formats, limited export options and poor scan quality due to motion blur, incomplete coverage or bad lighting. Participants also reported difficulty with scanning their own body, especially in terms of holding the phone and capturing the correct areas. Because of these problems, the design process continued using a scan from the previous cocreation project, which had already been integrated into the code.

To improve scan quality, a professional scanning session was organized at Anita Dr. Helbig GmbH. Two 3D scanners (Artec EVA and Spider II) were used to scan a breast model. These scans, after cleaning in Blender and Rhino, were used for testing mirroring, symmetry and surface extraction. The EVA scanner produced better results and enabled high-resolution anatomical modelling for the digital prosthesis workflow.

User feedback was collected through expert interviews, cocreation sessions and informal consultations. The MoSCoW method was used to define design priorities. Key 'Must Have' features included a lightweight, comfortable, anatomically accurate prosthesis that is soft, water-resistant and invisible under clothing. 'Should Have' aspects focused on aesthetics, replaceability and breathable materials. The removable nipple was positively received by experts at Anita and was considered a practical solution to enable support removal.

Finally, a material study was conducted to identify suitable silicones for 3D printing. Samples of Lynxter SIL-001 were tested. The student visited the 3D printer manufacturer OMD 3D and collected technical information about extrusion behaviour, print settings and maintenance. Visits to the Medica Fair also helped identify potential suppliers. While the full comparative material test could not be completed due to time and slicing issues, the work laid a solid foundation for future experiments with certified medical-grade silicone.

V. DISCUSSIONS

This chapter reflects on the main findings of the thesis and their implications for the development of external 3D printed breast prostheses. The research demonstrates that integrating 3D printing, parametric modelling and cocreation can support the design of more personalized, lightweight and comfortable prostheses for women who do not undergo breast reconstruction surgery.

A key outcome was the testing of various hole structures to reduce prosthesis weight. While internal holes significantly lowered the overall weight, they often compromised the firmness and stability of the prosthesis. In contrast, applying holes solely on the outer surface provided a better balance between weight reduction and structural integrity. This finding offers a clear design direction for future prototypes aiming to enhance both comfort and functionality.

Another important contribution was the use of Grasshopper, a parametric design tool integrated with Rhino. Although the script was not fully optimized, it enabled early-stage customization using 3D scan data. Parameters such as external shape, internal structure and a removable nipple were incorporated into the script, illustrating how parametric design tools can streamline the development of personalized medical devices and allow for flexible design iterations.

The design process was informed by input from cocreation sessions, expert interviews and collaboration with the breast care company Anita. A MoSCoW analysis helped prioritize user needs, identifying comfort, a secure fit, a natural shape and discretion under clothing as essential features. These priorities were directly translated into the prosthesis design, showing that technical development can be guided meaningfully by user-centered insights.

The thesis addressed seven sub-questions, highlighting the importance of soft, skin-friendly materials and the practical advantages of surface-based hole structures. Although medical-grade silicone could not be tested due to technical limitations, the study confirmed the relevance of customization and comfort. Expert input served as a valuable substitute for user testing, and the benchmark analysis revealed that current commercial options often lack adaptability and personalization.

Nevertheless, the thesis had several limitations. Real user testing was not feasible due to the limited quality of self-scanned data and time constraints. Only a few prototypes were printed and the slicing software posed usability challenges. Regulatory compliance was not fully addressed.

Future research should focus on higher-quality scanning methods, testing certified medical-grade silicone and involving

users in scenario-based testing. Optimizing print settings and expanding cocreation with diverse participants will also enhance outcomes. A promising direction is the continued development of surface-only hole structures, which may offer improved comfort and manufacturability.

VI. CONCLUSIONS

This master's thesis explored how 3D printing can enhance the design of lightweight external breast prostheses, with a focus on meeting medical requirements and improving user comfort. By combining benchmark analysis, cocreation, parametric modelling using Grasshopper and physical prototyping, the study investigated new design opportunities. The overarching goal was to create a prosthesis that is lighter, more personalized and more comfortable for women who cannot or choose not to undergo breast reconstruction surgery.

The research confirmed that 3D printing presents significant advantages for breast prosthesis development. It enables precise customization based on individual anatomy, supports lightweight design strategies and allows for rapid iteration through prototyping. One of the main innovations was the integration of hole structures to reduce the prosthesis weight. When applied only to the outer surface, these holes successfully reduced weight while preserving the shape and firmness, offering a more breathable and comfortable alternative to conventional designs.

A key technical contribution was the development of a functional Grasshopper script. Although still in the early stages of development, the script enabled parametric customization based on 3D scan data. It allowed adjustments to prosthesis shape, location of openings and internal geometry. This flexible approach provides a promising foundation for the future design of personalized medical devices tailored to individual users.

Beyond the technical achievements, the thesis emphasized the importance of understanding user needs. Through a MoSCoW analysis and feedback from breast care professionals, 3D printing specialists and representatives from the company Anita, the research identified key user requirements such as softness, secure and comfortable fit, natural appearance and easy cleaning. These insights were integrated into the design through features like a removable nipple and smooth exterior surfaces.

The benchmark study further revealed several limitations of current commercial prostheses, including excessive weight, insufficient customization and discomfort during wear. The findings indicate that 3D printing, when combined with cocreation and smart design tools, can offer more ergonomic and user-centered solutions.

However, the study also faced limitations. Certified medical-grade silicone could not be tested due to technical constraints. The slicing software was complex and printing parameters were not fully optimized. Additionally, real user testing was not feasible because of poor-quality self-scans. As such, comfort and usability assessments remain hypothetical and require further validation.

Despite these limitations, the thesis provides a strong basis for future research. With improved scanning techniques, validated materials and clinical testing, the concepts developed

in this study can support the creation of more inclusive, safe and emotionally supportive prosthetic solutions.

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Ontwerp en ontwikkeling van op maat gemaakt 3D geprinte borstprothesen: Een multidisciplinaire benadering die materiaalkunde, 3D scannen, productontwerp en productieproces integreert

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Abstract Deze thesis onderzoekt hoe 3D printtechnologie kan worden ingezet om lichte en gepersonaliseerde externe borstprothesen te ontwerpen voor vrouwen die een mastectomie hebben ondergaan. Traditionele prothesen zijn vaak zwaar, oncomfortabel en sluiten niet goed aan op de individuele lichaamsvorm. Door middel van een benchmarkanalyse, cocreatie met gebruikers en parametrisch modelleren in Grasshopper, richt dit onderzoek zich op het ontwikkelen van een nieuwe generatie prothesen die beter aansluiten bij de behoeften van de gebruikers. Er werd een aanpasbaar digitaal model ontwikkeld met interne perforatiestructuren om het gewicht te verminderen, terwijl de prothese zacht en stabiel bleef. Verschillende prototypes werden geprint in PLA, TPU en siliconen. Door technische beperkingen was uitgebreid testen met patiënten niet mogelijk, maar er werd wel feedback verzameld van experts. De studie toont aan dat 3D printen belangrijke voordelen biedt op het gebied van comfort, pasvorm en ontwerpflexibiliteit. Daarnaast benadrukt het onderzoek het belang van gebruikersbetrokkenheid in het ontwerpproces. De resultaten vormen een stevige basis voor toekomstig onderzoek en klinische validatie.

Trefwoorden borstprothese, 3D printen, personalisatie, cocreatie, Grasshopper

I. INLEIDING

Borstkanker is wereldwijd de meest voorkomende vorm van kanker bij vrouwen. In 2020 rapporteerde het International Agency for Research on Cancer (IARC) van de Wereldgezondheidsorganisatie 2,3 miljoen nieuwe gevallen, wat neerkomt op 11,7% van alle kankerdiagnoses wereldwijd [1], [2]. Dankzij vooruitgang in vroege opsporing en behandelingen bedraagt het vijfjaarsoverlevingspercentage voor borstkanker inmiddels meer dan 80% [3], [4]. Ondanks deze verbeterde prognose kampen veel overlevenden met langdurige fysieke en emotionele gevolgen, met name na een borstamputatie (mastectomie), een chirurgische ingreep waarbij één of beide borsten worden verwijderd. Deze ingreep leidt vaak tot gevoelens van lichamelijke disbalans en emotionele vervreemding van het eigen lichaam [5], [6].

Voor vrouwen die ervoor kiezen geen reconstructieve borstchirurgie te ondergaan, bieden externe borstprothesen een niet-invasief alternatief om de lichaamssymmetrie en het zelfvertrouwen te herstellen. Toch schieten bestaande prothesen vaak tekort op het gebied van comfort, esthetiek en personalisatie. Ze worden doorgaans in standaardmaten geproduceerd uit materialen zoals siliconen, die weliswaar

huidachtig aanvoelen, maar vaak te zwaar zijn en niet ademend. De meeste standaardprothesen wegen tussen de 200 en 400 gram, wat belastend kan zijn voor vrouwen met een kleiner postuur. Daarnaast is de beschikbaarheid beperkt; in de meeste winkels zijn slechts 10 tot 15 modellen te verkrijgen [7].

Een cocreatie project uit 2024 met borstkankerpatiënten benadrukte deze tekortkomingen. Deelnemers gaven aan dat er een gebrek is aan keuzevrijheid en maatwerk in de huidige prothesen. Eén deelnemer merkte op: “Er zijn twee keer zoveel borsten op aarde als er vrouwen zijn,” waarmee ze de noodzaak voor individuele oplossingen illustreerde. Ook plastisch chirurg Prof. Dr. Philip Blondeel bevestigde dat bestaande prothesen vooral voor vrouwen met een grotere cupmaat vaak oncomfortabel zijn, met negatieve gevolgen voor het zelfbeeld, de eigenwaarde en het emotioneel herstel [7].

Nieuwe technologieën zoals additieve productie (3D printen) bieden veelbelovende mogelijkheden voor innovatie. Deze technologie maakt het mogelijk om op basis van 3D scans gepersonaliseerde ontwerpen te ontwikkelen en lichte structuren te creëren met technieken zoals Voronoi-patronen of interne lattice [8], [9], [10]. Biocompatibele materialen zoals medische siliconen en thermoplastisch polyurethaan (TPU) bieden extra voordelen, waaronder zachtheid, duurzaamheid en wasbaarheid. Ondanks hun potentieel worden deze technologieën nog nauwelijks toegepast in externe borstprothesen. Bedrijven als EVE en Hashtagtwo nemen hierin het voortouw met oplossingen op basis van 3D scanning en -printen, maar hun producten zijn nog relatief duur en beperkt toegankelijk [11], [12], [13].

Een benchmarkstudie van zes bedrijven—Anita, Amoena, Trulife, ABC, EVE en Hashtagtwo—liet zien dat hoewel elk merk unieke innovaties introduceert, geen enkel product volledig voldoet aan de gecombineerde behoeften op het gebied van personalisatie, gewicht, ademend vermogen, realisme en toegankelijkheid [7], [11], [12], [13]. Dit duidt op een duidelijke leemte in de markt en de noodzaak voor een geïntegreerde, gebruikersgerichte ontwerpaanpak.

Deze thesis onderzoekt hoe 3D printtechnologie kan worden ingezet om het ontwerp van externe borstprothesen te optimaliseren op het gebied van lichtheid, maatwerk en

medische veiligheid. Daarbij worden de volgende zeven deelvragen gesteld:

1. Welke materialen zijn geschikt voor 3D printen om een lichte, duurzame, veilige en comfortabele borstprothese te realiseren?
2. Welke printinstellingen (zoals vulling-percentages, laagdikte, printsnelheid, bed- en kamertemperatuur en uithardingstijd) zijn optimaal voor gebruiksvriendelijke, veilige en duurzame prothesen?
3. Welke ontwerpinnovaties, zoals perforatiestructuren of lattice designs, kunnen het gewicht van de prothese verminderen?
4. Welke persoonlijke voorkeuren (zoals vorm, gewicht, textuur) kunnen worden geïntegreerd in het ontwerp?
5. Hoe kan gebruikersfeedback (bijvoorbeeld van borstkankerpatiënten) worden opgenomen in het ontwerpproces?
6. Welke inzichten uit de benchmarkstudie kunnen worden benut om het ontwerp van 3D geprinte prothesen te verbeteren?
7. Hoe kan Grasshopper worden ingezet om een gepersonaliseerd prothese-model te genereren?

Het resultaat is een proof-of-concept borstprothese die gebruikersfeedback, 3D scans en parametrisch ontwerp combineert om een ademende, lichte en aanpasbare oplossing te realiseren. Via een interdisciplinair en cocreatief proces streeft dit onderzoek ernaar de fysieke én emotionele levenskwaliteit van borstkanker-overlevenden te verbeteren door vertrouwen, comfort en waardigheid te herstellen.

II. STATE OF THE ART

Dit hoofdstuk bespreekt het huidige landschap van externe borstprothesen en belicht zowel de beperkingen van traditionele producten als de opkomende innovaties. Hoewel externe prothesen al lange tijd een waardevolle oplossing bieden voor vrouwen na een mastectomie, blijven er aanzienlijke uitdagingen bestaan op het gebied van comfort, esthetiek, personalisatie en toegankelijkheid. Op basis van benchmarkanalyse, bedrijfsbezoeken en verkenning van digitale technologieën—zoals 3D scanning, 3D printen en parametrisch modelleren—brengt dit hoofdstuk belangrijke hiaten in kaart en wijst het op kansrijke richtingen voor vernieuwing.

Traditionele externe borstprothesen worden meestal vervaardigd uit siliconen of schuim en gedragen in een speciale beha. Hoewel deze producten bijdragen aan het herstel van lichaamssymmetrie en zelfvertrouwen na een operatie, ervaren veel gebruikers ongemak door het gewicht, warmte-opbouw en een gebrek aan ademend vermogen. De meeste prothesen wegen tussen de 200 en 400 gram en sluiten vaak niet goed aan op de individuele lichaamsvorm. Dit ongemak is vooral merkbaar tijdens langdurig dragen, fysieke activiteit of in warme klimaten. Bovendien worden de prothesen doorgaans geproduceerd in vaste maten en vormen, waardoor het moeilijk is voor veel vrouwen om een goed passend model te vinden. De

meeste winkels bieden slechts 10 tot 15 varianten aan, wat leidt tot beperkte keuzevrijheid en lage gebruikerstevredenheid [7].

Partiële prothesen worden steeds belangrijker door de toename van borstsparende operaties, maar het aanbod voor deze toepassingen blijft onderontwikkeld. De huidige partiële modellen zijn vaak instabiel, onnatuurlijk van vorm en sluiten slecht aan, wat leidt tot zowel lichamelijk ongemak als emotionele ontevredenheid [14]. Veel vrouwen geven aan dat de beschikbare prothesen hun lichaamstype of persoonlijke identiteit onvoldoende weerspiegelen, vooral in gevallen van asymmetrie of niet-standaard borstcontouren. Het gebrek aan diversiteit in vorm, huidskleur en zachtheid versterkt het gevoel van vervreemding van het eigen lichaam.

Personalisatie is een belangrijke, nog on vervulde behoefte. Sommige bedrijven bieden weliswaar op maat gemaakte oplossingen, maar deze zijn vaak duur en moeilijk toegankelijk. Dit leidt tot ongelijkheid in beschikbaarheid van zorg [7]. Daarnaast zijn traditionele fabricagemethoden, zoals maltechnieken, tijdrovend, inflexibel en produceren ze relatief veel afval, wat de productiekosten verder opdrijft.

Om beter inzicht te krijgen in het huidige aanbod werd een benchmarkanalyse uitgevoerd van 32 producten van vier toonaangevende bedrijven: Anita, Amoena, Trulife en ABC. Elk merk heeft eigen sterke punten: Anita richt zich op eenvoud, lichte materialen en betrouwbaar comfort; Amoena biedt innovatieve kenmerken zoals luchtkamers en temperatuur regulerende Comfort+ lagen; Trulife gebruikt geavanceerde siliconen- en geltechnologieën voor verbeterde ademendheid; en ABC staat bekend om functionele diversiteit en comfortgerichte ontwerpen. Toch slaagt geen van deze merken erin om alle gebruikersbehoeften tegelijk te vervullen.

Naast traditionele producten onderzocht deze studie ook innovatieve bedrijven die 3D printtechnologie toepassen op borstprothesen. Twee van deze bedrijven—EVE en Hashtagtwo—zijn gevestigd in Nederland en leveren sterk gepersonaliseerde oplossingen. EVE gebruikt een netwerk van 20 camera's om het bovenlichaam te scannen, waarna een mal wordt geprint die later wordt opgevuld met siliconen en met de hand wordt afgewerkt [32]. Hashtagtwo maakt daarentegen gebruik van directe siliconen 3D printen met behulp van ARBURG Freeformer-technologie om prothesen te produceren uit medisch recyclebaar siliconenmateriaal. Zij hanteren bovendien een circulair abonnementsmodel waarbij prothesen kunnen worden teruggestuurd en gerecycled, wat bijdraagt aan duurzaamheid [11], [12].

De bedrijfsbezoeken aan het hoofdkantoor van Anita gaven meer inzicht in de huidige productiemethoden en de uitdagingen binnen de sector. Tijdens de bezoeken werd de precisie en zorgvuldigheid van hun traditionele productieproces zichtbaar [15]. Tegelijkertijd werd duidelijk dat er ruimte is voor verbetering, met name op het gebied van maatwerk en de integratie van digitale technologie. Er werd een 3D scan uitgevoerd van een borstmodel met behulp van Artec 3D scanners, wat de technische mogelijkheden van digitale modellering illustreerde. Het ontwikkelingsteam van Anita toonde daarbij interesse in parametrisch ontwerpen en lichte prototypes op basis van siliconen 3D printen, zoals die binnen dit onderzoek zijn ontwikkeld.

Deze thesis onderzoekt ook het gebruik van Grasshopper, een visueel programmeerplatform voor parametrisch ontwerpen, om prothesen aan te passen aan individuele gebruikers. Grasshopper maakt snelle en flexibele aanpassingen van 3D modellen mogelijk, evenals de integratie van scangegevens en toevoeging van geavanceerde eigenschappen zoals interne perforatiestructuren. Deze ontwerpen kunnen het gewicht verlagen, de grip verbeteren en de ademendheid verhogen zonder in te boeten aan duurzaamheid. In combinatie met zelfscantechnologieën—zoals mobiele apps als Polycam, xOne AI of DECAL—wordt het ontwerpproces toegankelijker en kunnen gebruikers zelf vanuit huis bijdragen aan het maatwerk.

Ondanks veelbelovende ontwikkelingen in bioprinting en interne implantaten heeft de markt voor externe borstprothesen nog niet volledig geprofiteerd van technologische innovatie. Er is nog altijd een gebrek aan onderzoek en commerciële toepassingen van 3D printen om realistische, lichte, ademende en betaalbare externe prothesen te maken [8], [9], [16], [17]. De integratie van 3D printen met scanning en parametrisch ontwerpen biedt de mogelijkheid om tekortkomingen in pasvorm, comfort en personalisatie te overwinnen. Daarnaast kunnen digitale workflows de productiekosten verlagen en de toegang tot hoogwaardige prothesen vergroten.

III. METHODES

Om de hoofdonderzoeksvraag te beantwoorden, werd in deze thesis een gestructureerde, multidisciplinaire en gebruikersgerichte ontwerpaanpak toegepast. Het onderzoek werd geleid door zeven deelvragen, elk gericht op een specifiek thema. Deze vragen vormden het kader voor de onderzoeksmethodologie en bepaalden de opbouw van het ontwerpproces. Hoewel niet alle onderzoekstappen volledig konden worden uitgevoerd vanwege tijdsdruk en technische beperkingen, werd elke deelvraag zo goed mogelijk binnen de scope van deze masterproef behandeld.

De eerste deelvraag richtte zich op het selecteren van geschikte materialen voor het 3D printen van borstprothesen. Via literatuuronderzoek werden materialen geïdentificeerd die biocompatibel, lichtgewicht, huidvriendelijk en duurzaam zijn. Er werd bijzondere aandacht besteed aan medische siliconen en flexibele thermoplasten zoals TPU. Deze materialen moesten tevens compatibel zijn met de 3D printer [18], [19], [20], [21], [22]. Hoewel praktijkproeven gepland waren, konden deze wegens vertragingen met de siliconenprinter niet worden uitgevoerd. Desondanks legde dit materiaalonderzoek een sterke basis voor toekomstig experimenteel werk.

De tweede deelvraag beoogde het bepalen van optimale printparameters (zoals vulling-percentages, laagdikte, printsnelheid en uithardingstijd) voor veilige, comfortabele en duurzame prothesen. Het oorspronkelijke plan was om zelf met slicer-software (Simplify3D) te experimenteren, maar vanwege complexiteit en tijdsdruk werd deze taak uitbesteed aan Yannick Christiaens, docent aan de Universiteit Gent met expertise in 3D printen. Printinstellingen werden daarom niet zelfstandig getest in deze thesis, maar vormen een aandachtspunt voor vervolgonderzoek.

De derde deelvraag onderzocht ontwerp oplossingen om het gewicht van de prothese te verlagen, bijvoorbeeld via interne perforatiestructuren. Deze werden getest door fysieke prototypes te printen met FDM 3D printers en materialen zoals

PLA en TPU. Er werden Voronoi- en lattice-geometrieën toegepast om gewicht te reduceren zonder structurele integriteit te verliezen [23], [24]. De resultaten toonden aan dat dergelijke structuren de ademendheid verbeteren en het materiaalgebruik verlagen, wat bijdraagt aan comfort en duurzaamheid.

De vierde deelvraag betrof de integratie van persoonlijke voorkeuren (zoals vorm, gewicht en textuur) in het ontwerp. Op basis van interviewgegevens uit eerdere cocreatiesessies en feedback van medewerkers van Anita werd een MoSCoW-analyse uitgevoerd. Deze prioritering hielp bepalen welke eigenschappen essentieel, wenselijk of overbodig waren en vormde de basis voor het gebruikersgerichte Programma van Eisen (PvE).

De vijfde deelvraag richtte zich op het integreren van gebruikersfeedback in het ontwerpproces. Hoewel individuele interviews en scenario-analyses waren voorzien, konden deze wegens vertragingen in de ontwikkeling van het Grasshopper-model niet doorgaan. In plaats daarvan werd kwalitatieve feedback verzameld van ontwerpers, medisch experts en het ontwikkelingsteam van Anita. Hun input beïnvloedde de ontwerpkeuzes, met name op het gebied van gevoel, gebruiksgemak en esthetiek. Volwaardige gebruikerstesten blijven aanbevolen voor toekomstig onderzoek.

De zesde deelvraag omvatte een benchmarkanalyse van 32 bestaande borstprothesen van bedrijven zoals Anita, Amoena, Trulife en ABC. De producten werden geëvalueerd op aspecten zoals comfort, pasvorm, materiaal, esthetiek, gewicht en toepassingsgebied (bijv. zwemmen, sport, postoperatief). Deze analyse bracht tekortkomingen aan het licht in personalisatie, comfort en diversiteit, en hielp bij het opstellen van ontwerpcriteria voor een 3D geprinte variant. Ook innovaties van EVE en Hashtagtwo werden hierin meegenomen.

De zevende deelvraag ging over het gebruik van Grasshopper, een visueel programmeerplatform binnen Rhino, voor het genereren van gepersonaliseerde prothesemodellen. Er werd een parametrisch script ontwikkeld dat modellen genereert op basis van 3D scans, zodat ze aangepast kunnen worden aan de individuele lichaamsvorm. Hoewel de definitieve siliconenprothese niet tijdig kon worden geprint, is het digitale model functioneel en vormt het een basis voor toekomstige massamaatwerk en snelle prototyping.

Het gehele ontwerpproces volgde een “research-through-design”-benadering, waarin gebruikersfeedback, iteratie en prototyping werden geïntegreerd. Hierbij werd gebruik gemaakt van methoden uit gebruikersgericht ontwerp, codesign en participatief ontwerp. Borstkankeroverlevenden werden niet louter als deelnemers beschouwd, maar als medeontwerpers. Ondanks beperkingen in tijd was hun perspectief bepalend voor de ontwerpkeuzes en eisen.

Voor structuur werd het ontwerpproces begeleid door het Pahl en Beitz model en de Biodesign-principes [25], [26]. Parallel daaraan werd onderzoek gedaan naar de regelgeving omtrent medische hulpmiddelen (MDR en ISO 13485) om veiligheid, documentatie en kwaliteit te waarborgen [27], [28], [29]. De prothese werd ingeschaald als een medisch hulpmiddel van klasse I, waardoor ontwikkeling binnen een beheersbare scope mogelijk was. Risico's werden geanalyseerd op het vlak

van gezondheid, techniek, gebruiker en planning, en vastgelegd in een centraal bestand over de medische regelgeving.



Figuur 1: Ontwikkelingscyclus van medische hulpmiddelen

Prototyping en vroege testen vonden plaats in fase 2 van de medische ontwikkelingscyclus (Figuur 1). Er werden functionele prints gemaakt in PLA, TPU en siliconen. Door problemen met slicer-instellingen en ondersteuningsstructuren ondervond het printen in siliconen vertraging, waardoor het eindprototype niet tijdig klaar was. Toch leverden eerdere prototypes waardevolle feedback op van Anita en het onderzoeksteam, wat bijdroeg aan ontwerpverbeteringen.

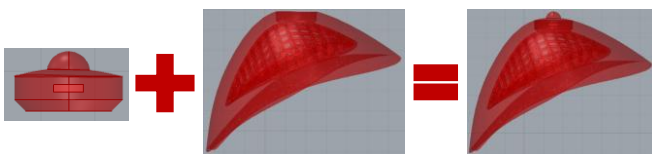
Tot slot werd via stakeholder mapping een overzicht gemaakt van alle betrokkenen—van beslissers tot geïnformeerde groepen. Dit omvatte patiënten, artsen, 3D printspecialisten, industriële partners en ethische commissies. Deelnemers werden geworven via ziekenhuizen, sociale media en persoonlijke netwerken. In totaal toonden zestien patiënten interesse om bij te dragen aan het onderzoek.

Dankzij de multidisciplinaire achtergrond van de student Industrieel Ontwerpen kon engineering, design en mensgericht denken effectief worden gecombineerd. Door toepassing van codesign methoden werd gezorgd dat het eindproduct niet alleen voldeed aan fysieke vereisten, maar ook aansloot op emotionele en esthetische behoeften.

IV. RESULTATEN

Dit hoofdstuk presenteert de belangrijkste technische en ontwerpresultaten die zijn behaald tijdens de ontwikkeling van een op maat gemaakte 3D geprinte borstprothese. De focus lag op het creëren van een parametrisch model in Grasshopper, het ontwikkelen en testen van verschillende interne perforatiestructuren, het verkennen van 3D scan workflows en het integreren van gebruikersfeedback in het ontwerpproces.

Het oorspronkelijke Grasshopper-bestand, ontwikkeld door een vorig cocreatie-team, diende als uitgangspunt. Dit bestand bevatte echter meerdere problemen, waaronder ontbrekende plug-ins (zoals Parakeet), ongebruikte codeblokken, fouten en een gebrekkige structuur. Bovendien was het script te zwaar voor de laptop van de student, waardoor het programma regelmatig crashte. Na advies van de begeleider werd tijdelijk gebruikgemaakt van een krachtigere universiteitscomputer, maar omdat deze thuis niet beschikbaar was, besloot de student het model opnieuw op te bouwen in een nieuw bestand. Voor een vereenvoudigde start werd een halve bol als testgeometrie gebruikt. Deze basisvorm benadert een vereenvoudigde borstvorm en maakte efficiënt testen mogelijk zonder het systeem te overbelasten.



Figuur 2: Eindresultaat borstprothese

Het uiteindelijke parametrische model werd opgezet als een modulair Grasshopper-script. Dit maakte het mogelijk om de prothese stap voor stap op te bouwen, inclusief de basisvorm, interne perforatiestructuren en een afneembare tepel (Figuur 2). Om de leesbaarheid en functionaliteit te verbeteren, werd de code ingedeeld in logische groepen met elk een specifieke functie, zoals het genereren van oppervlakken, invullen van cellen, omzetten naar meshes en voorbereiden van export. De logica van de code was helder gestructureerd, wat het debuggen en verder ontwikkelen vergemakkelijkte.

Er werden vijf verschillende interne structuren ontworpen en getest met behulp van halve bolvormige testmodellen. Deze omvatten een lattice-structuur via Crystallon, drie typen Voronoi-patronen (oppervlakte, volume en offset) en een lattice-huidstructuur. Elke structuur werd geprogrammeerd in Grasshopper en toegepast op zowel testgeometrieën als het uiteindelijke prothesemodel. De Dendro-plug-in werd gebruikt voor Booleaanse bewerkingen, het samenvoegen van geometrieën en het genereren van printbare meshes. Vooral de lattice-structuur en het volumetrisch Voronoi-patroon bleken veelbelovend op het vlak van gewichtsreductie en structurele integriteit [23], [24].

Een innovatieve eigenschap van het eindontwerp was de afneembare tepel. Deze toevoeging had zowel een esthetische als technische functie: ze gaf toegang tot het inwendige van de prothese om het hydrogel-ondersteuningsmateriaal te verwijderen na het printen. Zowel de tepel als de bijbehorende opening werden gemodelleerd in Grasshopper via een stapsgewijze logica met curveprojectie, Booleaanse operaties en mesh-verfijning. Verschillende prototypes werden geprint in PLA en TPU om de pasvorm en bruikbaarheid te evalueren. Twee ontwerpen—één met een cilindrische vorm en één met een afgeronde basis—werden getest, waarbij het laatste ontwerp werd gekozen vanwege de betere visuele integratie.

Fysieke testen speelden een belangrijke rol in de validatie van de perforatiestructuren. In totaal werden tien halve bollen en acht volledige prothesevormen geprint met verschillende materialen: standaard PLA (stijf), TPU 95A HF (flexibel) en Lynxter SIL-001 (siliconen) [22]. Het doel was om de printbaarheid, stevigheid, oppervlaktekwaliteit en het gewicht te evalueren. PLA was eenvoudig te printen, maar te stijf voor gebruik als prothese. TPU had betere flexibiliteit maar vereiste zorgvuldige verwijdering van supports. Siliconen 3D printen bleek technisch complex en slechts één volledige print kon worden voltooid voor de deadline. Toch leverde dit waardevolle inzichten op over materiaalgedrag en ondersteunde het verdere ontwerp.

De resultaten toonden aan dat het massieve PLA-model 66 g woog, terwijl modellen met 15% vulling of Voronoi-structuren tussen de 3 en 24 g wogen. Dunnere Voronoi-structuren waren fragiel, terwijl gyroid- en lattice-patronen een beter evenwicht boden tussen gewicht en stevigheid. TPU-modellen waren flexibel, maar moeilijker schoon te maken vanwege interne supports. Siliconen bood het meest realistische gevoel, maar bracht ook technische uitdagingen met zich mee op het gebied van slicen, supportstructuren en nabewerking.

Wat betreft 3D scanning was het doel om patiënten zichzelf te laten scannen met behulp van mobiele apps. Ondanks duidelijke instructies en tests met vier apps bleken de

ingediende scans van deelnemers niet bruikbaar. Veelvoorkomende problemen waren verkeerde bestandsformaten, beperkte exportopties en slechte scankwaliteit door bewegingsonscherpte, onvolledige dekking of slechte belichting. Deelnemers gaven ook aan moeite te hebben met het zelfstandig scannen van hun borstgebied. Daarom werd het ontwerp voortgezet met een scan uit het eerder cocreatie project die al was geïntegreerd in de code.

Om de scankwaliteit te verbeteren werd een professionele scansessie georganiseerd bij Anita Dr. Helbig GmbH. Twee 3D scanners (Artec EVA en Spider II) werden gebruikt om een borstmodel te scannen. Na schoonmaak in Blender en Rhino werden de scans gebruikt voor spiegeling, symmetrie en oppervlakextractie. De EVA-scanner leverde de beste resultaten op en maakte hoogwaardige anatomische modellering mogelijk binnen de digitale workflow van de prothese.

Gebruikersfeedback werd verzameld via expertinterviews, cocreatiesessies en informele consultaties. De MoSCoW-methode werd gebruikt om ontwerprioriteiten vast te stellen. Belangrijke ‘Must Have’-eigenschappen waren een lichte, comfortabele, anatomisch correcte prothese die zacht, waterbestendig en onzichtbaar onder kleding is. ‘Should Have’-eigenschappen richtten zich op esthetiek, vervangbaarheid en ademende materialen. De afneembare tepel werd positief ontvangen door experts bij Anita en beschouwd als een praktische oplossing om supports te kunnen verwijderen.

Tot slot werd een materiaalstudie uitgevoerd om geschikte siliconen te identificeren voor 3D printen. Samples van Lynxter SIL-001 werden getest. De student bracht een bezoek aan printerfabrikant OMD 3D en verzamelde technische informatie over extrusiegedrag, printinstellingen en onderhoud. Ook een bezoek aan de Medica-beurs leverde nuttige contacten op met potentiële leveranciers. Hoewel een volledige vergelijkende materiaalanalyse door tijdsgebrek niet kon worden uitgevoerd, legde dit werk een sterke basis voor toekomstig onderzoek met gecertificeerde medische siliconen.

V. DISCUSSIES

Dit hoofdstuk reflecteert op de belangrijkste bevindingen van deze thesis en hun implicaties voor de ontwikkeling van externe 3D geprinte borstprothesen. Het onderzoek toont aan dat de integratie van 3D printen, parametrisch modelleren en cocreatie kan bijdragen aan het ontwerp van meer gepersonaliseerde, lichtgewicht en comfortabele prothesen voor vrouwen die geen borstreconstructie ondergaan.

Een belangrijke uitkomst was het testen van verschillende perforatiestructuren om het gewicht van de prothese te verminderen. Hoewel interne perforaties het gewicht aanzienlijk verlaagden, gingen ze vaak ten koste van de stevigheid en stabiliteit van de prothese. Daarentegen bood het aanbrengen van perforaties uitsluitend aan het buitenoppervlak een betere balans tussen gewichtsreductie en structurele integriteit. Deze bevinding vormt een duidelijke ontwerprijtlijn voor toekomstige prototypes die zowel comfort als functionaliteit willen verbeteren.

Een andere belangrijke bijdrage was het gebruik van Grasshopper, een parametrisch ontwerptool geïntegreerd in

Rhino. Hoewel het script nog niet volledig geoptimaliseerd was, maakte het vroege personalisatie op basis van 3D scangegevens mogelijk. Parameters zoals de externe vorm, interne structuur en een afneembare tepel werden in het script verwerkt, wat illustreert hoe parametrische tools het ontwikkelingsproces van gepersonaliseerde medische hulpmiddelen kunnen versnellen en flexibiliteit in het ontwerp mogelijk maken.

Het ontwerpproces werd gevoed door input uit cocreatiesessies, expertinterviews en samenwerking met het borstzorgbedrijf Anita. Een MoSCoW-analyse hielp bij het prioriteren van gebruikersbehoeften, waarbij comfort, een veilige pasvorm, een natuurlijke vorm en discretie onder kleding als essentiële eigenschappen naar voren kwamen. Deze prioriteiten werden rechtstreeks vertaald in het ontwerp van de prothese, waarmee werd aangetoond dat technische ontwikkeling zinvol gestuurd kan worden door gebruikersgerichte inzichten.

De thesis behandelde zeven deelvragen en benadrukte het belang van zachte, huidvriendelijke materialen en de praktische voordelen van perforaties aan het oppervlak. Hoewel medisch gecertificeerd siliconenmateriaal door technische beperkingen niet getest kon worden, bevestigde het onderzoek het belang van personalisatie en comfort. Expertinput diende als waardevol alternatief voor gebruikerstests, en de benchmarkanalyse toonde aan dat huidige commerciële opties vaak tekortschieten op het gebied van aanpasbaarheid en personalisatie.

Desondanks kende de thesis enkele beperkingen. Testen met echte gebruikers was niet mogelijk door de beperkte kwaliteit van zelfscans en tijdsdruk. Slechts een beperkt aantal prototypes werd geprint en de slicing-software vormde een gebruiksvriendelijke uitdaging. Regelgevingsaspecten werden niet volledig behandeld.

Toekomstig onderzoek zou zich moeten richten op hogere kwaliteit van scans, het testen van gecertificeerd medisch siliconen en het betrekken van gebruikers via scenario-gebaseerde testmethoden. Het optimaliseren van printinstellingen en het uitbreiden van cocreatie met diverse deelnemers zal de resultaten verder verbeteren. Een veelbelovende ontwerpstrategie is de verdere ontwikkeling van perforatiestructuren uitsluitend aan het oppervlak, die mogelijk beter printbaar zijn en meer comfort en ademend vermogen bieden.

VI. CONCLUSIES

Deze masterproef onderzocht hoe 3D printen het ontwerp van lichtgewicht externe borstprothesen kan verbeteren, met een focus op het voldoen aan medische vereisten en het verhogen van het draagcomfort. Door benchmarkanalyse, cocreatie, parametrisch modelleren met Grasshopper en fysieke prototyping te combineren, werden nieuwe ontwerp mogelijkheden onderzocht. Het overkoepelende doel was het creëren van een prothese die lichter, persoonlijker en comfortabeler is voor vrouwen die geen borstreconstructie ondergaan of hiervoor niet kiezen.

Het onderzoek bevestigde dat 3D printen aanzienlijke voordelen biedt voor de ontwikkeling van borstprothesen. Het maakt nauwkeurige personalisatie mogelijk op basis van

individuele anatomie, ondersteunt lichtgewicht ontwerpstrategieën en bevordert snelle iteratie via prototypering. Een van de belangrijkste innovaties was de integratie van perforatiestructuren om het gewicht van de prothese te verminderen. Wanneer deze alleen aan de buitenzijde werden toegepast, verlaagden ze het gewicht effectief terwijl vorm en stevigheid behouden bleven. Dit bood een ademend en comfortabel alternatief voor conventionele ontwerpen.

Een belangrijke technische bijdrage was de ontwikkeling van een functioneel Grasshopper-script. Hoewel het zich nog in een vroege ontwikkelingsfase bevindt, maakte het script parametrische aanpassing mogelijk op basis van 3D scangegevens. Het bood opties voor het aanpassen van de prothesevorm, locatie van openingen en interne geometrie. Deze flexibele aanpak biedt een veelbelovend fundament voor toekomstig ontwerp van gepersonaliseerde medische hulpmiddelen op maat van individuele gebruikers.

Naast de technische verwezenlijkingen benadrukte de thesis het belang van inzicht in gebruikersbehoeften. Via een MoSCoW-analyse en feedback van borstzorgprofessionals, 3D printspecialisten en vertegenwoordigers van het bedrijf Anita, werden belangrijke gebruikersvereisten geïdentificeerd, zoals zachtheid, een veilige en comfortabele pasvorm, een natuurlijke uitstraling en eenvoudige reiniging. Deze inzichten werden vertaald in het ontwerp, onder andere door een afneembare tepel en gladde buitenoppervlakken.

De benchmarkstudie toonde bovendien verschillende beperkingen aan van huidige commerciële prothesen, waaronder overmatig gewicht, beperkte personalisatiemogelijkheden en ongemak tijdens het dragen. De bevindingen suggereren dat 3D printen, in combinatie met cocreatie en slimme ontwerpsoftware, ergonomische en meer gebruiksgerichte oplossingen kan bieden.

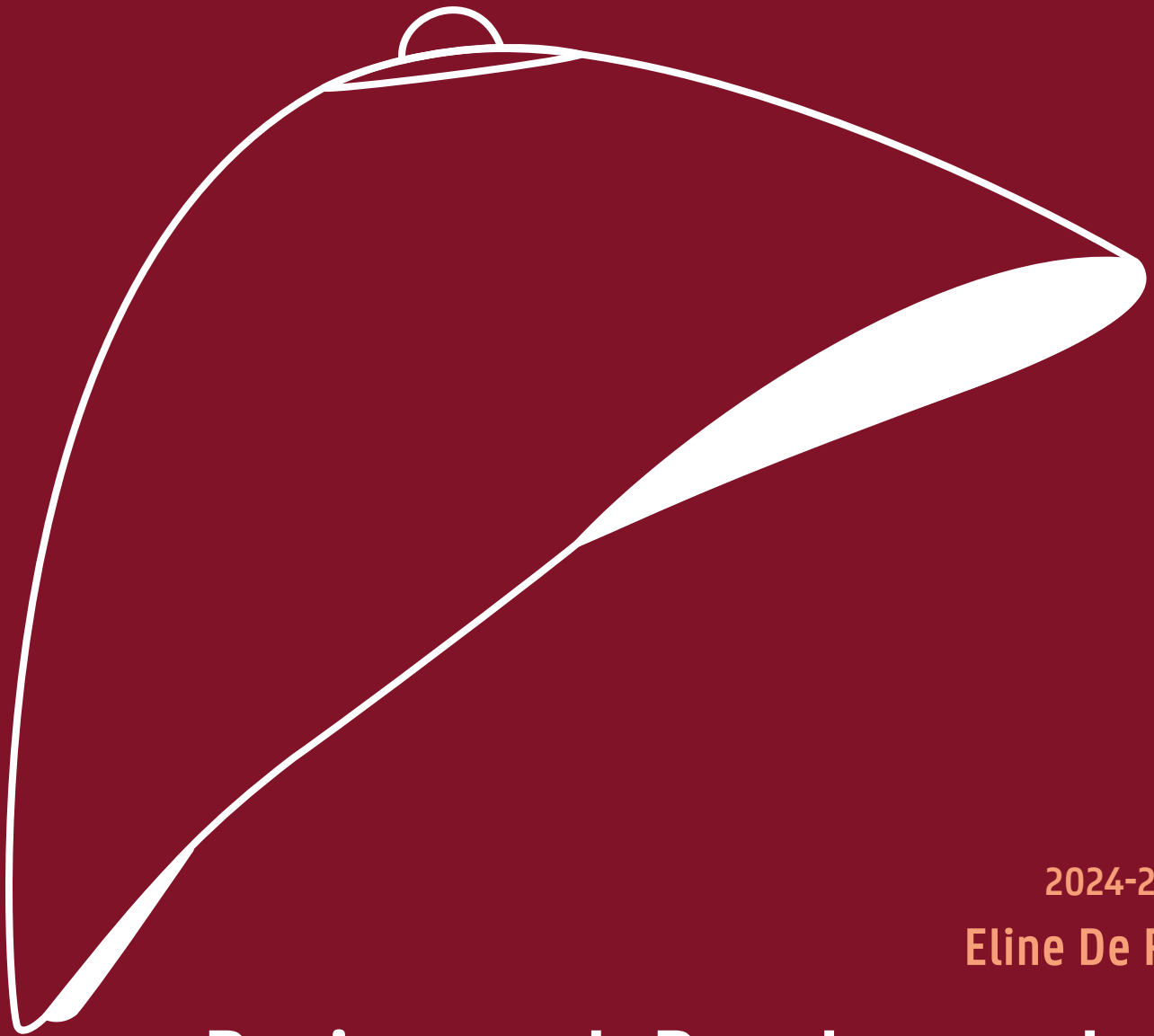
Het onderzoek kende echter ook beperkingen. Gecertificeerd medisch siliconenmateriaal kon door technische beperkingen niet worden getest. De slicersoftware was complex en printinstellingen werden niet volledig geoptimaliseerd. Daarnaast was het niet mogelijk om echte gebruikers te betrekken wegens de lage kwaliteit van zelfscans. Hierdoor blijven comfort- en bruikbaarheidsbeoordelingen hypothetisch en is verdere validatie nodig.

Ondanks deze beperkingen vormt deze thesis een sterke basis voor toekomstig onderzoek. Met verbeterde scantechnieken, gevalideerde materialen en klinische tests kunnen de in dit onderzoek ontwikkelde concepten bijdragen aan het creëren van inclusievere, veilige en emotioneel ondersteunende prothetische oplossingen.

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2024-2025

Eline De Roo

Design and Development of Custom-Made 3D Printed Breast Prostheses

A Multidisciplinary Approach Integrating Material Science,
3D Scanning, Product Design and Production Process

PREFACE

This master thesis is the final outcome of my studies in Industrial Design Engineering at Ghent University. The thesis was carried out during the academic year 2024–2025 and focuses on the development and optimization of 3D-printed external breast prostheses. Writing this thesis has been both a challenging and enriching experience, and I am truly grateful to everyone who supported me along the way.

I would like to express my sincere gratitude to my promotor, Dr. Ing. Lore Brosens, for her continuous guidance and constructive feedback throughout the entire process. Her critical insights and clear direction were invaluable to the structure and progress of this thesis.

I am also deeply thankful to my external supervisor Daniela Theil and the team at Anita Dr. Helbig GmbH for their openness, professional input, and ongoing support during our collaboration. Their contribution was essential in connecting this research to real-world industry practices and user needs.

Furthermore, I would like to thank my teacher, Ir. Yannick Christiaens, for his technical advice and support with the 3D printing process. Despite his busy schedule, I could always rely on his expertise and willingness to help.

Special thanks also go to the 16 patients who agreed to participate in this study. Although the planned tests could not take place, their willingness to contribute is sincerely appreciated.

I would also like to acknowledge the use of ChatGPT [1] for language support and writing assistance throughout the development of this thesis. Additionally, ChatGPT was used to generate examples of research questions during the early stages of the research process.

Lastly, I want to thank my family and friends for their endless encouragement and support throughout my studies.

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22 May 2025

EXPLANATION REGARDING THE MASTER THESIS AND THE ORAL PRESENTATION

This master's dissertation is part of an exam. Any comments formulated by the assessment committee during the oral presentation of the master's dissertation are not included in this text.

ABSTRACT

In recent years, the interest in 3D printed medical products has grown significantly. This master thesis focuses on the development of custom-made external breast prostheses using 3D printing technology. Traditional prostheses are often heavy, uncomfortable, and lack personalization. This study aims to explore how 3D printing can improve comfort, fit, and emotional support for breast cancer survivors who wear external prostheses.

To achieve this goal, a design process was followed that included benchmarking 32 existing prostheses from well-known brands, identifying user needs, and developing parametric 3D models using the visual programming software Grasshopper. Cocreation methods and feedback from experts and industrial partners (Anita Dr. Helbig GmbH) were used to define a clear Program of Requirements.

Several prototypes were printed using FDM technology and evaluated for shape, material, and weight. Special attention was given to hole structures, which were tested to reduce the weight of the prosthesis while keeping the necessary comfort and durability. Although some tests with patients could not be completed, 16 participants were willing to be involved in the study.

The Grasshopper code made it possible to generate fully personalized prosthesis models based on 3D scan data. While silicone printing and direct user testing were limited due to time and technical constraints, the research shows promising results for future applications in medical design.

This thesis forms a strong basis for further development in the field of digital prosthetics, aiming to make external breast prostheses more comfortable, inclusive, and adapted to the needs of individual users.

Keywords: breast prosthesis, 3D printing, customization, cocreation, Grasshopper

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1 INTRODUCTION

1.1 Context

Breast cancer is a type of cancer that starts in the cells of the breast, most commonly affecting women. It is one of the most common types of cancer in women worldwide and the number of cases is increasing [2], [3], [4]-[5]. In 2020, the International Agency for Research on Cancer (IARC) of the World Health Organization shared a report about cancer around the world. This report provides information on cancer cases, mortality and trends for 36 types of cancer across 185 countries [3]. It showed that breast cancer in women is now the most frequently diagnosed cancer, surpassing lung cancer. There were about 2.3 million new cases, which is 11.7% of all cancer cases [2], [3].

Advancements in diagnostic and treatment methods have significantly reduced the mortality rate of breast cancer patients, with a five-year survival rate now over 80% [6], [7]. Current breast care treatments involve a multidisciplinary approach, including surgical intervention, chemotherapy, radiation therapy, targeted drug therapy and hormonal drug therapy [8], [9], [10], [11], [12]. Among these, surgical procedures such as modified radical mastectomy (complete breast removal with axillary lymph node dissection) or simple mastectomy remain common in clinical practice [13], [14], [15]. Many patients still choose to undergo mastectomy on the affected side to prevent or reduce the chances of breast cancer recurrence [16].

Being diagnosed with breast cancer is a life-altering experience that often brings a wave of intense emotions. For many, the initial reaction is shock and disbelief, as they struggle with the uncertainty of what lies ahead [14], [15], [17]. Feelings of fear and anxiety are common, driven by concerns about the progression of the disease, treatment outcomes and potential changes to their body and lifestyle. This emotional distress can be aggravated by the pressure of making urgent medical decisions, often leaving patients feeling overwhelmed and emotionally drained [14], [15].

Throughout the journey, the emotional well-being of patients is deeply influenced by the physical and psychological challenges they face. Treatments such as surgery, chemotherapy and radiation can significantly impact body image and self-esteem, particularly if they involve visible changes like hair loss or mastectomy. Research highlights that patients who undergo total mastectomy often experience higher levels of depression compared to those choosing for breast reconstruction, emphasizing the importance of cosmetic outcomes on quality of life [18], [19]. Additionally, breast cancer in younger women can pose unique emotional challenges, as they often face concerns about fertility, relationships and long-term health [11]. Despite these challenges, many patients find resilience and strength through support networks and a focus on emotional self-care [20], [21]. Access to counselling, peer support groups and therapy provides a safe space for patients to process their emotions and connect with others who share similar experiences [15].

An ideal treatment strategy for breast cancer seeks to eliminate the disease while preserving the breast's natural form, thereby improving the patient's quality of life. This underscores the importance of breast prostheses in restoring a natural appearance and enhancing comfort. However, existing prosthetic options often fall short of meeting users physical and emotional needs, emphasizing the necessity of innovation and optimization in prosthetic design, as demonstrated by the comparative findings in Chapter 2, Section 2.2 Benchmark study .

Traditional breast prostheses often present significant physical challenges. Many models weighing between 200 to 400 grams, which can cause discomfort and strain, particularly for individuals with smaller body frames. Materials such as silicone or foam, are not breathable, leading to heat and moisture buildup, that aggravates discomfort during long periods of wear. Furthermore, the lack of personalized fit in many prostheses leaves users dissatisfied, as they often struggle to find options that accommodate their unique anatomical features. This lack of customization can hinder daily activities and significantly affect overall quality of life.

The emotional burden created by conventional breast prostheses goes well beyond their physical weight. During last year's cocreation project the women repeatedly stressed that the true limiting factor is the lack of availability: in a typical bandagist's shop only 10-15 models are considered "good enough" to sell, leaving most survivors with very few options and much frustration. One participant captured the feeling poignantly: "There are twice as many breasts on this earth as there are women," underscoring how limited choice erases individuality and fuels dissatisfaction [22].

Even when a form is available, its generic geometry rarely fits well. Prof. dr. Philip Blondeel confirmed in our expert session that many women—especially those with a larger cup size—describe standard silicone forms as too heavy and uncomfortable. Carrying that weight every day erodes self-confidence, intensifies body-image worries, and can slow psychological healing. These findings show that the problem is not merely cosmetic; it is emotional estrangement caused by devices that neither look nor feel like "their" breast [22]. A more personalized approach could not only enhance physical comfort but also restore a sense of normalcy and confidence, supporting both physical and emotional recovery [23], [24], [25].

Emotional recovery is a crucial part of the healing journey for breast cancer survivors, as it involves regaining confidence, self-esteem and a sense of identity after significant physical and emotional changes. The loss of a breast can deeply affect how individuals view themselves, impacting their body image and overall well-being. Personalized breast prostheses can play a vital role in this process by offering a solution that aligns with the wearer's unique anatomy and aesthetic preferences, helping them feel more like themselves again. By addressing both physical comfort and emotional needs, innovative prosthetic designs can foster a sense of normalcy and support survivors in reclaiming their lives with confidence.

1.2 Cocreation

This master thesis expands upon a previous project initiated as part of the course cocreation, which focused on utilizing 3D printing to support breast cancer survivors [22]. The original project aimed to address the physical, emotional and aesthetic needs of individuals who had undergone mastectomies, with an overarching goal of developing personalized solutions that help survivors regain their confidence and comfort. A defining feature of the project was its collaborative nature, involving breast cancer survivors in every step of the design process to ensure the resulting products were both practical and aligned with their personal preferences.

The project initially involved two groups of students, including participants from an Erasmus program, who worked independently during the first semester to explore different concepts. One group focused on improving bra fit and functionality using 3D scanning technology, while the other concentrated on designing customized breast prostheses through 3D printing. Both teams engaged in cocreation sessions with survivors, whose input played a critical role in shaping the direction of the designs. In

the second semester, the two groups were combined (excluding Erasmus students), allowing them to merge their efforts and create a unified solution by drawing on the strengths of their earlier work.

Toward the end of the second semester, professors overseeing the course invited students to continue the project as a master's thesis. This led to networking efforts through established contacts, culminating in a collaboration with Anita Dr. Helbig GmbH, a company specializing in breast prostheses for post-mastectomy patients. A presentation to six company representatives outlined the project's progress and laid out a vision for future development, establishing a framework for further research and refinement of the concept.

1.3 Research gaps

The combination of academic literature and benchmarking from current prosthetic companies shows there is still a big gap in the development of external breast prostheses that combine modern design methods with true user customization. Important areas of customization include more colour options, weight reduction using internal hole structures, a better surface texture for aesthetic appearance, and personal shape based on 3D body scans.

Based on academic research, 3D printing (also called additive manufacturing) is changing the healthcare sector by making it possible to create complex shapes and fully personalized medical products [26], [27]. While there has been a lot of progress in 3D printing methods like FDM, SLA and SLS, and even new techniques like silicone 3D printing, these are mainly used for internal implants. The potential of 3D printing for external breast prostheses is still not well explored. 3D printing makes it possible to use materials like silicone or thermoplastic polyurethane (TPU) to improve fit, reduce discomfort and make users more satisfied with their prosthesis. Lightweight designs, such as Voronoi structures, also give more breathability and comfort for long wear times.

An analysis of the main market leaders Anita, Amoena, ABC, Trulife, EVE and Hashtagtwo shows that each company offers different types of innovations in their breast prostheses, but also that there are still important limitations. These insights are summarised in five benchmark tables available on the Miro board. The tables evaluate seven key criteria—comfort, fit, aesthetics, attachment system, suitability for activities, material, and weight—which together encompass the full spectrum of a wearer's daily experience. Comfort and fit determine whether the form can be worn for hours without pain or skin irritation; aesthetics shapes body image and confidence; the attachment system governs security and ease of use; performance across different activities dictates how well the prosthesis integrates into daily life, from office work to swimming; the underlying material affects breathability, durability and allergen risk; and finally weight influences shoulder strain and long-term musculoskeletal health. By comparing each company across these interconnected factors, this analysis highlights their respective strengths and, just as importantly, reveals the persistent gaps that still need to be addressed.

Anita, for example, focuses on lightweight prostheses and has special products for activities like swimming or sports [28]. Their solutions are simple and easy to use, but mostly follow a standard form and have limited options for skin tone or aesthetics. Amoena introduces more technical features, such as adjustable air chambers for volume and pressure control, and adhesive backs for improved stability [29]. While these innovations enhance adaptability, most of their products are still based on standard sizes—though the company does also offer custom-made prostheses.

Trulife stands out because they offer handmade custom prostheses through the Radiant Impressions line [30]. They also use cooling materials and soft silicone to increase comfort [31]. However, these prostheses are not available everywhere and the production process is time-consuming. ABC has a very broad collection with different sizes, forms, and even custom-made options. Their prostheses use soft and lightweight silicone and offer extra comfort through different back shapes and materials [32]. But even with many models, the range is still limited for users with unique body shapes or skin tones.

EVE and Hashtagtwo are companies that work with 3D printing technologies to make custom breast prostheses. Both companies use a 3D scanner or a mobile app to scan the chest of the user and collect the data for a personalised fit. Based on this scan, a custom prosthesis is made. They also offer several visual personalisation options, such as choosing the skin tone or nipple shape.

There is a difference in how they use 3D printing. EVE prints the moulds of the prosthesis with 3D printing and then uses silicone casting to make the final product. In contrast, Hashtagtwo prints the whole prosthesis directly with silicone 3D printing [33]. Hashtagtwo also focuses on circular design with material re-use [34].

These companies show the possibilities of using new technology for better personalisation and comfort. However, they are still small companies. Their services are not yet available for a large group of users, and the prices are still high. This makes it difficult for many people to access their products.

Based on this visual comparison in the Miro board ([Master Thesis Eline De Roo - Miro](#)), It may be concluded that while some brands innovate in fit, others focus more on aesthetics, or comfort. But no brand fully combines all these aspects in a single, affordable and widely available solution. Many products still come in standard sizes and shapes, are heavy or uncomfortable, and do not look realistic enough under clothing. The prostheses often have a short lifetime and high cost, and the amount of personalisation is limited, especially for partial prostheses.

These conclusions from the benchmark analysis will be discussed in more detail later in this thesis. The visual comparison helps to make the differences visible and to understand where current solutions fall short and where new design opportunities are possible.

Traditional breast prostheses often make these problems worse. They are too heavy and not breathable. Many users experience pain, shoulder strain, sweating and dissatisfaction during wear [35], [36], [37]. Silicone gel, the most used material, adds to discomfort especially during summer or when exercising. Most women can only choose from 10 to 15 standard prosthesis designs, which don't fit all bodies or emotional needs [25], [36].

Partial prostheses, which are becoming more important due to more breast-conserving surgeries, are also not well developed. The sizes are limited, the shapes are often unnatural, and they don't always fit well or feel secure. According to a cocreation session in 2024 with plastic surgeon Prof. dr. Philip Blondeel [22], there is a strong need for lighter, better-fitting and more realistic options to support women's comfort and emotional healing.

Until now, research on 3D printing and research on external breast prostheses have mostly been done separately. Combining these two areas can offer new possibilities to meet users' needs. This raises several important questions that are still open.

For example:

- Can prostheses be both lightweight and realistic in feel and look? Does making them lighter always make them feel less real, or can better materials solve this?
- Are current materials strong enough for daily use? Can they resist sweat, movement, and frequent washing? How do they age over time?
- Are prostheses easy to clean and do they stay hygienic, or do they start to smell and collect bacteria after a while?
- Are there enough shape and size options for all kinds of bodies? Do the materials avoid allergic reactions or irritation, especially for sensitive post-surgical skin?
- Do the prostheses stay in place during walking, sports or daily activities?
- Do they feel breathable and soft enough for long-term wear?
- And lastly, do they look natural under clothes, also when wearing tight or light fabrics?

These are all open research questions and show that there is still a lot to improve. This thesis will focus on exploring these topics through cocreation and iterative testing with people with lived experience and people with lived expertise [38].

1.4 Research question

Before arriving at the research question, it is important to fully understand the problem and challenges involved. A strong research question must meet certain criteria. According to principles taught in the course “academic writing” and Farrugia et al. (2010), a good research question consists of three essential components: the domain, the outcome measure and the determinant [39]. The domain defines the general context of the research and sets the scope within a specific field. The outcome measure refers to the intended results or goals of the research. The determinant is the specific factor being studied to understand its impact on the outcome measure [39].

According to Hulley et al. (2013) and Creswell (2014), a strong research question should be complex enough to require thoughtful analysis and the generation of new knowledge, while also meeting key standards of relevance and quality by avoiding questions that can be easily answered with existing information [40], [41]. Furthermore, the question needs to be researchable, meaning that the required data and analysis can be completed within the constraints of available time and resources [40]. Finally, the question must have a well-defined purpose and be phrased clearly, often starting with terms like “how,” “what,” or “why,” to provide focus for the study and ensure that the results are relevant and actionable [40].

The main research question guiding this study is: *How can 3D printing technology be used to optimize the design of lightweight external breast prostheses to meet medical standards and user comfort?* To answer this question, seven sub-questions have been formulated to explore the topic in depth:

1. Which materials can be used in 3D printing to ensure that breast prostheses remain lightweight, durable, safe and comfortable for users?
2. What infill percentage, layer height, print speed, bed/chamber temperature and curing time should be used to ensure that the prostheses are safe, comfortable, lightweight and durable for users?
3. What design innovations, such as hole structures or lattice designs, can reduce the weight of 3D printed prostheses?
4. What types of personal preferences (e.g., shape, weight, texture) can be incorporated into 3D printed prostheses?
5. How can user feedback (e.g., from breast cancer survivors) be integrated into the design optimization process?
6. What insights can be drawn from the characteristics of breast prostheses from benchmarks to optimize the design of 3D printed breast prostheses?
7. How can a Grasshopper code be used to create a personalized prosthesis model?

The research question in this study satisfies the criteria for good research question. The domain is 3D printing technology. The outcome measure is achieving medical standards and user comfort. The determinant is the design of lightweight external breast prostheses. Together, these elements ensure the question is focused, purposeful and appropriately challenging for an academic thesis [39], [41].

Link between hypotheses and Program of Requirements (PoR)

The hypotheses serve as the foundation for evaluating whether the prosthesis design meets the requirements defined in the PoR (Table 14). Each hypothesis corresponds to one or more specific requirements, ensuring a focused and evidence-based development process.

Hypothesis 1: Medical-grade silicone 3D printing ensures high precision and efficient production.

- **Linked to R14:** Silicone 3D printing must be used to ensure efficient production and high precision. This supports efforts to reduce prosthesis weight while maintaining necessary strength and internal ventilation.

Hypothesis 3: Hole structures reduce overall prosthesis weight and improve breathability.

- **Linked to R13 & R10:** The use of hole-based structures supports both weight reduction and increased breathability, contributing to overall comfort.

Hypothesis 4: Soft, skin-like textures and anatomically accurate shapes increase user satisfaction and comfort.

- **Linked to R2, R5, R11:** Anatomical conformity and natural appearance promote body image satisfaction; surface must be smooth and irritation-free. This hypothesis validates user-centered design through both visual and tactile performance.

Hypothesis 5: Iterative prototyping and user feedback improve customization and accessibility.

- **Linked to R12, R15, R16:** Supports full customization through 3D scanning, enables self-scanning, and allows digital storage and modification for iterative improvements. These features enhance personalization and accessibility.

Hypothesis 6: A well-designed prosthesis can support physical activity and long-term durability.

- **Linked to R7, R8, R9:** The prosthesis should be suitable for sports and water use, support moderate physical activity, and maintain performance over a lifespan of at least two years. This links functionality with long-term reliability.

Hypothesis 7: Integrating Human UI in Grasshopper facilitates optimization of internal structures and surface features.

- **Linked to R17 & R18:** Supports the development of functional surface textures (grip, anti-slippage) and internal structural optimization for weight and durability. This ensures the parametric design environment directly enhances product performance.

Each hypothesis contributes to validating one or more core requirements in the PoR. Together, they provide a structured research framework that aligns technical feasibility with user expectations, ensuring that the final product meets both functional and emotional needs.

1.5 Purpose & goal

This research aims to develop a final proof-of-concept breast prosthesis using a personalized design system built with Grasshopper. By integrating inputs such as 3D scans and hole structures, the

system will enable customized prostheses. Alongside the design tool, the project will produce multiple 3D printed prototypes for testing.

The goal is to create lightweight, functional and user-specific prostheses that address both physical and emotional needs. By employing advanced 3D printing and a cocreation approach, this work seeks to improve the quality of life for breast cancer survivors and advance innovation in prosthetic design. Key materials and 3D printing parameters, such as print speed, layer height, infill density and curing time, will be refined using a silicone printer to ensure optimal comfort, safety and functionality.

A cocreation design approach is chosen because it actively involves users, specifically breast cancer survivors, in the development process, ensuring that the prostheses meet their unique preferences, comfort requirements and aesthetic desires. This collaborative method fosters empathy-driven innovation, leading to more personalized and meaningful solutions that not only restore physical balance but also support emotional well-being. By integrating user feedback throughout the design and testing phases, the resulting prostheses are more likely to align with real-life needs and enhance user satisfaction.

Beyond technical improvements, this research focuses on enhancing comfort, personalization and affordability. By incorporating user feedback and leveraging efficient 3D printing processes, the project aims to offer high-quality, accessible prostheses that reduce costs and manufacturing complexities, making them available to a broader range of users.

1.6 Structure thesis

The structure of this research thesis reflects a clear and organized flow [42], [43]. The abstract provides a brief overview of the study, outlining its objectives, methodology and key findings. The introduction offers background information and highlights the significance of the research. The state-of-the-art section reviews existing solutions and technologies in the field of breast prostheses. The methods section describes the research process, including the design and testing of prototypes. The results section presents the findings, while the discussion interprets these results and their implications. Finally, the conclusion summarizes the key takeaways and their significance and the references section lists all sources consulted throughout the research.

2 STATE OF THE ART

The development of external breast prostheses has improved a lot in recent years, but many problems are still not solved. Traditional prostheses are helpful for women who have had a mastectomy, but they often cause discomfort and do not fit well. They are also heavy and their appearance does not always feel natural. Additionally, because they are expensive to make, most products do not offer enough personalization or accessibility for many women.

With the introduction of new technologies like 3D printing and 3D scanning, there is a chance to create better prostheses. These technologies can help produce lightweight, fully personalized and cheaper prostheses that better meet the needs of users. They can improve both physical comfort and emotional well-being by offering solutions that are more tailored to individual preferences.

This chapter looks at the current state of external breast prostheses, including traditional products and new technologies. It compares existing prostheses from well-known manufacturers and discusses findings from visits to Anita's headquarters. In addition, it explains how advanced technologies like 3D printing, 3D scanning and design tools such as Grasshopper can help solve current problems.

The results of this chapter will be used to create a detailed Program of Requirements (PoR), which will guide the development of improved 3D printed breast prostheses. By focusing on both technical and emotional needs, this research aims to provide breast cancer survivors with prostheses that are more comfortable, affordable and suited to their personal needs.

2.1 Existing solutions breast cancer

External breast prostheses, typically made from silicone or foam and worn inside a bra, have long been the standard for individuals who have undergone mastectomy. However, these prostheses present several challenges that persist today. One primary concern is discomfort. Many users report discomfort due to the heavy and often poorly fitted nature of these prostheses. The weight, bulkiness and rigidity of traditional options contribute to an unnatural and restrictive experience. For many women, these discomforts undermine confidence, limit mobility and negatively impact their overall quality of life. The constant need to adjust and endure these limitations can lead to frustration and a reduced sense of normalcy.

Traditional external breast prostheses often pose challenges such as weight and inflexibility, leading to significant physical discomfort. Research highlights that these prostheses can cause shoulder strain, a common issue for survivors [35], [37]. Survivors have limited options, typically between 10 to 15 sizes, making it difficult to find a prosthesis that provides a natural fit and feel [36]. The need for customized solutions becomes apparent when considering the diverse anatomical variations among women, as noted in a cocreation session in 2024 with a patient: "There are twice as many breasts on this earth as there are women." This issue is especially pressing for partial prostheses, which remain underdeveloped despite the growing popularity of breast-conserving surgeries [36].

The growing prevalence of breast-conserving surgeries, which now account for 65% of all breast cancer surgeries, has further highlighted the need for partial breast prostheses. Unfortunately, the market offers few options for partial prostheses and these often come with numerous shortcomings. Poor fit, limited sizes and lack of stability are common complaints, leading to physical discomfort and a compromised sense of security.

A significant limitation of traditional prostheses is the reliance on silicone gel, which is both heavy and poorly breathable. These properties exacerbate discomfort, especially during prolonged wear or activities involving sweating [35], [37]. Despite the daily, long-term use required by most survivors, lightweight and breathable alternatives remain limited, highlighting the urgent need for innovation in comfort, flexibility and personalization.

Another gap in current prostheses is the lack of diversity in product designs and shapes. Women come in various body types and sizes, yet many prostheses are made with limited shapes and sizes in mind. This leads to dissatisfaction as many women struggle to find prostheses that match their body contours while feeling natural and supportive. The limited range of sizes and the difficulty in keeping prostheses securely in place contribute to discomfort and insecurity. In addition, the unnatural contours of existing designs often fail to restore a sense of normalcy and self-confidence.

Accessibility and cost also present significant challenges. Custom-made options are often prohibitively expensive, leaving a large portion of the population without viable alternatives. The financial burden, coupled with issues such as excessive weight and lack of personalization, contributes to emotional dissatisfaction. Standardized prosthetic designs often fail to address physical and emotional needs, leading to body image dissatisfaction and negatively impacting self-esteem and confidence [25], [44]. Survivors emphasize the need for solutions that promote comfort and natural aesthetics to aid their healing journey [24].

The emotional aspect of wearing a prosthesis is as important as its technical functionality. For many survivors, the ability to feel their physical form reflects their true identity is critical to their well-being. Poorly designed prostheses can hinder recovery and exacerbate feelings of inadequacy or frustration. Women deserve prosthetic options that prioritize both physical comfort and emotional well-being. Addressing these gaps requires innovative, customizable and cost-effective solutions that empower women and enhance their quality of life. Bridging the gap between current offerings and actual needs fosters greater confidence, comfort, and dignity.

Breast implants provide a more permanent alternative to external prostheses, offering a surgical solution for women who wish to restore their breast volume following mastectomy or other breast-related surgeries. However, they come with several notable risks and considerations. The implantation process is invasive and requires surgery, which can lead to complications such as infections, scarring, implant ruptures and the need for revision surgeries over time. These complications often necessitate further medical interventions, including additional surgeries for implant replacements, typically occurring every 10 to 15 years, depending on the type of implant and individual health factors. The possibility of these complications and the need for multiple surgeries throughout a woman's lifetime can act as significant deterrents, particularly for those who prioritize less invasive or non-surgical options. Additionally, some women may be concerned about the long-term implications of having implants, such as the potential for implant-associated illnesses, autoimmune responses, or complications related to aging implants. The physical and emotional toll of undergoing multiple surgeries, along with the associated financial costs, can discourage many from pursuing this option. For women who seek alternatives that minimize the need for ongoing medical intervention, the risks associated with implants present a considerable drawback, particularly for those who value non-invasive or less risky options in their decision-making process.

Link to the Program of Requirements (PoR):

Table 1: Requirements existing solutions

Requirement ID	Description	Measurement Method	Validation Method	Unit	Success Criteria
R1	The prosthesis must be lightweight for daily wear comfort.	Weight measurement	Comparison with average commercial prostheses	g	≤ 200g for full prosthesis
R2	The prosthesis must closely match the patient's anatomical contours.	3D scan comparison (pre-op/post-op if applicable)	User feedback, clinical fit evaluation	% Fit accuracy	≥ 90% anatomical conformity
R3	Must be made from skin-friendly, breathable materials.	Material testing (ISO 10993)	Dermatological evaluation, user testing	Qualitative	No irritation in 95% of test users
R4	The prosthesis must be cost-effective without compromising quality and usability.	Cost analysis per unit	Comparison to industry standards	Euro (€)	≤ market average for similar products
R5	The prosthesis must promote body image satisfaction by closely replicating the natural appearance of the breast.	Visual comparison with natural breasts	Expert review and user satisfaction	Visual appeal rating	85%+ users rate as natural appearance

2.2 Benchmark study

The commercial market for external breast prostheses is led by several well-established manufacturers, including Anita, Amoena, Trulife and ABC. These companies offer a wide range of products designed to meet various physical, medical, and lifestyle needs. This benchmark study focuses on a selection of 32 prostheses, including seven from Anita, seven from Amoena, nine from Trulife, and nine from ABC. The selection includes various types of prostheses, ranging from postoperative models to sport-specific and water-friendly prostheses. While not exhaustive, this sample provides a comprehensive overview of current trends, product features, and potential gaps in the market. The reasoning behind the selection criteria and product choices will be elaborated on in the accompanying text.

Anita

Anita's product range includes a variety of prostheses that cater to different stages of recovery, lifestyle needs and personal preferences (Table 2). The company's offerings are known for their high-quality materials and emphasis on comfort and durability [28].

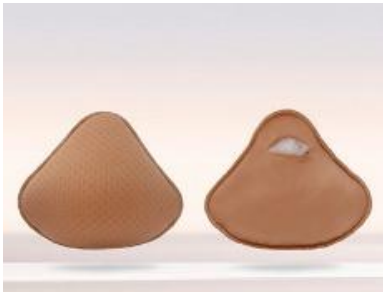


Figure 1: EquiLight 1018X

Anita's **EquiLight prosthesis 1018X** (Figure 1) is specifically designed for the immediate postoperative phase. This textile prosthesis is lightweight and soft, offering gentle support, which makes it particularly suitable for use during the early stages of recovery, especially at home. It was selected for this study as a representative example of classic post-operative prostheses due to its extremely light construction, soft materials, and cost-effectiveness. Importantly, textile prostheses are medically preferred during this phase, as silicone prostheses must not be worn on a freshly operated scar area. Silicone options are only

appropriate once the surgical site has fully healed. The EquiLight thus serves as a valuable reference point for evaluating immediate-care prostheses in terms of comfort and post-surgical suitability.



Figure 2: Velvety 1066X

The **Velvety model 1066X** (Figure 2), offers a more natural fit and appearance for everyday use. It combines comfort with a soft-touch surface that enhances wearability during daily activities. This model was chosen because it reflects Anita's standard full-weight prosthesis, with a Soft Touch film that makes it suitable for long-term use in everyday situations. It serves as the brand's core product for daily comfort and natural aesthetics.

For users seeking more advanced prosthetic features, Anita offers the **Softback 1050X** prosthesis



Figure 3: Softback 1050X

(Figure 33), which includes Flex-Gap Technology. This innovative design allows the prosthesis to move naturally with the body, adjusting dynamically to shifts in position. The Softback prosthesis is ideal for individuals with active lifestyles, as it minimizes discomfort by aligning with the body's movements. It is one of the few prostheses on the market with dynamic-movement capability, showcasing innovative Flex-Gap Technology.

Anita's **Sequitex Trapez 1045X** (Figure 44) is a multifunctional partial prosthesis designed to address mild breast asymmetry. It features a breathable microfiber backing and a skin-tone front, allowing it to blend naturally with the body while providing subtle contouring without compromising on comfort. This model is included in the study to represent the often under-served segment of women requiring discreet, partial correction rather than full-volume restoration. An added advantage of this textile-backed prosthesis is its adaptability—it can be individually customized by filling the back with medical fleece, allowing for personalized adjustment to the wearer's specific asymmetry.



Figure 4: Sequitex Trapez 1045X

For users with an active lifestyle, Anita offers two sport-specific models: the **Active Ocean 1086X** and the **Active 1054X** prosthesis.



Figure 5: Active Ocean

The **Active Ocean** (Figure 55), is particularly suited for swimming and other water-based activities, as it is designed to withstand both chlorinated and saltwater environments. Its ribbed design helps with water drainage, ensuring the prosthesis remains secure during aquatic activities. This model is selected to benchmark performance in water, combining chlorine and saltwater resistance with a structure that supports drainage and stability.



Figure 6: Active

The **Active** prosthesis (Figure 66), on the other hand, is optimized for general sports and physical activities such as running, yoga, or hiking. It includes a ventilated back and variable foam padding to ensure breathability and stability. This model was selected to illustrate how prostheses can support movement and comfort during high-motion situations, making it highly relevant for users with active lifestyles.

Anita's prostheses are easy to clean and many models can be worn symmetrically on either side, providing flexibility for users who need a prosthesis for both breasts. This adaptability increases user convenience and makes the products suitable for a broad range of personal needs and recovery stages.

Table 2: Benchmark Anita of commercial breast prostheses

Prostheses Characteristics	EquiLight 1018X	Velvety 1066X	Softback 1050X	Sequitex Trapez 1045X	Active Ocean 1086X	Active 1054X
Description	Postoperative	Full	Full	(Multifunctional) Partial	Swimming	Sport
Company	Anita	Anita	Anita	Anita	Anita	Anita
Comfort	Soft and light initial care and homewear	Soft Touch Softly structured back	Flex-Gap Technology Natural movement Falls smoothly against the body Weight reduction	Back made of breathable microfiber textiles	Suitable for thermal bathing, chlorine and salt water resistant	Suitable for sports activities
Fit	Can be worn on both sides Size: 60/65 - 110/115	Can be worn on both sides Enhanced fit	Can be worn on both sides Flex-Gap technology Falls smoothly against the body	Can be worn on both sides Variable padding with medicated fleece	Can be worn on both sides	Can be worn on both sides
Aesthetics	Skin colour Special layer on front prevents slipping in bra	Skin tone Velvety soft Ribbed design allows for proper water drainage and optimal airflow	Skin colour 2-layer technology	Skin colour Particularly thin flared shell edges for natural transition to skin	Transparent blue colour Ribbed design ensures proper water drainage and optimal airflow	Skin colour Ribbed design ensures proper water drainage and optimal airflow
Attachment system	Insert into the bra	Different wearing options	Insert into the bra	Insert into the bra	Insert into the bikini or swimsuit	Insert into the sport bra
Suitability for different activities	Initial care or daily use	Suitable for all conditions	Daily and sports use	Daily use	Swimming and other water activities	Sport activities

Maintenance and cleaning	Easy to clean with soap and water	Easy to clean with soap and water	Easy to clean with soap and water	Easy to clean with soap and water	Easy to clean with soap and water	Easy to clean with soap and water
Material type	Skin-friendly, breathable microfiber Individual padding with medicated cotton wool	SoftLite silicone gel	Soft standard gel on the back SoftLite silicone gel on the front	Special silicone gel Variable padding with medicinal fleece	Silicone gel	Silicone gel
Weight	Light	Up to 42% lighter than a full prosthesis	Up to 42% lighter than a full prosthesis	Light	Compared to comparable full prostheses up to 25% lighter	Compared to comparable full prostheses up to 25% lighter
Lifetime	Used until the wound is completely healed	Long term use with proper care	Long term use with proper care	Long term use with proper care	Long term use with proper care	Long term use with proper care

Amoena

Amoena's product line is renowned for its emphasis on comfort, fit and thermal regulation. Many of its prostheses are developed to address specific concerns such as heat buildup, lightweight wear, and achieving a natural look, offering solutions tailored to various user needs and situations [29].



Figure 7: Essential Light 2S

The **Essential Light 2S** (Figure 47Figure 7) and **Natura Xtra Light 2SN** (Figure 88) are full prostheses that prioritize comfort through lightweight construction and balanced shape. Both are made from Amoena's InTouch silicone, which is skin-friendly and offers a soft, natural feel. These prostheses are ideal for everyday wear, providing a well-balanced combination of comfort and aesthetics.



Figure 8: Natura Xtra Light 2SN

The **Essential Light 2S** was selected as an entry-level lightweight prosthesis, offering a cost-effective and reliable solution for daily use after mastectomy. In contrast, the **Natura Xtra Light 2SN** is one of the lightest full prostheses on the market—up to 40% lighter than standard silicone forms—making it a strong benchmark for assessing weight reduction strategies in breast prosthesis design.

Amoena's standout feature is the Comfort+® layer, which helps to regulate body temperature and prevent heat buildup, improving long-term wear comfort. This temperature-regulating material is based on phase-change technology: it absorbs excess body heat when the skin becomes warm and releases it again when the body cools down. As a result, it helps reduce sweating behind the prosthesis and maintains a more stable skin-prosthesis interface. This technology is integrated into models such as the **Energy Light 2S** (Figure 99) and the **Contact 3S** (Figure 100). The **Energy Light 2S** was included in the benchmark to evaluate thermal management strategies, since it allows for a more comfortable wearing experience during prolonged use or physical activity.



Figure 9: Energy Light 2S

The **Contact 3S** takes this feature a step further. In addition to Comfort+, it includes an adhesive back, allowing the prosthesis to be attached directly to the skin. This enables better weight distribution across the chest, improves stability, and enhances freedom of movement. It was chosen specifically to assess the performance of skin-direct adhesive systems, which are particularly important for active users and those seeking a more natural, integrated feel.

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Figure 10: Contact 3S

For users who have undergone breast-conserving surgery or experience mild asymmetry, Amoena offers the **Balance Natura Special Ellipse 231** (Figure 11). This partial shaper was selected because it addresses the need for subtle correction of asymmetry, offering a discreet and comfortable fit with a skin-tone finish that blends well under clothing.



Figure 11: Balance Natura Special Ellipse



Figure 12: Aqua Wave

In the category of swim prostheses, Amoena developed the **Aqua Wave** (Figure 122), a model specifically designed for use in water. It features a hollow back and wavy structure that allows water and air to flow through, preventing suction and enabling faster drying. This prosthesis was selected to represent Amoena's specialized aquatic solution, ideal for both pool and open-water swimming.

Overall, Amoena's range (Table 3) demonstrates how prosthesis design can be tailored to different stages of recovery and lifestyle requirements. From lightweight daily forms to advanced adhesive solutions and sport-specific designs, each model contributes uniquely to the overall benchmark of breast prosthesis innovation.

Table 3: Benchmark Amoena of commercial breast prostheses

Prostheses Characteristics	Essential Light 2S	Natura Xtra Light 2SN	Energy Light 2S	Contact 3S	Balance Natura Special Ellipse 231	Aqua Wave
Description	Full	Full	Full	Full	Partial	Swimming
Company	Amoena	Amoena	Amoena	Amoena	Amoena	Amoena
Comfort	Meet all the basic needs of breast care after mastectomy Comfort for natural symmetry Soft, natural contour and combines all our leading expertise with the latest materials	Very natural movement and wearing experience Comfort+ layer that regulates the temperature between the breast prosthesis and the skin - for less heat build-up and sweating behind the prosthesis Natural feel 30% more Comfort+ than other breast prostheses with Comfort+ (except Cosmetic prostheses)	Optimal air circulation and ventilation Comfort+ layer that regulates the temperature between the breast prosthesis and the skin - for less heat build-up and sweating behind the prosthesis Natural feel 30% more Comfort+ than Natura breast prostheses	Follows every movement of the body Chest wall bears the greatest weight of the breast prosthesis Relieves pressure on the shoulder and neck area More secure and confident	Soft prosthesis that embraces the body to fit the unique shape of the chest	Extra comfort while swimming
Fit	Symmetrical shape (can be worn on the left or right side) Balanced and comfortable fit	Symmetrical shape (can be worn on the left or right side)	Medium cup fit Gentle transition toward the upper chest wall where less volume is needed Symmetrical shape (can be worn on the left or right side)	Symmetrical shape (can be worn on the left or right side)	Rounded semicircle shape that can be placed anywhere on the chest and is suitable for the lower part of the cup Provide symmetry when you experience unevenness or asymmetry naturally	For a flat to medium fit Symmetrical shape (can be worn on the left or right side)

Aesthetics	Available in different skin colours	Available in different skin colours Ribbed design on the back	Skin colour Special 3D beads on the back Super soft film	Available in different skin colours Self-adhesive backing Super soft film Comfort+ technology	Skin colour Comfort+ technology Narrow edges make it invisible in bra	Transparent blue colour Hollow back with a wavy shape, allowing air and water to flow past it; this reduces the amount of suction so your wet prosthesis will not pull down your swimsuit
Attachment system	Insert into the bra	Insert into the bra	Insert into the bra	Directly on the skin	Placed in the bra or directly on the skin	Insert into the bikini or swimsuit
Suitability for different activities	Daily use	Daily use	Daily and sport use	Daily use	Daily use	Swimming and other water activities
Maintenance and cleaning	Wash daily with Soft Cleanser and water	Wash daily with Soft Cleanser and water	Wash daily with Soft Cleanser and water	Wash daily with Soft Cleanser and water	Wash daily with Soft Cleanser and water	Wash daily with Soft Cleanser and water
Material type	Intouch light or standard silicone	Intouch light or standard silicone	Intouch light or standard silicone	Soft InTouch Light silicone	Intouch light or standard silicone	Blueish silicone
Weight	Nearly 40% lighter than standard silicone prostheses of the same shape and size	40% lighter than standard breast prostheses of the same size	40% lighter than standard breast prostheses of the same size	40% lighter than standard breast prostheses of the same size	Light	Light
Lifetime	Used until the wound is completely healed	Long term use with proper care	Long term use with proper care	Long term use with proper care	Long term use with proper care	Long term use with proper care

Trulife

Trulife offers a broad range of prostheses that combine advanced materials with a focus on comfort, realism, and functionality. Each model selected for this benchmark was chosen to represent a unique use case, material innovation, or user need within Trulife's product line [31].



Figure 13: 607 FirstFit

The **607 FirstFit** (Figure 1313) is a soft, hypoallergenic prosthesis designed for immediate use after surgery. It is filled with medical-grade polyester and provides gentle support during the early recovery phase. This model was selected as a typical example of Trulife's immediate-care line, offering a comfortable textile solution that can be adjusted to individual needs with additional fiberfill.



Figure 14: 495 BodiCool Wave Triangle

The **495 BodiCool Wave Triangle** (Figure 1414) integrates phase-change cooling gel—a rare feature among full prostheses. This gel helps reduce heat buildup, making it especially useful for users in warm climates or during physical activity. It was included in the benchmark because it is currently the only full silicone prosthesis with active thermal cooling technology, allowing assessment of advanced temperature management in breast forms.



Figure 15: 101 Impressions II

The **101 Impressions II** (Figure 15) and **471 Silk Triangle** (Figure 166) models are designed to mimic the softness and natural movement of real breast tissue, offering a lifelike appearance and feel. The **Impressions II** was selected because it uses ultra-soft silicone combined with a honeycomb core, which enhances breathability and ensures a lightweight fit. This design provides a high level of comfort, especially during warmer weather or extended wear, and illustrates Trulife's approach to advanced realism in prosthesis development.



Figure 16: 471 Silk Triangle

The **Silk Triangle**, Trulife's best-selling model, was included in the benchmark to represent a widely used, standard triangle-shaped prosthesis. It is made from soft silicone with a natural drape and smooth skin feel, making it suitable for everyday use across a broad range of users. This model serves as a market baseline in terms of shape, fit, accessibility, and pricing.



Figure 17: 478 Silk Xtend

To address users who require more coverage, especially in the upper chest and underarm area, Trulife offers the **478 Silk Xtend** (Figure 177). This asymmetrical full form provides extended coverage while maintaining the brand's signature softness and drape. It was chosen to represent specialty prostheses for patients with upper-chest deficits, expanding the benchmark beyond symmetrical shapes.



Figure 18: 641 Tropez

Trulife also caters to users with active lifestyles. The **641 Tropez** (Figure 188) and **630 ActiveFlow** (Figure 1919) are swim prostheses made from quick-drying materials. The **Tropez** is a swim-specific silicone form with a concave back that allows for buoyancy and shape retention during aquatic activities. It was selected to illustrate Trulife's solution for water-based use.



Figure 19: 630 ActiveFlow

The **ActiveFlow** combines monoprene beads and spacer fabric, creating a lightweight, flexible prosthesis that drains water and air efficiently. This model was included for its unique air-and-water-draining performance, making it suitable for both swimming and high-movement activities like jogging.



Figure 20: 533 Triangle Partial

Lastly, the **533 Triangle Partial** (Figure 200) is a lightweight shaper designed for post-lumpectomy correction or enhancing natural symmetry. Its thin, tapered design makes it ideal for users seeking a discreet solution after breast-conserving surgery. It reflects the growing demand for partial prostheses that offer subtle balance and comfort.

Each Trulife prosthesis included in this study was selected to highlight a specific design strategy or user context, from immediate post-surgical recovery to aquatic activity and asymmetry correction, providing a diverse and representative comparison within the benchmark (Table 4).

Table 4: Benchmark Trulife of commercial breast prostheses

Prostheses Characteristics	607 FirstFit	495 BodiCool Wave Triangle	101 Impressions II	471 Silk Triangle	478 Silk Xtend	641 Tropez	630 ActiveFlow	533 Triangle Partial
Description	Postoperative	Full	Full	Full	Full	Swimming	Swimming	Partial
Company	Trulife	Trulife	Trulife	Trulife	Trulife	Trulife	Trulife	Trulife
Comfort	Soft and gentle, easily adjustable and lightweight for optimized comfort	Silky soft matte skin Cooling properties regenerate once the breast form is removed from the chest wall	Natural contours provide an intimate fit.	Silk: soft and natural Natural drape not found with other breast forms Silky-soft Unparalleled softness and suppleness	Silk: soft and natural Natural drape not found with other breast forms Silky-soft Unparalleled softness and suppleness	Retain their shape in and out of water Used in chlorinated and salt water New soft silky skin	Retain their shape in and out of water Used in chlorinated and salt water The perfect combination of beads and moulded spacer fabric provide a flattering, natural profile, whether active or lying down.	Soft silicone with an exterior silky-soft skin
Fit	Symmetrical Triangle Adjustable – Shallow to Full Sizes: 1-14	Symmetrical Triangle Average to Full Sizes: 1-14	Shallow to Average Sizes: 2-12	Symmetrical Triangle Shallow to Average Sizes: 1 – 17	Asymmetrical shape replaces tissue at upper chest and underarm Average to Full Sizes: 1-14, Left or Right	Symmetrical Triangle Sizes: 1 – 14	Symmetrical Triangle Sizes: 1 – 14	Triangle shape offers thin, overall coverage Lightest and most natural symmetry for post-lumpectomy, post-reconstruction and enhancement of underdeveloped breasts Symmetrical Triangle Sizes: 3-9

Aesthetics	Available in Light and Dark Tone Seamless moulded front with a breathable and moisture-wicking COOLMAX® back Easily adjusted to any fullness required Extra fiberfill included for adjustment	Raised channeling system promotes enhanced air circulation Versatile triangle shape fits a variety of body and surgery types	Honeycomb core which ensures optimum breathability Tapered edges allows these breast forms to be worn directly against the skin for the most intimate fit Integrated nipple and areola enhances and restores femininity Includes a COOLMAX® breast form cover Features a shallow profile based on the world's #1 selling breast form, Trulife's 471 Silk Triangle	No. 1 selling breast form in the world Versatile triangle shape fits a variety of body and surgery types	Concave back accommodates excess tissue	Concave back allows for buoyancy, water flow and shape retention Firm translucent triangle shape fits a variety of body and surgery types	Lightweight monoprene beads do not absorb water and dry quickly The beads also move and flatten when sunbathing	Tapered edges to ensure a flawless, smooth profile under clothing.
Attachment system	Insert into the bra	Insert into the bra	Directly on the skin	Insert into the bra	Insert into the bra	Insert into the bikini or swimsuit	Insert into the bikini or swimsuit	Insert into the bra
Suitability for different activities	Post-surgery and leisure wear Daily use	Daily use	Daily use	Daily use	Recommended for use with bilateral or extensive surgery Daily use	Ideal for all water activities	Ideal for all water activities Popular for all activities including swimming and jogging	For post-lumpectomy, post-reconstruction and enhancement of underdeveloped breasts. Daily use

Maintenance and cleaning	Wash with TruKleen and (cold or warm) water	Wash with TruKleen and (cold or warm) water	Wash with TruKleen and (cold or warm) water	Wash with TruKleen and (cold or warm) water	Wash with TruKleen and (cold or warm) water	Wash with TruKleen and (cold or warm) water	Wash with TruKleen and (cold or warm) water	Wash with TruKleen and (cold or warm) water
Material type	100% hypoallergenic polyester fluff	TruCool Gel, a Trulife proprietary silicone blend that uses an advanced cooling technology	100% pure silicone	Highest quality of silicone for lasting comfort and softness	Highest quality of silicone for lasting comfort and softness	Soft silicone	Combination of lightweight monoprene beads and moulded spacer fabric	Soft silicone
Weight	Lightweight	Lightweight	Lightweight	30% lighter than traditional silicone breast forms	30% lighter than traditional silicone breast forms	Lightweight	Lightweight	Lightweight
Lifetime	Used until the wound is completely healed	Long term use with proper care	Long term use with proper care	Long term use with proper care	Long term use with proper care	Long term use with proper care		

ABC breast care

ABC's product range combines practical solutions with a focus on comfort, support, and targeted care. Each prosthesis included in this benchmark was chosen to represent a distinct functional feature, user need, or design innovation in ABC's portfolio [32].



Figure 21: First Form

The **First Form** (Figure 211) is designed for use immediately after surgery. It features a soft textile cover and a lightweight foam core that gently adapts to the body's shape. This model was selected as a baseline for immediate post-surgical care, offering a hypoallergenic, pressure-free solution for the early recovery period.



Figure 22: Basic Triangle Lightweight

The **Basic Triangle Lightweight** (Figure 222) and **Flowable Back Symmetric** (Figure 233) are full prostheses intended for long-term use. The **Basic Triangle Lightweight** represents ABC's classic everyday model, combining affordability with reliable comfort, and was chosen for cost-to-comfort benchmarking.



Figure 23: Flowable Back Symmetric

The **Flowable Back Symmetric** includes a gel-flow back layer that adapts to scars and uneven tissue, improving the fit and reducing pressure. It was selected to illustrate ABC's innovation in adapting prostheses to post-surgical irregularities.



Figure 24: MyShape RFS

The **MyShape RFS** (Figure 244) is notable for its adaptable shape and unique multi-zone contouring. The RFS stands for Round, Full, and Shallow, describing the prosthesis' variable geometry. It was included in the benchmark to explore how a flexible, multi-contour design can provide better fit for various body types and surgical outcomes.



Figure 25: Active Form

The **Active Form** (Figure 255) is designed for active users. It features moisture-wicking materials that help to prevent heat buildup and discomfort during exercise. This model was selected to assess sport-specific sweat management, especially for individuals with higher physical activity levels.



Figure 26: Active Swim Form

For aquatic activities, ABC offers the **Active Swim Form** (Figure 266), a prosthesis resistant to heat, chlorine, and saltwater. It maintains its shape during swimming and dries quickly, making it ideal for water-based use. This model was chosen to represent swim-specific performance in demanding environments.



Figure 27: Massage Form Shaper Attach

ABC also includes partial prostheses in its product line. The **Massage Form Shaper Attach** (Figure 277) features massage bubbles and adhesive backing, promoting air circulation and secure attachment to the skin. It was selected as a unique approach to skin aeration and partial symmetry correction after breast-conserving surgery.



Figure 28: Diamond Shaper Lightweight

The **Diamond Shaper Lightweight** (Figure 288) offers a light and breathable solution with a diamond-vented back, demonstrating an alternative cooling geometry designed for everyday comfort and natural appearance.

Together, these prostheses reflect ABC's commitment to delivering solutions that address a variety of anatomical, thermal, and lifestyle needs. Each prosthesis offers a distinct function, from post-operative care to advanced sports and swim solutions, as well as options for asymmetry and partial correction (Table 5).

Table 5: Benchmark ABC of commercial breast prostheses

Prostheses Characteristic	First Form	Basic Triangle Lightweight	Flowable Back Symmetric	MyShape RFS	Active Form	Active Swim Form	Massage Form Shaper Attach	Diamond Shaper Lightweight
Description	Postoperative	Full	Full	Full	Sport	Swimming	Partial	Partial
Company	ABC	ABC	ABC	ABC	ABC	ABC	ABC	ABC
Comfort	The skin-friendly textile cover ensures a comfortable fit, while the moulded front offers a natural look	1-layer lightweight denture is designed so that the front and back are made of the same silicone and are equipped with a smooth back.	The larger contact surface ensures that the breast prosthesis sits perfectly in the bra pocket and uncomfortable slipping is reduced.	Offers a particularly soft and malleable inner layer	Low moisture absorption Prevents heat from accumulating, especially at higher temperatures	Our swimming prosthesis nestles gently against the upper body and ensures feminine curves in a bikini or swimsuit Resistant to heat, salt water, sand and chlorine	The comfortable standard silicone for a natural feel and the wider footprint ensure a good fit.	Special structure of Diamond back promotes air exchange and creates pleasantly cool wearing climate
Fit	During the first few weeks after the operation and during radiation, care must be taken to ensure that nothing presses on the scar.	Size: 1-17 = bra size: 70AA-115G	Size: 1-12 = bra size: 70 AA - 110 C Optimal fit due to the increased footprint	Size: 3-14 = bra size: 75A-115D Adapts optimally to the uneven scar area and the topography of the surgical area	Size: 1-14 = bra size: 70 AA -110 E Very flexible	Size: 1-12 Anatomical shape for a secure fit	Size: 4-12 Thanks to the self-adhesive backing, it guarantees a secure and comfortable fit all day long. No slipping, secure hold.	Size: 1-12 Optimal visual compensation after breast-conserving surgery, reconstruction or natural breast asymmetry

Aesthetics	The viscoelastic foam shape adapts optimally to your own anatomical conditions through body heat and can be worn during the day as well as at night.	Light brown skin tone (= tan), which is perceived by many women as extremely pleasant	All ABC Flow breast prostheses are equipped with a soft, cuddly and transparent silicone gel on the back.	The RFS = unique shape of this prosthesis: R = curve in the lower prosthesis area F = fullness in the lower cup area S = slender breast insertion	Over-the-counter, available without prescription	Over-the-counter, available without prescription Vertical ribbed structure on the back of the Active Swim Form for efficient water drainage	The Massage Shaper Attach Balancing Shell offers a variety of benefits for women who need optimal balancing after breast-conserving surgery	Balances more than one bra cup size
Attachment system	Insert into the bra	Insert into the bra	Insert into the bra	Insert into the bra	Insert into the sport bra	Insert into the bikini or swimsuit	Direct on the skin or Insert into the bra (using fabric covers)	Insert into the bra
Suitability for different activities	Post-surgery and leisure wear Suitable for daily wear	Daily use	Daily use	Daily use	Ideal for sports and leisure	Specifically designed for swimming and water activities	Daily use	Daily use
Maintenance and cleaning	Hand wash with soap and water	Hand wash with soap and water	Hand wash with soap and water	Hand wash with soap and water	Hand wash with soap and water	Hand wash with soap and water	Hand wash with water and cleaning paste Form Clean	Hand wash with soap and water
Material type	Soft textile Viscoelastic foam core	Standard silicone	Transparent silicone gel	Amadasil silicone	Breathable saver material Filling: small, light, movable microbeads	Unobtrusive transparent silicone	Standard silicone	Soft silicone
Weight	Light as a feather (Lightweight)	Approx. 33% weight reduction	Lightweight silicone cup reduces shoulder and back strain by ~20%.	Approx. 33% weight reduction	Lightweight	Lightweight	Lightweight	Lightweight
Lifetime	Postoperative initial care for the first weeks	Long term use with proper care	Long term use with proper care	Long term use with proper care	Long term use with proper care	Long term use with proper care	Long term use with proper care	Long term use with proper care

Customization options

The customization of external breast prostheses is becoming an increasingly important factor in the industry. Some models offer advanced features that allow for personalization in terms of fit, comfort, aesthetics, and suitability for different activities. The prostheses included in this benchmark were selected to illustrate different approaches to customization, ranging from manual adjustability to fully personalized, 3D scanned solutions.

For instance, the **Equitex Volume 1157X** (Figure 2929) by Anita is a multifunctional partial prosthesis



Figure 29: Equitex Volume 1157X

designed with a symmetrical triangle shape and a reinforced center section. It can be worn on either side and is crafted from special silicone gel that mimics the natural feel of breast tissue. The model includes variable padding with medicated fleece, allowing the wearer to adjust volume manually. This prosthesis was selected to represent a low-tech, user-controlled form of customization, offering comfort and adaptability without the need for complex technology.

Amoena's **Adapt Air Xtra Light 1SN** (Figure 300) is a full prosthesis that excels in on-the-spot volume



Figure 30: Adapt Air Xtra Light 1SN

adjustability. Its integrated air chamber can be inflated or deflated using a small hand pump, allowing the wearer to adapt the fit as their body changes over time. This model is unique among mass-market prostheses for its advanced customization function. It was selected to showcase how technological innovation enables personalized fit in readily available products. In addition to this model, Amoena also offers fully custom-made prostheses, extending their commitment to individualized care.

Trulife's **Radiant Impressions** (Figure 311) is a custom-made prosthesis offering a high level of

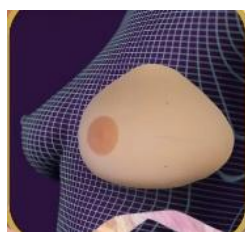


Figure 31: Radiant Impressions

personalization [30]. Using 3D laser scanning, the prosthesis is crafted to match the exact contours of a woman's chest. The process is highly detailed and includes optional features such as realistic skin tones, nipples, freckles, and even tattoos. Each prosthesis is hand-finished in soft silicone, making it gentle on scar tissue and suitable for sensitive skin. It was selected to represent the high-end, craftsman approach to fully individualized prosthetic care.

Similarly, ABC's **Made-to-Measure breast prosthesis** (Figure 322) is created using 3D scanning and



Figure 32: Made-to-measure breast prosthesis

machine molding, tailored to the unique body profile of the wearer. It uses medical-grade lightweight silicone that adapts well to body movements and remains secure without slipping. Users can choose between different back designs and skin tones to ensure a lifelike result. This model was selected to contrast Trulife's handcrafted method by showcasing a streamlined, high-precision custom workflow that still prioritizes comfort and natural appearance.

These prostheses illustrate the diversity of customization approaches in modern breast prosthesis design—from manual volume control and air-based adjustments to full digital body scanning (Table 6). Each selected model brings a different perspective on how personalization can improve prosthetic fit, aesthetics, and quality of life.

Table 6: Benchmark of the customization options

Prostheses Characteristics	Equitex Volume 1157X	Adapt Air Xtra Light 1SN	Radiant Impressions	Made-to-measure breast prosthesis
Description	(Multifunctional) Partial	Full	Full	Full and Partial
Company	Anita	Amoena	Trulife	ABC
Comfort	Optimal wearing comfort due to a soft foil and special silicone gel Excellent balance of extremely uneven scar area and larger tissue deficits The microfiber allows the skin breathe to ensure a feeling of comfort	More confident and self-assured No one will notice you are wearing breast prosthesis	Enhanced softness to match natural breast tissue May help restore a sense of wholeness and confidence Radiant Impressions is soft and comfortable	Want to give women new self-confidence and a positive body image Gentle wearing comfort, even in the case of lymphoedema Cool and dry: Our materials keep your skin pleasantly cool and dry, for more comfort and less worry. Gentle scar care: The silicone nourishes your skin and keeps scars supple, for your well-being.
Fit	Symmetrical triangle shape with reinforced center section Can be worn on the both side Variable padding with medicated fleece	Volume can be easily adjusted - a perfect fit for every occasion, even as your body changes Symmetrical shape (can be worn on the left or right side)	Custom made to a woman's unique contour, shape and profile With the use of a laser scanner, a 3D image	It takes sensitive scar and skin areas into account and reliably compensates for uneven surgical sites. Perfect fit: Each of our dentures is custom-made, adapts perfectly to your body and makes you feel like you're yourself again. Thanks: to the adapted back and the high-quality silicone, the prosthesis fits securely and does not slip. Move freely and confidently.
Aesthetics	More volume in the middle of the prosthesis Covered with a matte film that closely resembles skin Microfiber fabric on the back of the standard silicone form	Available in different skin colours Air chamber	Unique to the surgery site With over 30 skin tone options available, we can match your desired skin tone and add freckles, veins, realistic nipple and tattoos to make your prosthesis unique to you	You can choose from three different backs and perfectly match the skin colour of the prosthesis/shell to your own skin tone so that it feels and looks as natural as possible.

Attachment system	Insert into the bra	Insert into the bra	directly against the chest wall in a non pocketed bra	Insert into the bra
Suitability for different activities	Daily use	Daily use	Daily use	Daily use, sport activities, leisure and swimming
Maintenance and cleaning	Hand wash with soap and water	Wash daily with Soft Cleanser and water	Hand wash with soap and water	Hand wash with soap and water
Material type	100% silicone Variable padding with medicinal fleece	Soft InTouch Light silicone	100% natural silicone	Medical-grade lightweight silicone
Weight	Ultra lightweight	40% lighter than standard breast prostheses of the same size	Lightweight	Lightweight and relieves the shoulders and neck
Lifetime	Long term use with proper care	Long term use with proper care	Long term use with proper care	Long term use with proper care

Companies about 3D printing in breast prostheses sector

After conducting an extensive analysis of the commercial market for external breast prostheses, I shifted my focus to companies that are already implementing 3D printing technologies in this field. Two companies were identified that are active in this domain: EVE breast prostheses and Hashtagtwo. Both are located in the Netherlands and take a different but innovative approach to the production of customized external breast prostheses.

EVE breast prostheses (Figure 333) uses advanced 3D scanning technologies to produce highly personalized breast prostheses. They employ a system of 20 cameras to create accurate digital models of the body. Based on these scans, molds are 3D printed, and then silicone is used to cast the prostheses. This technique ensures a close fit to the body, especially around scarred areas, and aims to achieve a natural and seamless appearance. Even though the scanning and mold-making process is supported by digital tools, a large part of the production still involves manual craftsmanship, including colour matching, the application of realistic nipple details, and fine aesthetic adjustments. The EVE prosthesis was selected for this benchmark because it combines 3D body scanning with printed molds and detailed hand-finishing, offering a high degree of personalization while maintaining artisanal quality. Scanning takes place at the company's facility using professional equipment, and prostheses are offered through direct sales. In addition to customization, EVE emphasizes sustainability in its production processes [33].



Figure 33: Breast prosthesis of EVE breast prostheses

Hashtagtwo (Figure 344), on the other hand, adopts a distinct production and service model. This company uses direct silicone 3D printing via the ARBURG Freeformer system to create custom prostheses with a focus on scalability and reusability. The material used is Cawiton, a medical-grade, recyclable silicone with a shore value of 40, which gives the prosthesis a soft and flexible feel that resembles natural breast tissue. The prosthesis absorbs body heat and adapts slightly to skin temperature, which improves comfort during wear. Hashtagtwo was chosen for this benchmark because it demonstrates a unique circular subscription model, where the prosthesis remains company property and can be recollected and recycled after use. This approach reflects a strong commitment to environmental sustainability.



Figure 34: Breast prosthesis of Hashtagtwo

Hashtagtwo also stands out for its user-friendly customization process: customers can perform a 3D scan using a smartphone app, which creates a point cloud image between the chin and the navel while protecting user privacy. Alternatively, scanning can be done at a company facility. The company offers three model variants and allows users to choose colours and styles that match their favourite bras and lingerie, blending functionality with emotional well-being [34].

Both companies demonstrate how digital technologies like 3D scanning and additive manufacturing can transform the design and user experience of external breast prostheses. However, their methods differ significantly (Table 7). While EVE emphasizes craftsmanship, individual ownership, and aesthetics, Hashtagtwo focuses on digital automation, material innovation, and circular design. Together, they represent two complementary visions for the future of personalized breast prostheses enabled by 3D printing.

Table 7: Benchmark of companies about 3D printing in breast prostheses sector

Prostheses Characteristics	Custom-made prosthesis	Custom-made prosthesis
Description	Full and Partial prosthesis	Full and Partial prosthesis
Company	EVE breast prostheses	Hashtagtwo (#2)
Comfort	Accurately mirrored copy of your own breast and fits almost seamlessly onto the scar on the inside Absorbs body heat, Natural, light feeling	Breathable, pain relieving and aesthetic. The best alternative to your own real breast. Absorbs body heat
Fit	The custom-made prosthesis fits well to the scar area, but does not change shape. The prosthesis is flexible and moves slightly, but is more static than the natural breast. This also means that the prosthesis does not change shape without a bra. The prosthesis is therefore made as a breast that is in the bra. Use of 3D scanning: 2 scans of your upper body are made. A scan with bra, and a scan without bra. In case of a double-sided amputation, we can scan before the operation, or afterwards together determine what the most beautiful shape is	Suitable for your scar provides comfort Use of 3D scanning: The application does not take a photo but a point cloud and automatically uses only the part between your navel and your chin so that your privacy is guaranteed.
Aesthetics	14 different colours so that it matches your skin colour. In addition, nipple colour and size are determined (optional). It is also determined how far the prosthesis must extend to fit your body properly. If the scar tissue extends above the bra, it is better to have the prosthesis extend above the bra as well. We prefer not to have the prosthesis extend too far under the armpit, because otherwise it will rub against the arm	The colour of your skin changes four times a year. Skin colour prostheses never match your own skin. For this reason, we make prostheses with colour and art, custom-made for you and your favorite bra, so that it matches your lingerie and makes you happy.
Attachment system	Insert into a bra	Insert into a bra
Suitability for different activities	Daily use, sport activities, swimming	Daily use
Maintenance and cleaning	Hand wash with water and soap	Hand wash with water and soap

Material type	Silicone material and is filled with air and soft filling	Cawiton → Freeformer print material with shore value 40: Our material is soft, airy, recyclable and valuable. That is why we want to keep ownership of our products and ensure that they are reused infinitely.
Weight	Light	Light
Lifetime	Long term use with proper care	Long term use with proper care

Link to Program of Requirements (PoR):

Table 8: Requirements benchmark study

Requirement	Description	Measurement Method	Validation Method	Unit	Success Criteria
R6	The prosthesis must incorporate adjustable features to allow for a personalized fit.	Analysis of adjustable components	User feedback on fit flexibility	% Fit satisfaction	≥ 90% of users report adjustability
R7	The prosthesis must maintain shape and integrity in water.	Submersion and wear tests	User feedback after swimming	% Performance retention	≥ 90% form stability
R8	The product must support moderate physical activity (e.g. walking, yoga).	Functional test during activity	User satisfaction survey	% Activity suitability	≥ 85% positive feedback
R9	The prosthesis must have a minimum lifespan of 2 years.	Accelerated wear testing	Expert review and simulated use	Years	≥ 2 years without degradation

2.3 Visits Anita Headquarters

On August 7th, a visit to Anita's headquarters in Brannenburg, accompanied by Stephan Volk, Product Manager and Head of Silicone, provided a valuable opportunity to gain a comprehensive understanding of the company's approach to manufacturing high-quality external breast prostheses. Conducted under strict confidentiality in accordance with a signed Non-Disclosure Agreement (NDA), the visit offered general insights into production methods, research initiatives, and Anita's commitment to product excellence.

The tour covered several key stages of the production process, starting with the preparation of specialized materials used for the outer shell of the prostheses. Observing the precise handling and assembly techniques revealed the company's focus on consistent quality and durability. Each production step is carefully designed to balance visual appearance with functional performance, ensuring the prostheses meet the diverse needs of users.

One of the most notable aspects of the visit was Anita's emphasis on innovation through research and development. The R&D department is continuously exploring new material combinations and refining existing designs to improve comfort, reduce weight, and enhance usability. This future-oriented mindset was visible throughout the facilities, reinforcing the company's commitment to continuous improvement and user-focused solutions.

Additionally, the visit provided an overview of Anita's product portfolio, highlighting their emphasis on comfort, functionality, and long-term durability. The thoughtful design and meticulous production processes align closely with high medical and industry standards.

Overall, the experience offered a valuable look into the complex and detailed processes involved in creating external breast prostheses. It emphasized the importance of precision, innovation, and user-centered design in the development of medical products. These insights will serve as a useful reference for further research and application.

A second visit to Anita's headquarters took place on April 15th and 16th, this time accompanied by Daniela Theil, who is the external supervisor at Anita of this thesis. This visit expanded on the previous experience and provided additional feedback and information.

On this occasion, the visit included a building that had not been seen during the August tour, where the marketing, testing, textile development, and executive offices are located.



Figure 35: Artec 3D Spider II

During the visit, 3D scans were performed using Anita's in-house scanning equipment from Artec 3D, specifically the Spider II (Figure 355) and EVA (Figure 366) models. The scans were taken of one of Anita's in-house breast models. In accordance with the informed consent agreement (Appendix K), the model's name and identity are not disclosed to protect privacy.



Figure 36: Artec 3D EVA

Despite some technical challenges, such as repeated software errors, a program crash and difficulties in capturing complete scans. The final results were successful after approximately one hour of work. Among the two devices, the EVA scanner produced significantly better results than the Spider II. Throughout the process, the positioning and distance of the scanner relative to the model had to be adjusted multiple times to optimize scan quality.

On April 16th, an update on the progress of the thesis was presented to Daniela Theil (external supervisor and Development/ new technology), Stephan Volk (Product Manager and Head of Silicone), and Stefan Schildhauer (Production Manager). This presentation included samples created during the research as well as silicone 3D printed samples received from Yannick Christiaens, lecturer at Ghent University and researcher at Design Nexus, who has extensive expertise in 3D printing. Additionally, the Grasshopper code used in the project was demonstrated and briefly explained. The response was highly positive. The team expressed enthusiasm about the results and showed particular interest in samples printed on the Lynxter 3D printer, especially the thin hexagon structures and white printed pieces (Figure 377) which had an appealing tactile quality.



Figure 37: Two samples Lynxter 3D printer

Further feedback revealed that Anita already produces adaptable volume prostheses. In comparing different brands, Amoena was seen as the most promising for future 3D scanning applications due to its use of conventional films and molds, while ABC prostheses were noted to have an unsatisfactory tactile feel and do not utilize film-based techniques.

Of particular interest to the Anita team was the prototype prosthesis with a lattice skin structure made of TPU 95A HF. While the material was not yet soft enough for final production use, the concept was promising and aligned with Anita's goals.

During the discussions, questions were raised about whether a final visit would be scheduled to present the completed thesis. There was also interest in whether the full 3D scanning processes used by other companies were understood and could be compared.

Link to Program of Requirements (PoR):

Table 9: Requirements visits Anita Headquarters

Requirement	Description	Measurement Method	Validation Method	Unit	Success Criteria
R10	The product must use lightweight materials that retain softness, shape, and durability in daily use.	Material analysis, user feedback	Weight and compression tests, tactile assessment	g, N, Softness rating (1-5)	Weight $\leq$ 200g maintains form and feel over 2 years
R11	The external surface must have a smooth, seamless finish with a texture optimized for user comfort and to minimize potential irritation.	Surface texture analysis	User feedback on comfort and irritation levels	Smoothness rating (1-10)	Rating $\geq$ 8 for smoothness and comfort

2.4 3D printing medical sector & breast prostheses

3D printing, also known as additive manufacturing, is a revolutionary technology that fabricates three-dimensional objects by depositing materials layer by layer according to a digital design. Unlike traditional manufacturing methods, which often involve subtracting material from a larger block or using molds, 3D printing offers unparalleled flexibility in design, allowing for the creation of highly complex geometries with minimal waste [23], [45]. The process begins with a digital model, typically designed using computer-aided design (CAD) software. This model is sliced into numerous thin cross-sections and the 3D printer builds the object one layer at a time based on these slices. Depending on the application, different types of 3D printing technologies and materials are used.

There are several types of 3D printing technologies, each with unique strengths and applications. Fused Deposition Modelling (FDM) is one of the most common and affordable 3D printing methods. It involves extruding a continuous filament of thermoplastic material through a heated nozzle, which deposits the material layer by layer. FDM is widely used for creating durable prototypes, simple prosthetic components and medical models due to its affordability and versatility [26]. Another important technology is Selective Laser Sintering (SLS), which uses a laser to sinter powdered material, fusing it into a solid structure. Since SLS does not require support structures, it is ideal for producing complex geometries and is commonly used for durable prosthetics, implants and high-performance medical devices [42]. Stereolithography (SLA) employs a UV laser to cure liquid resin into hardened plastic, offering high precision and smooth surfaces, making it suitable for intricate prosthetic parts, dental models and surgical guides [27], [46].

In addition to these methods, silicone 3D printing has emerged as a game-changer in producing soft, flexible and biocompatible parts. Traditional silicone manufacturing often involves time-consuming mold-based processes, but direct 3D printing of silicone eliminates the need for molds, enabling more precise control over design and customization while reducing production time and costs [23], [34]. Bioprinting is another cutting-edge development in which living cells, scaffolding materials and growth

factors are deposited layer by layer to create tissues and (potentially) functional organs. While fully functional organ printing is still in its early stages, bioprinting has shown significant promise in tissue engineering and regenerative medicine [47], [48].

The integration of 3D printing into healthcare has transformed how medical devices, implants and prostheses are designed and manufactured. Its ability to produce highly customized solutions tailored to individual patients has led to significant improvements in treatment outcomes and patient satisfaction [26], [27]. One of the most notable applications is the creation of patient-specific implants and prostheses. By leveraging imaging technologies such as CT scans, 3D printing can produce custom implants that fit perfectly with a patient's unique anatomy, improving both comfort and functionality [27], [49]. Another key application is the use of 3D printed models for surgical planning and training. Surgeons can practice complex procedures on patient-specific models, which helps improve surgical precision and reduces the risk of complications [46], [50]. In addition to implants and surgical models, bioprinting is advancing rapidly, offering new possibilities in regenerative medicine. Researchers are working on bioprinted skin grafts, bone scaffolds and even vascularized tissues, all of which have the potential to revolutionize patient care [47], [51].

Despite the significant advancements in 3D printing for internal implants and surgical prosthetics, external prostheses, particularly for breast cancer survivors, have received comparatively less attention [23], [24], [51], [52]. Most research has primarily focused on 3D printing breast implants rather than external breast prostheses [52]. Traditional external breast prostheses are typically manufactured using molds filled with silicone. This approach, while functional, comes with several limitations. The reliance on molds restricts the ability to fully customize prostheses for individual users. Since each mold has a fixed shape and size, traditional prostheses often fail to achieve a perfect fit, resulting in discomfort and dissatisfaction among users [34], [47]. Additionally, silicone-based prostheses tend to be heavy and lack ventilation, which can cause discomfort, especially in warm climates or during physical activities [24], [30], [34]. The density of silicone further contributes to the bulkiness of traditional prostheses, making them less suitable for long-term use [30], [34], [47].

The application of 3D printing to breast prostheses offers several distinct advantages over conventional manufacturing methods. By using advanced scanning technologies, 3D printing enables the production of fully personalized prostheses that precisely match the shape of an individual's chest wall [12], [22]. This level of customization significantly improves comfort, fit and overall user satisfaction [1], [22]. Additionally, 3D printing provides greater flexibility in material selection. Thermoplastic polyurethane (TPU) and lightweight silicone are two of the most promising materials for 3D printed prostheses. TPU offers excellent flexibility, durability and breathability, making it ideal for long-term wear, particularly in warmer climates [22], [32]. Lightweight silicone, when used in combination with advanced hole structures, can further reduce the weight of prostheses while maintaining a realistic feel and appearance [12], [22], [32].

The use of hole structures, such as Voronoi patterns (Figure 38), in the internal design of 3D printed prostheses has proven highly effective in reducing weight and improving ventilation. These designs maintain structural integrity while minimizing material usage, resulting in prostheses that are lighter and more breathable than their traditional counterparts [53], [54]. Studies have demonstrated that hole-structured prostheses not only improve comfort but also enhance long-term usability, making them a preferred choice for active individuals [53], [54]. Projects involving Mexican students who incorporated hole structures into their designs highlight the practical potential of these innovations in creating user-friendly prosthetic devices [53].

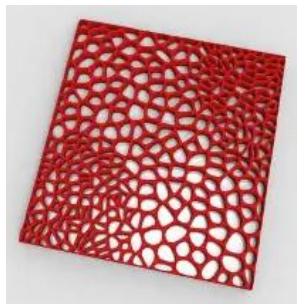


Figure 38: Voronoi Pattern

One of the most exciting developments in 3D printing for breast prostheses is the emergence of silicone 3D printing techniques. Unlike traditional mold-based methods, which require multiple steps and significant time, silicone 3D printing allows for direct fabrication of prostheses with minimal post-processing [23], [34], [49]. This approach reduces production time and costs while enabling a higher degree of customization. The resulting prostheses are not only lightweight and comfortable but also capable of adapting to the unique anatomical features of each user. By eliminating the need for molds, silicone 3D printing streamlines the entire manufacturing process, making it easier to produce high-quality prostheses on demand [23], [34].

Despite the promising advancements, there remain significant challenges in applying 3D printing to external breast prostheses. Ensuring the biocompatibility and durability of new materials is critical to long-term success [47], [49]. Additionally, while the reduction in manufacturing costs is a major benefit, the initial investment in 3D printing technology can be substantial. Making these advanced prostheses affordable and accessible to a wider population will require continued research, development and collaboration among medical professionals, engineers and manufacturers [23], [51], [53]. User engagement and feedback are also essential in refining the designs and ensuring that the final products meet the specific needs of patients [33], [34].

3D printing has already demonstrated its transformative potential in the medical sector by enabling highly personalized and efficient solutions. In the field of breast prostheses, it offers a unique opportunity to address long-standing issues of comfort, fit and usability. By leveraging cutting-edge technologies and innovative materials, 3D printing can provide breast cancer survivors with prostheses that enhance their quality of life. Continued research and technological advancements will be key to unlocking the full potential of 3D printing in healthcare, paving the way for more accessible, personalized and user-centric solutions [23], [26], [27], [53].

Link to Program of Requirements (PoR):

Table 10: Requirements 3D printing medical sector

Requirement	Description	Measurement Method	Validation Method	Unit	Success Criteria
R12	The prosthesis must be fully customizable using 3D scanning data.	3D scanning of user	User satisfaction on fit accuracy	% Customization success	95%+ users report satisfactory customization
R13	The internal structure must use a hole structure design to reduce weight and improve breathability.	Internal structure analysis	Breathability and weight testing	cm ³ /s/cm ² , g	Breathability > 100 cm ³ /s/cm ² , weight reduction ≥ 15%
R14	Silicone 3D printing must be used to ensure efficient production and high precision.	3D printing process evaluation	Comparison of prototypes with traditional methods	Production time, precision	≥ 95% precision and reduced production time

2.5 3D scanning

3D scanning technology is revolutionizing the medical sector by enabling precise and personalized solutions tailored to individual needs. For custom prostheses, 3D scanning offers unmatched accuracy in capturing the complex geometry of the human body. This precision ensures a perfect fit, enhances comfort and improves functionality, critical factors for medical applications. By creating digital replicas of anatomical structures, 3D scanning supports the development of devices that address both medical and aesthetic requirements.

In healthcare, 3D scanning is widely used to personalize products like orthotic braces, dental implants and surgical guides. The technology allows healthcare professionals to design devices that align with a patient's unique anatomy, improving treatment effectiveness and user satisfaction. Furthermore, the ability to digitally store and modify scans facilitates iterative adjustments, ensuring that the device remains functional and comfortable over time.

Customization through 3D scanning is especially valuable for breast prostheses, where achieving a balance between lightweight design, realistic aesthetics and comfort is essential. The ability to accurately capture the contours of soft tissue ensures a natural appearance, while tailoring the prosthesis to the user's body enhances wearability and reduces discomfort. This approach not only meet functional needs but also contributes to emotional well-being by restoring confidence after a mastectomy.

By incorporating self-scanning methods, this thesis seeks to make the customization process more accessible. Self-scanning enables individuals to create prostheses in the privacy and convenience of their own homes, reducing costs and simplifying the process. This research aims to explore how self-scanning can optimize the design and production of breast prostheses, addressing the unique challenges of this application while enhancing accessibility, practicality and user empowerment.

Self-scanning allows for the accurate capture of body geometry, making it possible to create prostheses that are tailored to an individual's specific needs. Smartphone apps such as xOne AI, DECAL and Polycam for Android and 3D Scanner App, xOne AI and Polycam for IOS offer cost-effective alternatives to expensive clinical scanners (Table 11).

Table 11: List of Apps for the 3D scans

DECAL-3D SCANNER Android	 Figure 39: Logo DECAL App
xOne AI: 3D Scanner & 3D Editor Android, IOS	 Figure 40: Logo xOne AI App
Polycam: 3D Scanner & Editor Android, IOS	 Figure 41: Logo Polycam App
3D Scanner App IOS	 Figure 42: Logo 3D Scanner App

These apps leverage photogrammetry or depth-sensing technology to generate detailed 3D models. The apps of IOS have better quality results than the apps of Android. While research shows that these methods can produce sufficiently accurate results for non-critical medical applications, further investigation is needed to determine their effectiveness in achieving clinical-grade accuracy for breast prostheses.

Existing studies have extensively explored 3D imaging applications for facial reconstruction, dental procedures and limb prosthetics. However, research specific to breast prostheses remains limited. These prostheses present unique challenges, such as replicating soft tissue contours and maintaining symmetry, while ensuring a lightweight and comfortable design. Limited data exists on the accuracy of self-scanned models for these purposes and the integration of such scans into the 3D printing workflow has not been thoroughly studied.

This thesis will address these gaps by using self-scanning as the primary method for capturing body geometry. Scanning procedures will be tailored to the patient's circumstances:

- **Pre-surgery** (Figure 4343): Patients will scan both breasts while wearing a bra before surgery, followed by post-mastectomy scans without a bra.

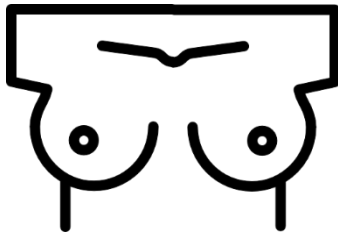


Figure 43: Pre-surgery

- **Post-surgery with one breast remaining** (Figure 444): A scan of the unaffected breast will be taken while wearing a bra, along with a scan of the mastectomy site without a bra. The unaffected breast will then be mirrored to produce a symmetrical prosthesis.

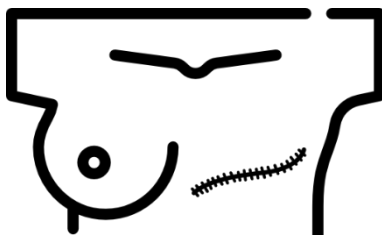


Figure 44: Post-surgery with one breast removed

- **Post-surgery with both breasts removed** (Figure 455): Scans will be conducted of the mastectomy site without a bra. If pre-surgery scans are unavailable, standard prosthesis sizes will be used as a reference.

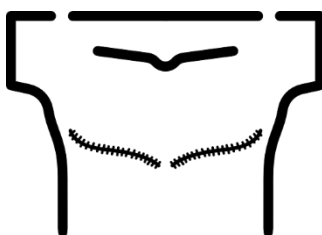


Figure 45: Post-surgery with two breasts removed

Scanning instructions will be provided to ensure consistency and accuracy and a list of recommended apps will be included for user convenience. The research will assess the reliability of smartphone-based scanning in capturing soft tissue details and achieving symmetry, as well as its integration into the 3D printing workflow.

This thesis aims to bridge the gap between self-scanning technology and the design of custom breast prostheses. By investigating the accuracy, practicality and feasibility of self-scanning methods, the study will contribute to the development of accessible, personalized solutions. The findings will not only advance the application of 3D scanning in medical prosthetics but also empower individuals to actively participate in the creation of their own prostheses, fostering greater control and satisfaction with the outcomes.

Link to Program of Requirements (PoR):

Table 12: Requirements 3D scanning

Requirement	Description	Measurement Method	Validation Method	Unit	Success Criteria
R15	The prosthesis design process must support self-scanning for improved accessibility.	Self-scanning system testing	User feedback on ease of use	% User success rate	90%+ users can successfully perform self-scanning
R16	The workflow must enable digital storage and modification of scanned models for iterative improvements.	Digital workflow analysis	Testing for ease of storing and modifying models	% Ease of use	90%+ users find the system easy to use for modifications

2.6 Grasshopper program/code

Grasshopper is a powerful visual programming environment integrated with Rhino 3D, widely applied in architecture, product design and engineering for creating complex parametric models and algorithm-driven designs. Unlike traditional coding, Grasshopper uses a node-based interface where users connect components with wires to define relationships, generate geometries and manipulate data in a dynamic, real-time workflow. This parametric approach allows designers to quickly explore design variations and optimize forms by simply adjusting input parameters. Its extensibility through numerous plugins, such as Kangaroo for physics simulations or Crystallon for lattice structures and 3D printing optimization, enhances its versatility across fields ranging from structural analysis to digital fabrication. By enabling precision, flexibility and creative experimentation, Grasshopper has become an essential tool for professionals pushing the boundaries of computational design.

Grasshopper's visual programming capabilities offer a robust platform for developing detailed, customizable prosthesis models, particularly in integrating and processing 3D scan data. This application is crucial in prosthesis development, where scans taken before and after surgery are combined to create prosthetic models that closely replicate the natural shape of the breast. The pre-surgery scan acts as a guide to replicate the original breast contours, while the post-surgery scan forms the foundation for the prosthesis design. This process ensures that the resulting product aligns perfectly with the patient's anatomy and meets their specific needs. In cases where pre-surgery scans are unavailable, standard prosthetic models can be adapted using the post-surgery scan as a base, ensuring flexibility in design and inclusivity for various patient profiles.

A standout feature of Grasshopper is its ability to introduce advanced customization into prosthetic design. Surface textures can be added to improve grip and minimize slippage during use, while also enhancing ventilation to reduce sweating and increase wearer comfort. Additionally, Grasshopper enables the optimization of the prosthesis' internal structure, reducing weight without sacrificing durability or functionality. This feature is particularly useful in designing partial prostheses for lumpectomy patients, where only a portion of the breast requires reconstruction. By offering lightweight, tailored solutions, Grasshopper ensures the prostheses are comfortable for long-term use and tailored to the patient's medical and aesthetic requirements.

Grasshopper's computational design approach offers significant advantages over traditional prosthesis manufacturing methods, which often involve high costs and limited design flexibility. Grasshopper provides a more cost-effective solution, enabling rapid prototyping and iterative improvements. Its parametric design capabilities allow for the creation of prostheses that are lightweight, flexible and compliant with stringent medical standards. These features make Grasshopper an invaluable tool in addressing the growing demand for personalized and affordable prosthetic solutions.

This research aims to explore how Grasshopper can revolutionize the production of 3D printed prostheses by making them more accessible, affordable and tailored to individual needs. By combining computational modelling with additive manufacturing, this approach seeks to deliver prostheses that are not only functionally superior but also emotionally and aesthetically fulfilling for the user. A critical aspect of this exploration involves ensuring that the designs meet medical standards while optimizing comfort and fit, which are key challenges in the field. Utilizing Grasshopper's capabilities could drive significant advancements in prosthesis development, ultimately improving the quality of life for patients through innovative, personalized solutions.

Link to Program of Requirements (PoR):

Table 13: Requirements grasshopper code

Requirement	Description	Measurement Method	Validation Method	Unit	Success Criteria
R17	The prosthesis design must support surface textures to improve grip and reduce slippage.	Surface texture evaluation	User feedback on grip and stability	Grip rating (1-10)	Rating ≥ 8 for grip and slippage reduction
R18	Grasshopper must be used to optimize internal structures for weight reduction and durability.	Grasshopper optimization analysis	Comparison of optimized vs. non-optimized structures	% Weight reduction	$\geq 15\%$ weight reduction with maintained durability

2.7 Summary research gaps

Although many breast prostheses are already available on the market, this research reveals several important gaps that still exist in the current solutions. These gaps are not only technical, but also concern comfort, aesthetics, accessibility, and emotional support. The insights gathered from the benchmark analysis, company visits, cocreation sessions, and technological explorations show that many aspects of the prosthesis experience can still be significantly improved.

One major gap is the lack of comfort in traditional prostheses. Many survivors report that standard silicone prostheses are too heavy, rigid, and poorly ventilated. This results in discomfort during daily wear, especially in warm climates or during physical activities. Although lighter models are available, they often still rely on outdated materials that are not breathable or adaptable to the user's body temperature.

Another important gap concerns the limited personalization. Many prostheses are offered in a fixed number of sizes and shapes, which do not reflect the diverse anatomical needs of users. Especially for women who underwent breast-conserving surgery, partial prostheses are still underdeveloped and rarely available in a variety of forms. The result is often a poor fit, which affects both physical comfort and emotional well-being. There is also little room for users to adapt their prostheses over time as their body changes, such as during recovery, weight fluctuation, or aging.

From a production point of view, the traditional mold-based manufacturing methods limit the potential for customization and flexibility. These processes are time-consuming, generate material waste, and require multiple steps before reaching a final product. This makes custom-made prostheses expensive and often inaccessible to a larger audience. In contrast, modern technologies such as 3D printing offer more efficient and personalized production options, but are still rarely used for external breast prostheses.

In terms of design and structure, there is a lack of innovation in internal geometries. Most prostheses are made with a solid silicone core, which makes them heavier and less adaptable. The integration of hole structures or lattice designs—such as Voronoi patterns—could significantly reduce weight and increase breathability, but are not yet widely applied in this sector. Research into these lightweight structures shows great potential, especially for users with an active lifestyle.

Another research gap is the limited use of digital tools such as 3D scanning and parametric design software. While these technologies are increasingly common in other areas of medical design, their application in external breast prostheses is still at an early stage. Self-scanning using smartphones, for example, offers a low-cost and accessible solution, but has not yet been systematically tested for this purpose. The combination of self-scanning with parametric tools like Grasshopper can enable faster, cheaper, and more customized prosthesis design.

Finally, the emotional and psychological dimension of wearing a prosthesis is often overlooked in current designs. A prosthesis is not only a medical device, but also a personal object that plays a role in body image, confidence, and self-esteem. Existing solutions often fall short in offering natural aesthetics, personalization, and emotional support through design. Users are looking for prostheses that feel like a part of their body and identity—not just a replacement.

This thesis addresses these research gaps by exploring how digital tools, such as self-scanning and 3D printing, can be combined with cocreation design strategies to create lightweight, personalized, and emotionally supportive breast prostheses. The integration of advanced materials, adjustable features, and digital workflows aims to offer a more flexible, inclusive and accessible solution for breast cancer survivors.

2.8 Program of Requirements

The final Program of Requirements (PoR) collects the main points derived from earlier research, company visits, expert feedback, and emerging technologies. It defines the key criteria for designing improved external breast prostheses. These requirements directly address the most common limitations in current solutions, such as discomfort, poor fit, limited lifespan, and lack of

personalization. By focusing on both physical and emotional needs of women after mastectomy, this PoR aims to guide the development of prostheses that are lighter, more comfortable, more affordable, and more natural in appearance.

Each requirement in the PoR is clearly linked to insights from the literature review, benchmark analysis, and company visits (e.g., to Anita), as well as to technical innovations like 3D printing, 3D scanning, and parametric modeling. This ensures that every criterion is grounded in real user needs and aligned with medical and industry standards. The PoR is not only a checklist but also a strategic framework to guide the iterative development process toward patient-centered, sustainable, and functional outcomes.

Table 14 presents the complete Program of Requirements. All requirements listed in Table 14 are consolidated from earlier tables—specifically Tables 1, 8, 9, 10, 12 and 13. By gathering them into one structured overview, this PoR offers a practical and comprehensive design guideline for future development and prototyping. These requirements will support the creation of a new generation of external breast prostheses that combine comfort, usability, customization, and emotional support.

Table 14: Final Program of Requirements (PoR)

Requirement	Description	Measurement Method	Validation Method	Unit	Success Criteria
R1	The prosthesis must be lightweight for daily wear comfort.	Weight measurement	Comparison with average commercial prostheses	g	$\leq 200\text{g}$ for full prosthesis
R2	The prosthesis must closely match the patient's anatomical contours.	3D scan comparison (pre-op/post-op if applicable)	User feedback, clinical fit evaluation	% Fit accuracy	$\geq 90\%$ anatomical conformity
R3	Must be made from skin-friendly, breathable materials.	Material testing (ISO 10993)	Dermatological evaluation, user testing	Qualitative	No irritation in 95% of test users
R4	The prosthesis must be cost-effective without compromising quality and usability.	Cost analysis per unit	Comparison to industry standards	Euro (€)	$\leq$ market average for similar products
R5	The prosthesis must promote body image satisfaction by closely replicating the natural appearance of the breast.	Visual comparison with natural breasts	Expert review and user satisfaction	Visual appeal rating	85%+ users rate as natural appearance
R6	The prosthesis must incorporate adjustable features to allow for a personalized fit.	Analysis of adjustable components	User feedback on fit flexibility	% Fit satisfaction	$\geq 90\%$ of users report adjustability
R7	The prosthesis must maintain shape and integrity in water.	Submersion and wear tests	User feedback after swimming	% Performance retention	$\geq 90\%$ form stability
R8	The product must support moderate physical activity (e.g. walking, yoga).	Functional test during activity	User satisfaction survey	% Activity suitability	$\geq 85\%$ positive feedback
R9	The prosthesis must have a minimum lifespan of 2 years.	Accelerated wear testing	Expert review and simulated use	Years	≥ 2 years without degradation
R10	The product must use lightweight materials that retain softness, shape, and durability in daily use.	Material analysis, user feedback	Weight and compression tests, tactile assessment	g, N, Softness rating (1-5)	Weight $\leq 200\text{g}$ maintains form and feel over 2 years

R11	The external surface must have a smooth, seamless finish with a texture optimized for user comfort and to minimize potential irritation.	Surface texture analysis	User feedback on comfort and irritation levels	Smoothness rating (1-10)	Rating ≥ 8 for smoothness and comfort
R12	The prosthesis must be fully customizable using 3D scanning data.	3D scanning of user	User satisfaction on fit accuracy	% Customization success	95%+ users report satisfactory customization
R13	The internal structure must use a hole design to reduce weight and improve breathability.	Internal structure analysis	Breathability and weight testing	cm ³ /s/cm ² , g	Breathability > 100 cm ³ /s/cm ² , weight reduction $\geq 15\%$
R14	Silicone 3D printing must be used to ensure efficient production and high precision.	3D printing process evaluation	Comparison of prototypes with traditional methods	Production time, precision	$\geq 95\%$ precision and reduced production time
R15	The prosthesis design process must support self-scanning for improved accessibility.	Self-scanning system testing	User feedback on ease of use	% User success rate	90%+ users can successfully perform self-scanning
R16	The workflow must enable digital storage and modification of scanned models for iterative improvements.	Digital workflow analysis	Testing for ease of storing and modifying models	% Ease of use	90%+ users find the system easy to use for modifications
R17	The prosthesis design must support surface textures to improve grip and reduce slippage.	Surface texture evaluation	User feedback on grip and stability	Grip rating (1-10)	Rating ≥ 8 for grip and slippage reduction
R18	Grasshopper must be used to optimize internal structures for weight reduction and durability.	Grasshopper optimization analysis	Comparison of optimized vs. non-optimized structures	% Weight reduction	$\geq 15\%$ weight reduction with maintained durability

3 METHODS

3.1 Approach to Answering the Sub-questions

To address the main research question—how to optimize the product development of 3D-printed breast prostheses—several sub-questions were formulated. These sub-questions each focus on a specific aspect of prosthesis development, including materials, design strategies, personalization, and user involvement. Together, they guided the methodological approach throughout the thesis. However, due to time constraints and technical limitations, not all sub-questions could be fully explored within the scope of this project. This section outlines the methods and tools used to address each sub-question.

Sub-question I – Which materials can be used in 3D printing to ensure that breast prostheses remain lightweight, durable, safe, and comfortable for users?

To explore suitable materials, a material study was conducted based on an extensive literature review and targeted online searches. The goal was to identify materials that are biocompatible, skin-friendly, lightweight, and durable enough for use in external breast prostheses. In addition to these user-related criteria, materials also had to meet the technical specifications of the 3D printer to ensure printability. Although physical material testing was initially planned to validate these findings through prototyping and user evaluation, this could not be carried out due to practical constraints. Nevertheless, the findings from the literature provide valuable insights and are further discussed in Chapter 4, Section 4.5.

Sub-question II – What infill percentage, layer height, print speed, bed/chamber temperature and curing time should be used to ensure that the prostheses are safe, comfortable, lightweight and durable for users?

This sub-question could not be systematically addressed within this research phase. The original plan involved experimenting with different print settings using slicer software (Simplify3D). However, due to the software's complexity and limited available time, this was not feasible. Consequently, slicing and 3D printing tasks were outsourced to Yannick Christiaens, who managed these technical aspects. As a result, the print parameters were not formally tested or analysed within the thesis scope.

Sub-question III – What design innovations, such as hole structures or lattice designs, can reduce the weight of 3D printed prostheses?

This sub-question was explored through hands-on prototyping and structural experimentation. Different internal geometries, including voronoi structures and lattice designs, were developed and tested to evaluate their effect on weight reduction and structural stability. These prototypes were produced using FDM printing techniques and assessed for printability and performance. The results are presented in Chapter 4, Section 4.2, and provide promising directions for improving the comfort and wearability of 3D printed prostheses.

Sub-question IV – What types of personal preferences (e.g., shape, weight, texture) can be incorporated into 3D printed prostheses?

User preferences were explored using a MoSCoW analysis, which prioritized needs into Must-haves, Should-haves, Could-haves, and Won't-haves. This analysis was based on qualitative data collected during interviews conducted in the previous academic year as part of the *Cocreation* course, as well as feedback from Anita representatives during company visits and interim presentations. These

findings were instrumental in defining user-centered design requirements and are elaborated in Chapter 4, Section 4.4.

Sub-question V – How can user feedback (e.g., from breast cancer survivors) be integrated into the design optimization process?

While the original methodology included user testing and scenario testing to integrate feedback, these activities could not be executed as planned due to time constraints and delays in the development of the Grasshopper code. As a result, one-on-one interviews with patients were not carried out, as they were intended to take place after these testing activities. However, qualitative feedback was collected through discussions with doctors, prosthesis experts, and design professionals. These insights were valuable for shaping design considerations and highlight the importance of incorporating formal user testing methods—such as scenario testing and QAP (Questionnaire After Protocol)—in future iterations.

Sub-question VI – What insights can be drawn from the characteristics of breast prostheses from benchmarks to optimize the design of 3D printed breast prostheses?

This sub-question was addressed through a detailed benchmark study of 32 commercially available breast prostheses from companies including Anita, Amoena, Trulife, and ABC. Products were compared on aspects such as fit, weight, materials, aesthetics and comfort. This analysis revealed both best practices and gaps in the current market, which informed the design direction of the 3D printed alternative. The findings are discussed in Chapter 2, Section 2.2.

Sub-question VII – How can a Grasshopper program/code be used to create a personalized prosthesis model?

This sub-question was addressed through the development of a parametric model using Grasshopper, a visual scripting environment integrated within Rhino. The script enables the generation of personalized prosthesis models based on individual parameters, such as 3D breast scans. Although technical issues delayed the completion of the script, a functional version was developed and is discussed in Chapter 4, Section 4.1. This Grasshopper tool forms the foundation for mass customization and virtual prototyping in future product iterations.

3.2 Design Process

The research methodology employed in this project integrates several complementary approaches, creating a seamless, iterative process focused on developing a 3D printed breast prosthesis that meets both functional and emotional needs of breast cancer survivors. The overall process follows a research-through-design approach, which is structured around continuous cycles of iteration, testing, and refinement.

3.2.1 Integration of Methodologies

At the core of this methodology is an iterative design protocol, which forms the backbone of the development process. This approach enables rapid prototyping and testing, allowing for ongoing improvements based on real user feedback. Each design and evaluation cycle brings the product closer to fulfilling the practical, emotional, and contextual needs of its intended users.

This project is methodologically situated within the broader domain of human-centered innovation, drawing specifically on concepts from **user-centered design (UCD)**, **human-centered design (HCD)**, **participatory design (PD)**, and **codesign**. While UCD and HCD focus on understanding user needs through observation and testing, participatory design and codesign move beyond observation by actively involving users as cocreators throughout the process. In this thesis, users—specifically breast cancer survivors—are considered partners rather than subjects, contributing meaningfully

through cocreation sessions, design feedback, and scenario-based testing. This participatory role fosters greater empathy, personalization, and alignment between product and user experience [55].

This position is visually supported by Sanders and Stappers' (2008) framework, *The Landscape of Human-Centered Design* (Figure 466), which illustrates the spectrum between user-as-subject and user-as-partner, and between research-led and design-led approaches. The methodology applied in this thesis occupies the upper-right quadrant—**design-led, participatory design research**—where generative design tools and emotional engagement drive innovation in close collaboration with users.

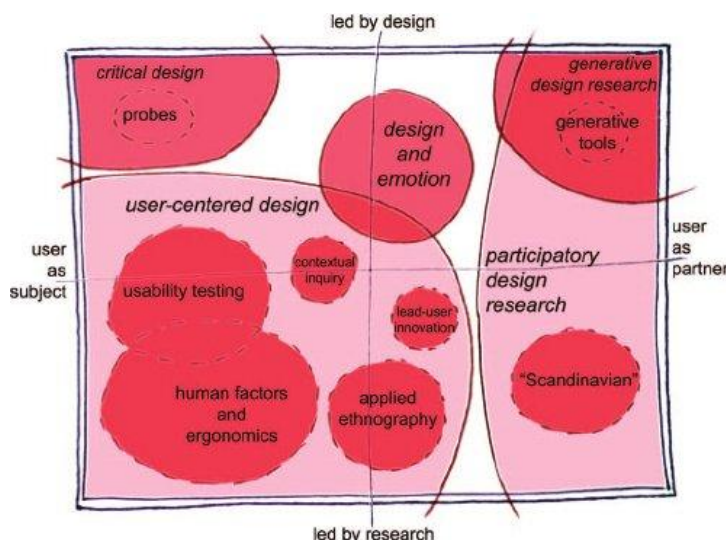


Figure 46: The Landscape of Human-Centered Design

The design process begins with problem definition, where gaps in current prosthetic solutions are identified through benchmarking and user research. These early insights serve as the foundation for conceptual exploration and prototyping, ensuring that the design direction remains grounded in real-world challenges and user expectations.

Once the problem is clearly defined, the conceptual design phase begins. Here, initial ideas are developed and visualized using 3D models. These early concepts are informed by insights gained from the problem definition phase, ensuring that the design process is driven by user-centered needs. The integration of cocreation in this stage further strengthens the design process. In a cocreation approach, users are directly involved, not just as testers but as collaborators who share their lived experiences to shape the design. This continuous collaboration helps refine concepts in alignment with users' preferences, making the design more personal and impactful.

The prototyping phase involves translating conceptual designs into physical form using advanced 3D printing techniques. These prototypes are intended to be tested for both functional performance and emotional resonance with users. The evaluation phase was designed to include user assessments based on criteria such as comfort, appearance, and overall usability. Ideally, feedback from this phase would inform the next design iteration by identifying areas for improvement in terms of fit, material, and aesthetics.

However, due to technical constraints and limited time, it was not possible to gather user feedback on the silicone prototypes before the submission deadline. The use of the new silicone printer was delayed by unresolved technical issues, particularly regarding long struggling with the parametric code in Grasshopper and the generation of proper support structures in the slicer software. A potential solution for the support involving a removable nipple module required adjustments to the parametric code in Grasshopper. The updated files were sent to Yannick Christiaens, lecturer at Ghent University and researcher at Design Nexus, who has extensive expertise in 3D printing, to attempt slicing and 3D printing. As of 19 May, the silicone prototype had not yet been completed. The first print attempt on 21 May failed shortly after a material change, which disrupted the process. A second attempt was initiated on 22 May; however, due to the required printing time, it could not be completed before the final thesis deadline of 22 May. As a result, it was not possible to include a

photo of the completed prototype in this thesis. Moreover, the limited timeframe did not allow for additional iterations or user testing. These crucial steps will need to be addressed in the subsequent phase of the development process to validate the prototype's fit, comfort, and functional performance.

Despite this, valuable feedback was already collected on earlier prototypes made of PLA and TPU 95A HF during visits to Anita's headquarters. Representatives from Anita provided expert insights regarding the look, feel, and usability of these prints. Additionally, feedback was gathered from fellow students, thesis mentor Lore and Yannick, all of whom contributed to refining the design direction. While formal user testing remains a recommended next step, the existing evaluations offered relevant input for iterative improvements within the available timeframe.

Each iteration in this process is further informed by the Pahl and Beitz design method (Figure 477), which structures product development in a systematic way. This model ensures thorough technical consideration while integrating user-centered thinking. It supports the iterative process by offering a clear framework that progresses logically from conceptual to detailed design. In the detailed design phase, engineering constraints are evaluated, and decisions regarding material selection, dimensions, and production methods are refined. These choices are re-evaluated after each round of testing and feedback to ensure ongoing alignment with user and technical requirements.

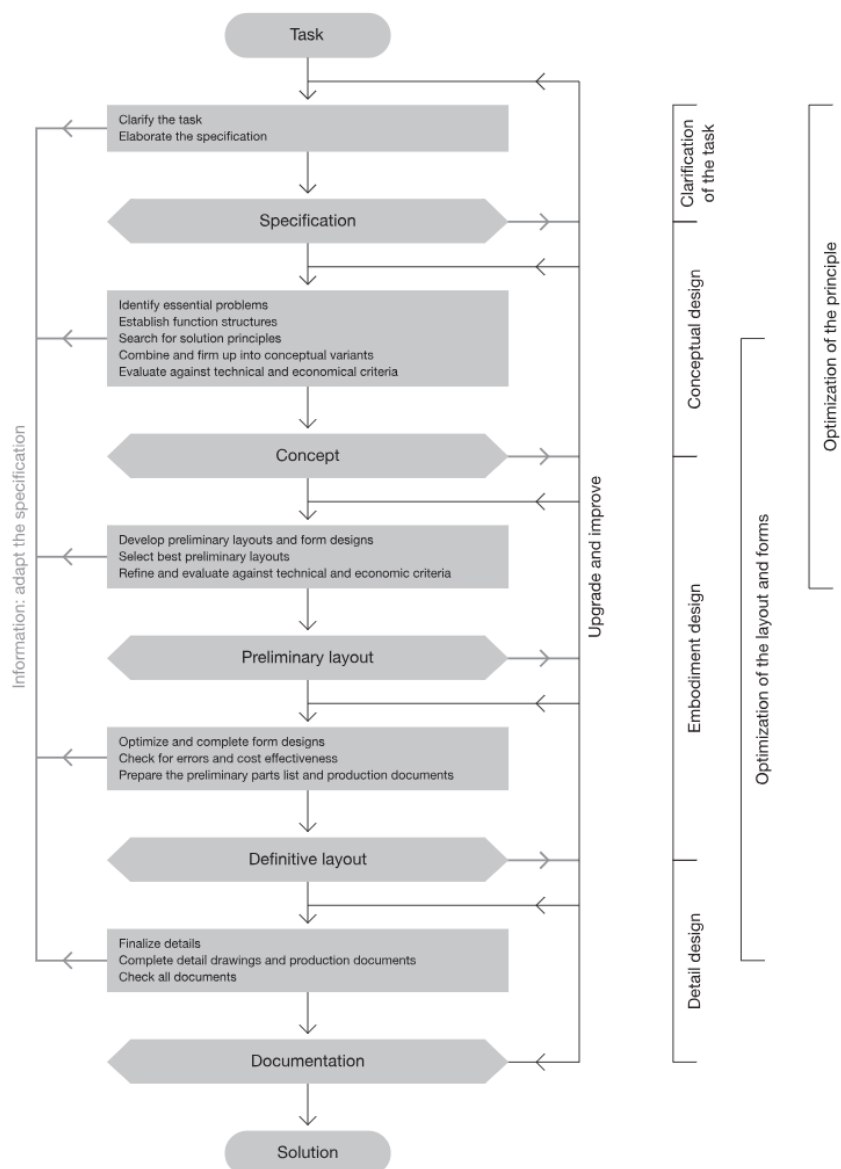


Figure 47: Pahl and Beitz's design process [56]

Through the combined use of research-through-design, iterative design, cocreation and the structured Pahl and Beitz approach, this project avoids redundancy while ensuring that each stage builds logically on the previous one. The integration of these methodologies results in a development process that is both flexible and robust, leading to a breast prosthesis that meets the functional, aesthetic and emotional needs of breast cancer survivors. This methodology highlights the critical role of continuous user involvement, ensuring that the final design is not only technically sound, but also personally meaningful and widely accepted by its intended users.

3.2.2 Medical Device Design Process

The development of a medical device typically follows a structured, phase-based approach to ensure regulatory compliance, user safety, and product quality. This process (Figure 488) supports the gradual refinement of the product through multiple stages, starting from the identification of user needs and progressing towards design, prototyping and testing. At the center of this process is the iterative translation of user and technical requirements into tangible solutions, validated step by step through research, risk management and feedback integration.

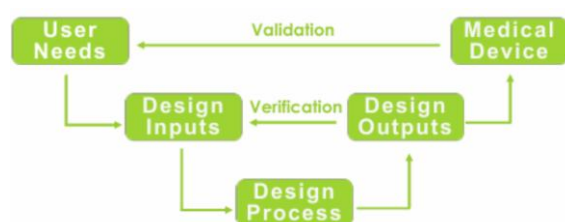


Figure 48: Medical Device Design process in Regulatory Affairs S4040

In the early stages of this project, particular emphasis was placed on understanding the European Medical Device Regulation (MDR) and the ISO 13485 quality management standard. A discussion with Pieter Beerten, researcher at Ghent University with expertise in medical device development, clarified that while MDR provides the legal framework for medical devices within the European Union [57], ISO 13485 offers a practical, process-based guide for managing design control, documentation, and risk assessment [58], [59]. Although ISO 13485 is not legally required for Class I devices, it was recommended as a structuring tool due to its operational clarity and alignment with best practices for this thesis. Any deviations from or omissions of regulatory requirements were deliberately documented and justified to demonstrate responsible design decisions.

To further strengthen the regulatory foundation of the project, additional research was conducted throughout the development process. This included analysis of official MDR classification guidelines [60], [61], the ISO 13485 standard [58], content from the Regulatory Affairs S4040 module [62], and relevant academic literature such as Biodesign [63] and Medical Device Design [64]. This regulatory research influenced important strategic decisions, including device classification, risk management approach, material traceability and sustainability considerations. It also ensured that, despite limited time and scope, the project maintained alignment with the essential principles of compliant medical device design. The knowledge gained will continue to guide future iterations, including verification, validation and CE marking efforts.

This thesis focuses on the initial development stages of a 3D printed, custom-made breast prosthesis—specifically Phases 0 to 2, as outlined in Figure 499. The later phases—Verification (Phase 3), Validation (Phase 4), and Market Launch (Phase 5)—fall beyond the scope of this thesis due to time constraints and the significant regulatory workload required for full conformity assessment. Nevertheless, the structured methodology applied here lays a solid foundation for future continuation.

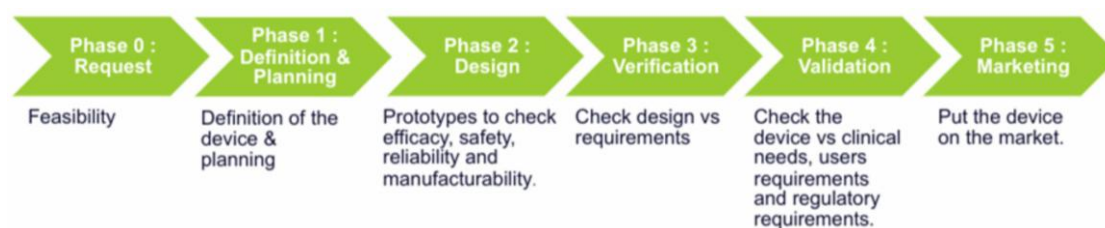


Figure 49: Design and Development process

3.2.2.1 Phase 0: Request (Feasibility Assessment)

Phase 0 focused on evaluating the feasibility of developing a custom 3D printed breast prosthesis that meets both user expectations and medical device regulations. This included assessments of technical viability, market potential, and regulatory classification.

Although ISO 13485 recommends the creation of formal documentation such as a Feasibility Report and Design Request Form, these were not developed as separate files during this thesis. Instead, all relevant decisions and insights were logged in a central working document titled 'MDR research Notes'. Planning and task management were facilitated using Miro board, allowing the process to remain organized and traceable even in the absence of formal design control records.

Benchmarking and Market Research

As introduced in section 2.2, a comprehensive benchmark study was conducted on 32 commercially available breast prostheses from companies including Anita, Amoena, Trulife, and ABC. These products were evaluated based on key attributes such as comfort, materials, aesthetics, and suitability for activities like sports and swimming.

Additionally, two innovative companies—EVE and Hashtagtwo—were analysed for their use of emerging technologies such as digital body scanning, 3D printing, and advanced materials like silicone and recyclable compounds. Their custom production methods demonstrated how such technologies can better address individual user needs. These insights played a crucial role in defining key requirements and shaping the direction of this thesis project.

Regulatory Classification and Strategy

In parallel with the technical and user-centered research, a preliminary regulatory classification was established. Based on the classification rules in Annex VIII of the Medical Device Regulation (MDR) [57], the proposed prosthesis is expected to fall under Class I. This classification is justified by the fact that the device is non-invasive, contacts only intact skin, and is intended for long-term use (over 30 days) [60], [61].

While Class I devices are subject to relatively simple regulatory pathways, it remains important to thoroughly substantiate the classification rationale. This justification was developed with support from the S4040 Regulatory Affairs [62] and relevant MDR documentation [57]. These sources also emphasized the importance of CE marking, correct labelling, and the eventual assignment of a Unique Device Identifier (UDI), even for devices in the lowest risk class [65], [66].

Intellectual Property and Freedom to Operate

To reduce the risk of potential intellectual property conflicts, a preliminary freedom-to-operate (FTO) analysis was performed on Google Patents. Several existing patents relevant to 3D printed breast prostheses were briefly reviewed, including:

- CN105997313A – *3D printed breast external prosthesis and manufacturing method*
- WO2019164390A1 – *Custom-made external breast prosthesis*
- CN104783924B – *Breast prosthesis manufacturing method based on 3D printing*
- WO2024127312A1 – *Breast prosthesis*

The analysis showed that while some aspects of 3D printed breast prostheses have already been patented, there remains space for innovation in areas such as custom design workflows, unique structural features, and modularity. This supports the continuation of development without immediate concerns of infringement.

3.2.2.2 Phase 1: Definition and Planning

Phase 1 built upon the initial findings of Phase 0 by translating user insights, sustainability goals, and regulatory requirements into concrete design inputs and an actionable development strategy. This phase focused on the structured definition of product requirements, preliminary risk management, and planning—guided by ISO 13485 principles. While the approach followed the intent of regulatory standards, it was adapted to suit the scope and practical constraints of this thesis.

Definition of Requirements

The definition of requirements was a crucial step in aligning the design process with medical, technical, and user-specific expectations. These requirements were categorized into three main groups: medical, technical, and design-related, and were formulated based on insights from literature, benchmarking studies, user feedback, and sustainability goals.

To ensure traceability and facilitate validation, each requirement was formally documented in the Program of Requirements (PoR), see Table 14, which outlines the associated success criteria, measurement methods, and validation approaches. This structured overview guided decision-making throughout the design process and will serve as the basis for future testing and regulatory evaluation.

Medical Requirements

Medical requirements aimed to ensure user safety and compliance with relevant standards and regulations. These included:

- Use of biocompatible materials (e.g., ISO 10993 compliance)
- Hypoallergenic properties
- CE marking conformity under MDR
- Minimization of skin irritation or adverse reactions during long-term use

These correspond to PoR entries such as **R3** (skin-friendliness) and **R11** (seamless surface finish for comfort).

Technical Requirements

Technical requirements focused on functional and performance aspects essential for everyday use. These included:

- Use of lightweight, breathable, and water-resistant medical-grade materials
- Customizability based on 3D body scans or measurements
- Durability under daily wear conditions, including exposure to moisture, friction, and temperature fluctuations
- Stability in water and during moderate physical activity

Relevant PoR entries include **R1** (lightweight), **R2** (anatomical match), **R7** (form stability in water), **R8** (physical activity suitability), and **R9–R10** (durability and material performance).

Design Requirements

Design considerations focused on comfort, usability, and aesthetic satisfaction. These included:

- A natural and discreet appearance under clothing
- A secure fit that prevents slipping or shifting
- Easy donning, adjusting, and maintenance
- Integration of user-friendly elements, such as a removable nipple module

These design objectives align with **R5** (appearance and body image satisfaction), **R6** (adjustability), **R17** (surface texture for grip), and **R12** (full customization).

In addition to traditional design requirements, several innovative and sustainability-oriented goals were incorporated into the PoR, such as:

- **R13**: Weight-reducing and breathable internal hole structures
- **R14**: Precision and efficiency through silicone 3D printing
- **R15–R16**: Accessibility through self-scanning and digital model iteration
- **R18**: Structural optimization via parametric design in Grasshopper

Together, these requirements provided a comprehensive framework that ensures the prosthesis meets user needs, adheres to regulatory expectations, and incorporates forward-looking, inclusive, and sustainable design strategies.

Risk Management Approach

An initial risk analysis was conducted to identify potential challenges that could arise during both the development and use of the 3D printed breast prosthesis. The risks identified were categorized into five main areas:

- **Health risks**: Potential for skin irritation, allergic reactions, or discomfort caused by poor fit.
- **Material risks**: Challenges related to the compatibility of selected materials with 3D printing technologies, failure to meet safety standards, or high material costs.
- **Production risks**: Possible delays in gaining access to necessary equipment, disruptions in material supply chains, or setbacks in finalizing the parametric design code used to generate the 3D models.

- **User-related risks:** Difficulties in recruiting participants for user testing, limited availability of users to provide feedback, or poor-quality 3D scans compromising fit accuracy.
- **Time constraints:** Limitations affecting the scope of prototype testing, iteration cycles, and completeness of technical documentation.

While ISO 13485 recommends the establishment of a formal *Risk Management File*, a separate document was not created for this thesis. Instead, all identified risks, corresponding mitigation strategies, and relevant reflections were systematically documented in the central working file 'MDR research notes' that accompanied the thesis throughout its duration. This file was continuously updated based on new insights, test results, or changes in planning.

By integrating risk management directly into the development workflow, this approach upheld the intent of ISO 13485—ensuring proactive identification and control of risks—while maintaining a streamlined and flexible format suitable for a research-driven thesis.

Planning and Traceability

Project planning and coordination were facilitated using Miro and Trello, which provided a flexible and visual approach to managing tasks, milestones, and timelines. These tools were chosen for their practicality within a student research context and supported an agile working style throughout the thesis.

In Miro, two timeline-based calendars—one for each academic semester (Figure 5050 and Figure 5151)—were created to map out key phases and deliverables. This allowed for a clear visual overview of the project's progression and enabled adjustments based on evolving insights and priorities. Additionally, Miro served as a central platform for documenting and organizing all design developments, supporting traceability and coherence across iterations.

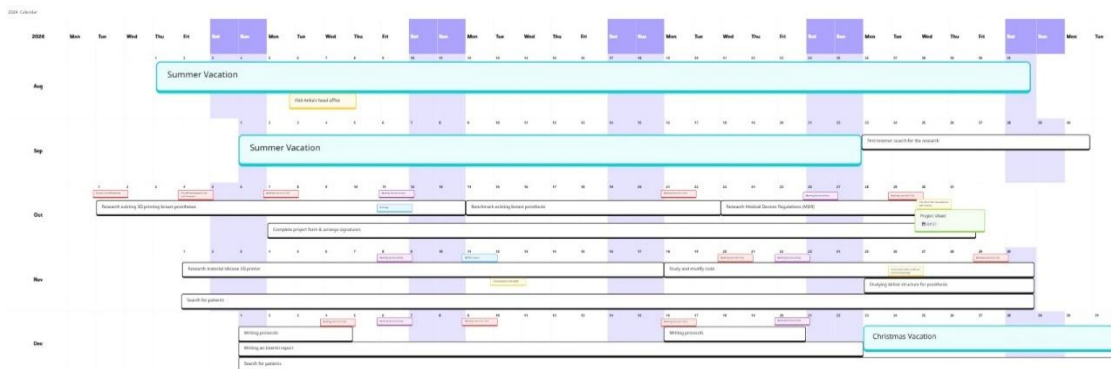


Figure 50: Planning semester 1

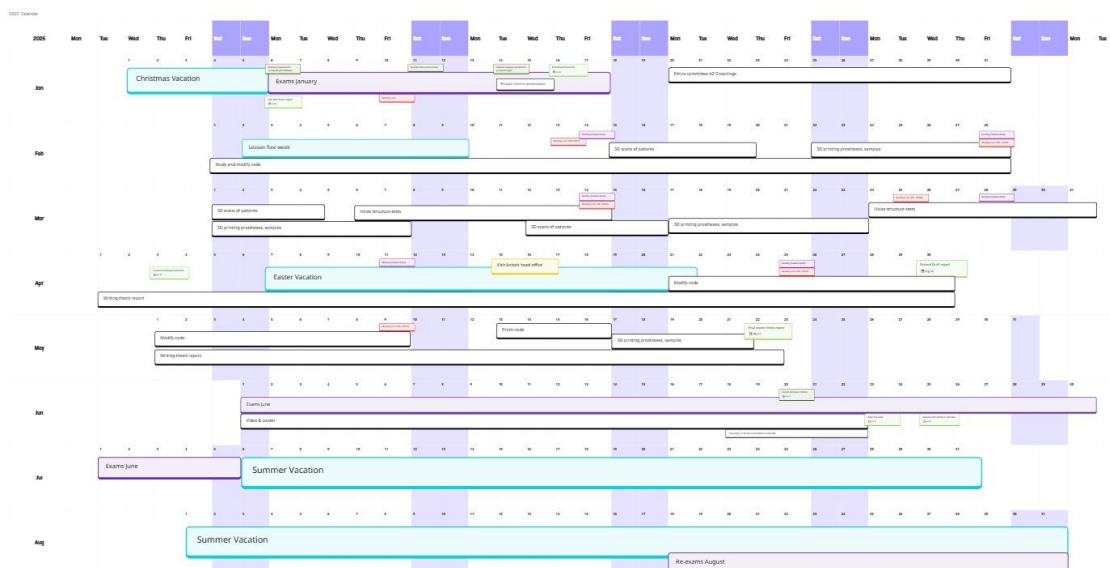


Figure 51: Planning semester 2

Trello was used as a dynamic to-do list, helping track completed tasks and outstanding activities. This enabled efficient task management and ensured continuous progress, even in the face of shifting deadlines or unforeseen challenges.

Together, these tools provided an effective and transparent planning structure that aligned well with the iterative nature of the design process.

Although ISO 13485 recommends the development of a formal Project Management Plan and a clearly defined RACI matrix, these were not created as standalone documents in this thesis. Instead, project roles and responsibilities were informally assigned and monitored through Trello boards and project meeting notes. To ensure transparency and traceability, a structured RACI matrix was later compiled and is presented in Table 15. This matrix summarizes the key responsibilities, consulted stakeholders, and informed parties involved throughout the development process, thereby aligning with the intent of ISO 13485 in a format appropriate for an academic research context.

Table 15: RACI Matrix

Task / Area	Student (Author)	Yannick (3D Printing)	Pieter (MDR/ISO 13485)	Prof. Jan Detand (Ethics committee)	Ethics Committee AZ Groeninge	Breast Care Nurses AZ Groeninge	Daniela & Anita Team	Lore (Promoter)	Manu (AZ Groeninge)	OMD 3D	Patients	Fellow Students	Guidance & Assessment Committees
Project execution	R/A												
3D printing workflow	R/A	C								C		C	
MDR and regulatory strategy	R/A		C										
Ethics compliance	R/A			C	C	C							
Prototype development	R/A	C					C			C	C	C	
User feedback integration	R/A					C	C	C	C		C	C	
Thesis writing and refinement	R/A						C/I	C/I				C	I
Overall project oversight	R/A						I	I					I

3.2.2.3 Phase 2: Design (Prototyping and Early Testing)

In Phase 2, functional prototypes were developed using FDM 3D printing and various materials, including PLA, TPU 95A HF and silicones. The prototypes were tested to evaluate aspects such as weight reduction, material flexibility and ease of printing. Initial results, including those from the hole structure test, will be discussed in more detail in Chapter 4, Section 4.2.

All testing outcomes were documented and fed back into the design loop, allowing for continuous refinement of the prototype. Although clinical validation and formal CE marking under MDR are not part of this thesis, the methodology ensures that the groundwork is in place for future verification and validation stages.

3.2.3 Biodesign Principles

The Biodesign Principles, process shown in Figure 52, presents the different stages for developing a new medical device innovation [63]. It follows a structured approach that helps to move from understanding the clinical need up to preparing a business and development plan for the device. The process is divided into six main phases, which are necessary to ensure the solution is desirable for users, technically feasible, and also viable in the market.

The Biodesign Principles were introduced during the elective course Biomedical Product Development, where I also received a first brief introduction to medical device regulations such as the MDR and GSPR [57], [65], [66]. This foundational knowledge provided valuable context for integrating regulatory considerations early in the product development process.

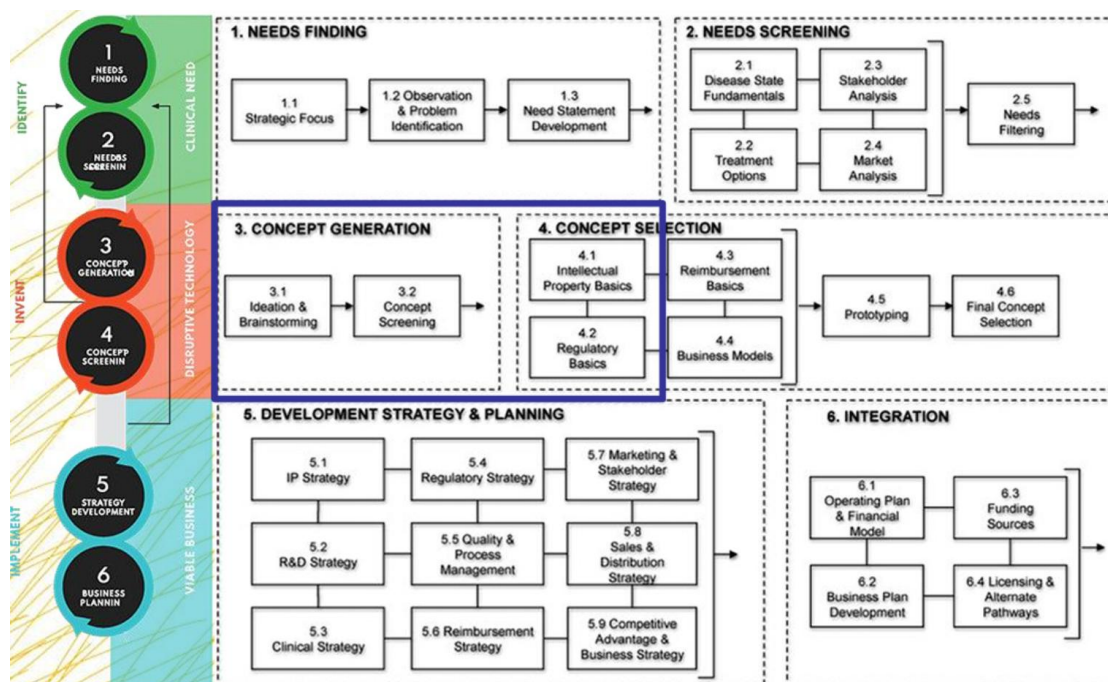


Figure 52: The Biodesign Principles

The first phase is Needs Finding. In this phase, it is important to study the clinical environment, talk with stakeholders and observe the real situation to identify unmet needs. The needs should not only

be understood in general but also need to be described in a strategic way to see which needs are the most important and where innovation can have the biggest impact.

After that, the second phase is Needs Screening. Here the needs that were identified are analysed deeper. Stakeholders and market size are evaluated and needs are filtered to select only those that are realistic to solve and have enough importance. Not all needs found at the beginning are suitable to develop into products, so this phase is important to focus the resources correctly.

The third phase is Concept Generation. In this part, I start to create ideas and brainstorm possible solutions. Different concepts are generated based on creativity and the understanding from the previous phases. It is important to explore a wide range of possibilities at this step before deciding which ones are the most promising.

Then, the fourth phase is Concept Selection. In this phase, the different generated ideas are compared. Important knowledge about intellectual property and regulatory aspects is considered to check if the concepts are feasible from a legal and regulatory point of view. Also, business models are discussed to see if there is a path to market. Prototyping is used to create first versions of the device or solution and at the end, a final concept is selected based on evaluation of all these criteria.

The fifth phase is Development Strategy & Planning. Once a final concept is selected, it is necessary to create a plan for how to develop the device further. This includes building strategies for product development, quality assurance, reimbursement, regulatory approval and business strategy. Good planning in this phase is critical for the success of the innovation.

The sixth and last phase is Integration. This phase focuses on creating an operating plan and financial models, finding funding sources and also preparing for licensing or alternative business pathways. Integration is about combining the technical, clinical and business aspects into a single strong strategy to move forward toward commercialization.

This structured process helps to ensure that medical device development is systematic and considers not only technical feasibility but also user needs, regulatory requirements and market viability from the beginning. Following this model increases the probability that the developed product will be successful in the real world.

3.3 Stakeholder mapping

A comprehensive stakeholder mapping (Figure 5353) was conducted in the early stages of the project in order to obtain a thorough understanding of all the individuals, groups, and organizations who were involved in or could be affected by the development of the 3D printed breast prosthesis. Identifying and mapping stakeholders from the beginning helped to ensure that a wide range of relevant perspectives, needs, and expectations could be considered and integrated into the product development strategy. This approach made it possible to build a design process that is not only innovative and technically feasible, but also socially relevant, patient-centered, and aligned with medical practice.

To structure the stakeholder engagement, all stakeholders were categorized based on their level of involvement and influence in the project. Three main levels were defined: core stakeholders, involved stakeholders, and informed stakeholders. This classification helped to determine how frequently and in what way each stakeholder should be consulted or communicated with, depending on their role and relevance to the design process.



Figure 53: Stakeholder Map

Core stakeholders represent the most central actors in the project. They were involved directly in shaping the development process and decision-making. This core group included the promoter at Ghent University, who guided the academic research of the thesis. Furthermore, both the assessment committee and the guidance committee played important roles in the academic supervision and evaluation of the project. As the designer and author of this thesis, I was also part of the core team, responsible for the execution of the research, the conceptual and technical design of the prosthesis, and the facilitation of cocreation sessions. In addition, the external supervisor from Anita Dr. Helbig GmbH, a key industry partner, was included in the core stakeholder group. This person provided professional expertise in the field of breast prostheses.

Involved stakeholders were those who contributed meaningfully to the project but were not involved in daily decision-making. These stakeholders were consulted regularly, especially during specific stages of the design process, such as idea generation, prototype testing, and feedback evaluation. This group included patients, whose input was absolutely essential for understanding the physical, emotional, and practical needs related to external breast prostheses. Their experiences provided direct insight into daily challenges such as comfort, weight, skin sensitivity, and appearance. In addition, various professors offered support on their expertise and knowledge. Doctors and medical professionals, including plastic surgeons and breast care nurses, contributed medical knowledge and patient care perspectives, helping to ensure that the design was safe, suitable, and medically sound. Moreover, external experts, such as specialists in 3D printing, or medical device regulations, were involved when their input was necessary to solve specific challenges or to validate certain choices.

Informed stakeholders were individuals or groups who were not directly involved in the design process but were kept up to date with project developments through newsletters, meetings, or informal discussions. Their awareness and support were still valuable for creating a broad base of understanding and for possible future collaborations. This group included the families of patients, who sometimes offered emotional or logistical support to participants and whose views helped to frame the social and psychological impact of the prosthesis. Fellow students were informed primarily for academic exchange and peer learning purposes. Several hospitals and breast clinics, even if not directly collaborating, were contacted or informed about the research, especially during recruitment. Online support groups and platforms related to breast cancer recovery were also considered important for broadening the communication network. Additionally, the home care store Goed, a potential distribution partner, was informed to understand their practical experience with prosthesis users. Lastly, the 3D printer manufacturer OMD 3D was informed regarding the possible application of their technology, particularly for silicone-based additive manufacturing.

By building this layered stakeholder network, the project was able to ensure that the final product would be well-aligned with medical, emotional, and practical user needs, while also being realistic in terms of technical production and regulatory approval. This mapping not only structured the cocreation process but also contributed to transparency and collaboration throughout the different phases of the development, supporting a user-centered and sustainable innovation in breast prosthesis design.

3.3.1 Finding patients for involvement

The process of finding patients for my thesis was not straightforward. It involved multiple steps, different strategies and a lot of back-and-forth communication. I began by using materials like folders (Figure 544 and Figure 555) and posters to reach potential participants. With permission from Katia Fosselle, one of the contact persons at Goed from the previous year, I placed these materials in two branches of Goed stores, one in Brugge and another in Gentbrugge (Figure 566 and Figure 577). This required coordination by email, but since the contact was already familiar with the process, things went smoothly.



Figure 54: Front side of the folder



Figure 55: Back side of the folder



Figure 56: Folders placed at Goed store



Figure 57: Posters placed at Goed store



Figure 58: Flyer and poster lay-out

At UZ Gent, I was able to distribute flyers (Figure 58) and posters in various departments, including Medical Oncology and the Cancer Center. These areas were important because they're directly connected to the kind of patients I needed for my study. Staff at the Cancer Center were also supportive and helped by placing some of the flyers in extra locations throughout the hospital. This early support from UZ Gent made a big difference later on.

I also contacted AZ Alma Eeklo. My contact person there, Linda Buysse, was helpful and agreed to distribute the materials on my behalf. I provided her with printed posters and flyers to place in the hospital's waiting areas.

In parallel, I attempted to reach participants via social media by posting on Facebook (Figure 599) and Instagram (Figure 6060). While the Instagram post did not generate any responses, Facebook proved to be more effective. I received two direct responses to my post, and because it was shared 13 times, the visibility of my request increased considerably. Although only two persons ultimately responded, the post reached a wider audience that I would not have been able to connect with through hospitals alone.



Figure 59: Facebook post



Figure 60: Instagram post

In an effort to broaden my search, I contacted four different hospitals by email. I asked whether I could place flyers, posters and folders in their waiting areas to find patients willing to participate. Each hospital responded differently. UZ Gent allowed me to place materials without any issues. I was able to deliver everything and get started quickly.

AZ Groeninge was more complex. They advised me to contact their ethics committee before placing any recruitment materials. I had already spoken with my contact person there, Manu Janssens, industrial product designer in health and innovation, along with two breast care nurses, Kathleen Denauw and Corine Duyck, before officially registering my thesis. The process for the ethics committee began in November. I exchanged many emails with my contact person, preparing the required documents and gathering the needed signatures. By mid-January, everything was ready and I submitted the full set of documents to the ethics committee in early February.

In early March, I received their advice. After reviewing the feedback, I realized that several documents were still not in order. It became clear that even if I revised and improved everything, I would have to wait for the next ethics meeting in April. Given that my thesis had to be completed by May, this delay would have left me with too little time to still recruit patients afterward. After carefully considering the timing and workload, I decided not to continue with the ethics process at AZ Groeninge.

At AZ Alma Eeklo, although the initial response from my contact person was good, the overall communication with the hospital was poor. They were extremely busy and replies to my emails were slow or non-existent, except when I contacted Linda Buysse directly. Because of this communication gap and the expected delays in getting approval from the ethics committee, I quickly decided not to pursue that route further either.

I also reached out to Sint Andries Hospital in Tielt by email, but unfortunately, I never received a reply. Despite following up, there was no response from their side.

Throughout this process, a total of 14 patients showed interest in participating. I stayed in touch with them through various communication channels, primarily email, WhatsApp, and phone calls. This flexible approach allowed me to adapt to each person's preferred method of communication, which helped maintain consistent and comfortable contact. Interestingly, even after the initial recruitment phase, I continued to receive messages and calls from potential participants—particularly through UZ Gent. Some doctors there have even started referring patients to me directly, which has been a great support in expanding my outreach.

In total, I have found 16 patients so far (Table 16). It was a long and sometimes frustrating process (Figure 6161), with several dead ends and last-minute decisions, especially regarding ethics approvals. But despite the obstacles, I was able to find a good number of participants thanks to persistence, strategic communication and the support of a few key contacts.

Table 16: Number of patients

Channels	Number of patients
AZ Alma	1
AZ Groeninge	0 → stop ethics committee
UZ Gent	13
Sint Andries Tielt	0 → no response
Social Media	2
Total	16

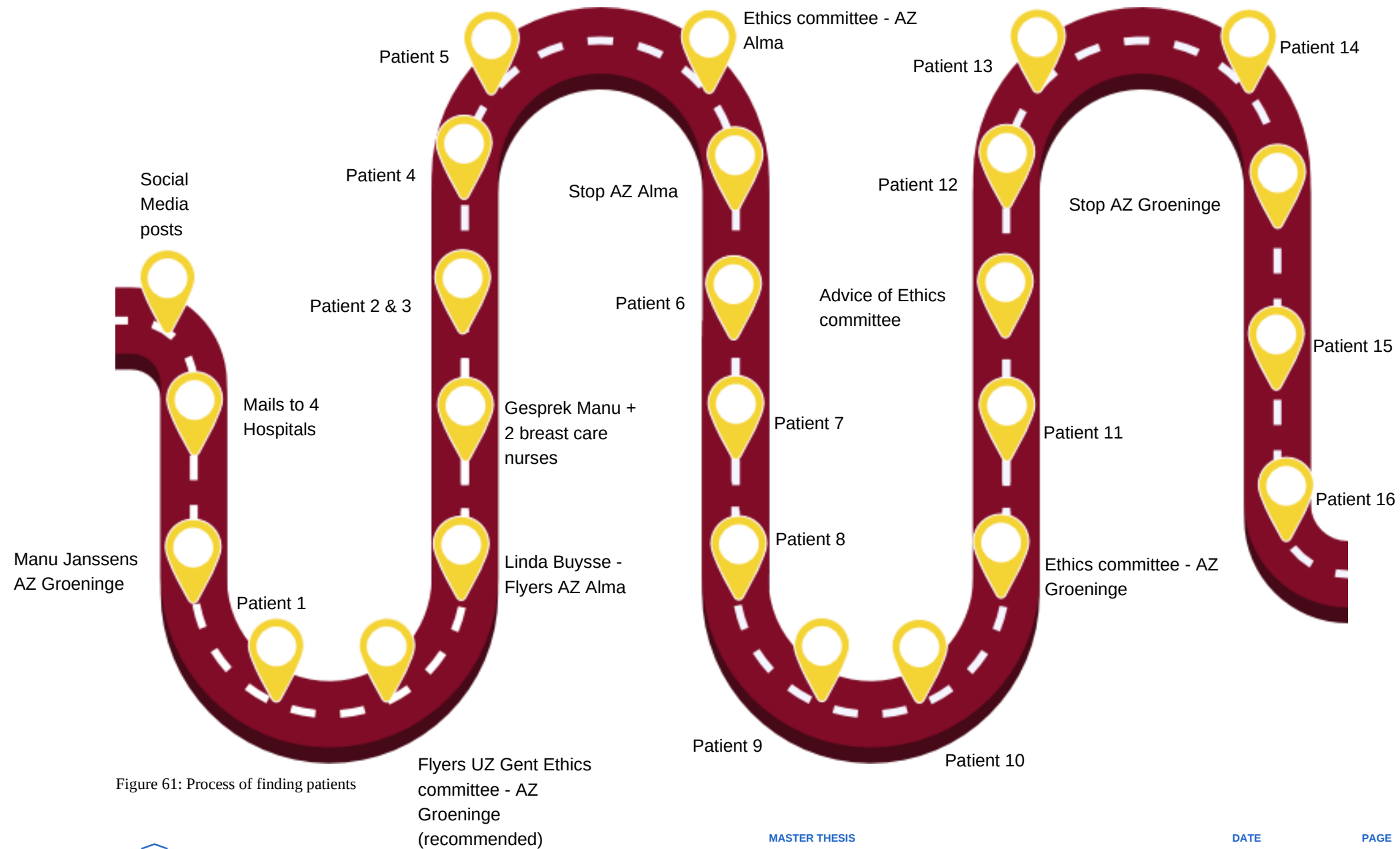


Figure 61: Process of finding patients

3.4 Bridging Engineering and Design

An Industrial Engineering Industrial Design (IO) student is well-prepared to conduct this thesis because of their multidisciplinary education, which brings together a strong knowledge of engineering with advanced design methods, including cocreation approach. This unique combination gives them the technical skills, creative problem-solving abilities and human-focused perspective needed to deal with the complex challenges of designing 3D printed breast prostheses.

IO students have a broad technical education in subjects like mechanics, electricity, chemistry, physics, mathematics, materials science, statistics and electrical systems. Their training in research methodologies and academic writing helps them to approach the project in a structured and scientific way, ensuring that they can perform detailed research, analyse data properly and apply engineering principles in practice.

Besides their technical knowledge, IO students are also well-trained in design. They learn how to sketch, create CAD models and use advanced shaping techniques, which are very important for developing precise and visually appealing designs. Through hands-on experience with production methods such as CNC machining, 3D printing and laser cutting, they are able to bring ideas to life by creating fully working prototypes. This ability to move smoothly from design to production is critical in making a successful product.

Another key strength of IO students is their expertise in user-centered design and codesign. While both approaches focus on incorporating user needs, there is a distinction: user-centered design ensures that user needs, preferences, and constraints guide the design process, while codesign takes this a step further by actively involving users as cocreators throughout the development phase. In this project, a codesign approach is chosen because it empowers breast cancer survivors to actively participate in the design process, allowing their lived experiences, preferences, and feedback to directly shape the final product. This inclusive method ensures that the prostheses are not only technically sound but also emotionally and functionally aligned with users' daily lives. By treating users as experts of their own experiences, codesign leads to more personalized, accepted, and effective solutions. It also helps to build trust and empathy between designers and users, resulting in products that better support physical comfort, psychological healing and personal identity.

4 RESULTS

4.1 Grasshopper code

4.1.1 3D model prosthesis

The starting point for the code of this thesis was the Grasshopper file developed by last year's cocreation team. When I first opened the file, I encountered several issues. Some parts of the code wouldn't load due to a missing plugin, Parakeet (**Error! Reference source not found.62**).

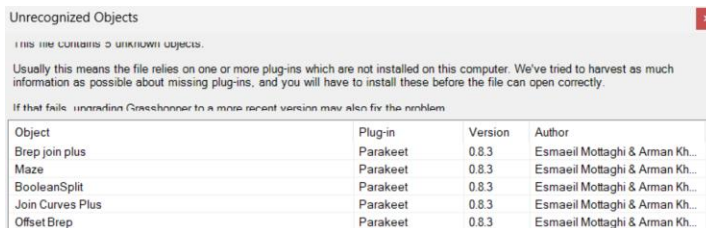


Figure 62: Missing plugin Parakeet

Although I tried to install it multiple times, the plugin was not correctly recognized. After more detailed research online, I finally succeeded in installing it properly. Once the file opened (**Error! Reference source not found.63**), I spent time going through the complete code to understand how it worked. I began refining the file by removing unused code blocks, correcting visible errors indicated by orange and red components, and reorganizing the remaining elements into grouped sections to enhance clarity and overall readability.

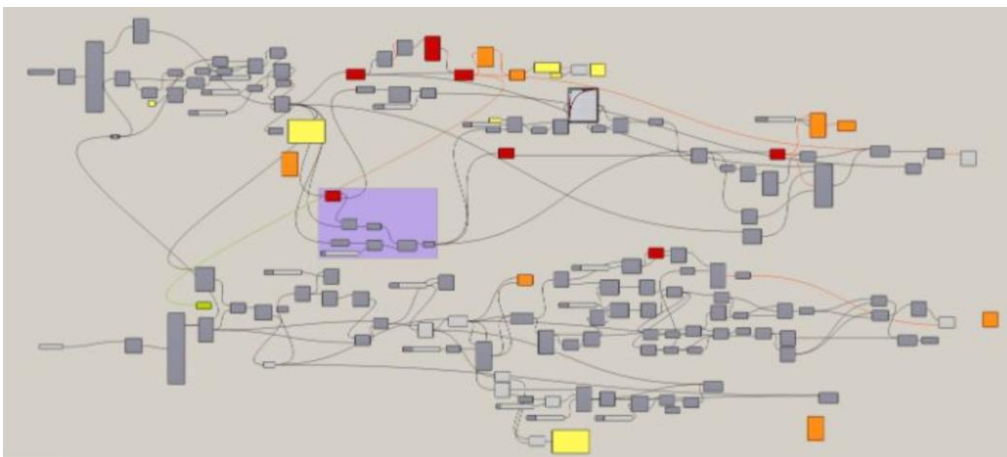


Figure 63: Starting file of last year's cocreation team

However, I ran into performance issues early on. The file quickly became too heavy for my laptop, often causing the screen to freeze or even crashing the entire Grasshopper session. After discussing this with my promoter, Lore, she advised me to use a more powerful computer available at the university in Kortrijk. This device was capable of handling the heavier scripts, and it helped a lot during working sessions on campus. Unfortunately, since I could not take the computer home, my working time with it was limited. I attempted again to working on my own laptop, restarting from the original file and focusing on a different section of the code. This worked for a while, but when I reached the part related to generating the hole structure, the file again became too heavy.

To solve this, I decided to start from scratch in a new file. First, I built the logic for the hole structures using a simpler shape: a hemisphere, which also matched the shape of the test samples that I planned to use during physical prototyping. I chose a hemisphere because it represents a minimalist version of the breast prosthesis while keeping the geometry light and manageable. Once the code worked well on the hemisphere, I gradually applied it to a simplified prosthesis model and finally, to the full breast prosthesis geometry.

For the final 3D model of the prosthesis, I created and tested five different hole structures using a hemispherical shaped test sample. These variations are explained in detail in section 4.1.2 -Hole structure, and include:

- Lattice structure using Crystallon
- Voronoi structure using surface offsetting
- Voronoi structure on the surface of the hemisphere
- Voronoi structure on the full volume of the hemisphere
- Lattice skin on the surface of the hemisphere

Each structure was developed in a separate Grasshopper script, tested independently and then implemented in the larger script for the final prosthesis model. The full program (**Error! Reference source not found.4**) is explained group by group. Within each group, the function and logic of every component are described step by step to give a complete understanding of the parametric design process.

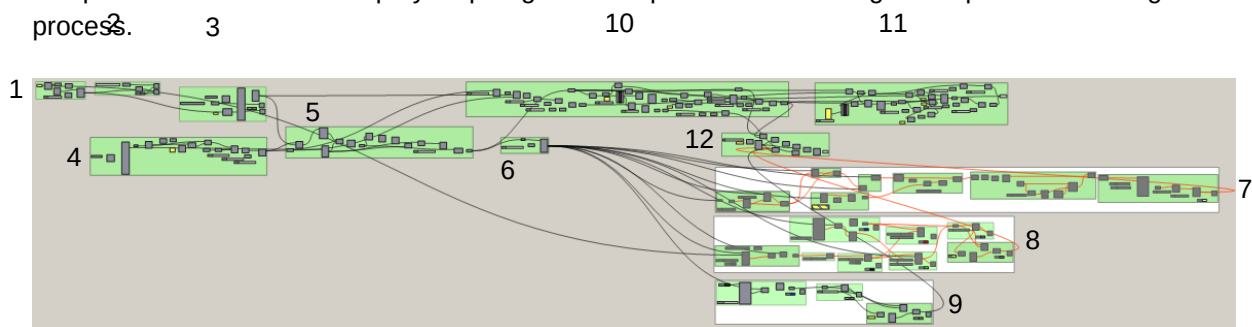


Figure 64: Overview of the final code for the 3D model of the breast prosthesis

4.1.1.1 Shape 3D model prosthesis

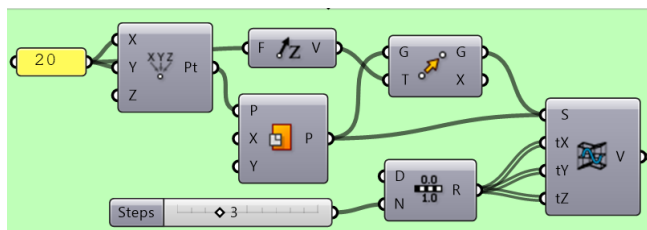


Figure 65: Group 1 of the overview of the final code

This part of the Grasshopper script (**Error! Reference source not found.5**) is used to create a series of interpolated surfaces between two flat planes, using the Morph Between Surfaces component. The process starts with a Note panel that contains the value 20. This value is used to define both the X and Y coordinates in a Construct Point component, creating a point at (20, 20, 0). This point becomes the base for generating the initial plane with the Plane Surface component.

At the same time, the same value (20) from the Note panel is also used as input for a Unit Z vector. This creates a vertical translation vector (0, 0, 20), which is then applied to the plane surface using the Move component. The result is a copy of the original surface, moved 20 units upward in the Z direction.

To create the intermediate surfaces between the original and the moved one, the code uses the Morph Between Surfaces component. This takes both the base plane and the moved plane as inputs (S). A Range component, driven by a Numeric Slider labelled "Steps" with a default value of 3, is used to generate evenly spaced values between 0 and 1. These values are connected to the tX, tY, and tZ inputs of the Morph component. The result is a series of interpolated surfaces that blend smoothly between the bottom and top planes, depending on the number of steps defined in the slider.

Unit cell selection

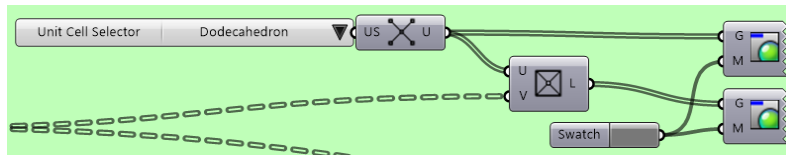


Figure 66: Group 2 of the overview of the final code

After the morphing surfaces are created, this part of the script (**Error! Reference source not found.6**) is focused on filling those volumes with a repeated lattice pattern based on a selected unit cell. The process begins with the Unit Cell Selector, which is a dropdown menu (Figure 67) that allows the user to choose a specific unit cell type, such as BC, Auxetic, or other common lattice structures. The selected option is passed into the Cell Type component, which defines the geometric shape and logic of the chosen unit cell.

This unit cell is then connected to the Cell Fill component. Here, the input U receives the unit cell definition, while the input V is connected to the morph surfaces generated in the previous step. The Cell Fill component takes this combination and populates the morphed volume with repeated instances of the unit cell, aligning them based on the volume's shape and structure.

For visualization, two Custom Preview components are used. The first one shows the geometry of the selected unit cell and the second one displays the complete filled volume after the cell filling process. Both previews use the same Colour Swatch for consistent visual appearance. This helps the user to clearly see both the unit cell definition and how it fills the larger structure.



Figure 67: Unit cell selector drop down menu

Mesh before surgery

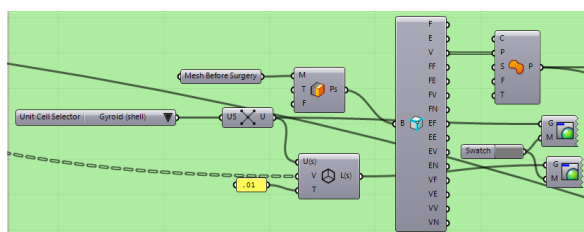


Figure 68: Group 3 of the overview of the final code

In this part of the Grasshopper script (**Error! Reference source not found.8**), the focus is on preparing an existing mesh geometry—labelled “Mesh Before Surgery”—for a shell-based lattice filling operation. The selected mesh is first imported from Rhino and then connected to the Mesh to Polysurface component, which converts the mesh into a NURBS-based polysurface. This conversion is important for creating clean surface topology that can be used in further operations. The resulting polysurface is then analysed using the Topology component, which extracts surface information such

as vertices, edges or UV data. This data is passed into a Patch component, which creates a continuous surface from the topology's points and allows a clean domain to apply lattice structures.

At the same time, the user selects a shell-based Unit Cell from a dropdown menu (Figure 67) using the Unit Cell Selector. This choice defines the base pattern that will be used to fill the geometry. The unit cell is processed through the Cell Type component and then visualized using a Custom Preview, with a shared Colour Swatch applied for consistency. After visualization, the unit cell is input into the Cell Shell Fill component at input U(s), which supports shell-type unit cells. A panel note is connected to input T, setting a numerical thickness value of 0.01, which defines the shell thickness applied to the unit cell structure. The final result is another Custom Preview showing the filled shell lattice, now shaped and scaled according to the surface derived from the original mesh.

Mesh after surgery

This section of the Grasshopper script (**Error! Reference source not found.9** and **Error! Reference source not found.70**) focuses on analysing and processing the mesh labelled "Mesh After Surgery", which is also imported from Rhino. The goal is to extract and manipulate a subset of points from the surface based on their Y-coordinates and use those to generate directional structural lines.

In the first part of the workflow (Figure 69), the selected mesh is converted into a polysurface using

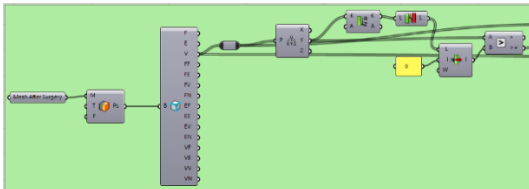


Figure 69: Group 4 of the overview of the final code, part 1

the Mesh to Polysurface component, ensuring it has proper NURBS topology. The resulting polysurface is passed into the Topology component to extract relevant vertex information. A Relay organizes the output, which is then deconstructed into X, Y and Z values using the Deconstruct Point component. To identify the highest points in the vertical (Y) direction, the Y-values are sorted using the Sort List component

and the sorted list is reversed so that the highest values appear first. A List Item component extracts the first item from the reversed list—effectively the highest Y-value—controlled by a Panel Note with index 0. This value is compared to all other Y-values using the Larger Than component. The output is a Boolean pattern that marks which points are at or above the extracted height threshold.

In the second part (Figure 70), the Cull Pattern component filters these points, keeping only those that

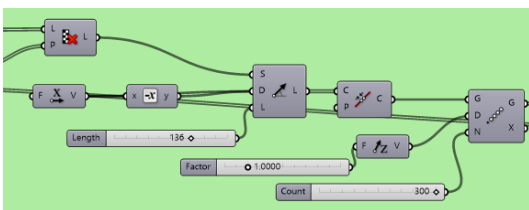


Figure 70: Group 4 of the overview of the final code, part 2

meet the condition. The remaining points are used as base locations in the Line SDL (Start-Direction-Length) component. These lines are created by taking the culled points as starting points and then projecting them along the X-direction, which is defined by a Unit X vector. To ensure the lines go in the negative X-direction, this vector is passed through a Negative component before use. The length of each line is controlled by a Numeric Slider labelled Length, here

set to a value of 136. The resulting lines are joined using the Join Curves component, creating continuous curves from the individual line segments. These curves are then copied vertically using the Linear Array component. The array moves the curves along the Z-axis, controlled by a Unit Z vector and a Factor slider (set to 1.0000) and the number of layers is defined by a Count slider (set to 300). The final result is a stacked array of directional lines aligned to filtered points from the post-surgery mesh.

Creating base shape prosthesis

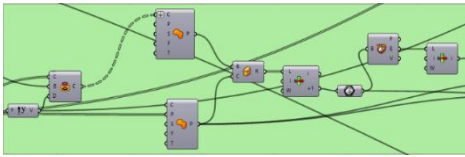


Figure 71: Group 5 of the overview of the final code, part 1

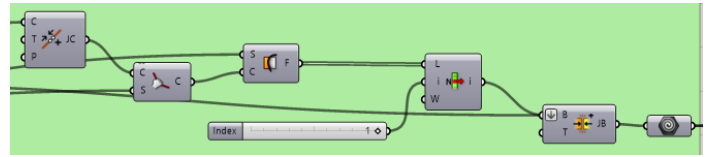


Figure 72: Group 5 of the overview of the final code, part 2

This section of the script (**Error! Reference source not found.71** and **Error! Reference source not found.72**) builds on the post-operative surface data and introduces a method for aligning and merging geometry based on point projection, surface patching and brep manipulation. The goal is to extract a controlled region from the altered geometry and reconnect it with pre-operative structures, forming a hybrid model that preserves continuity between pre- and post-surgical forms.

In the first part of the script (**Error! Reference source not found.71**), the linear array of curves generated in the previous step is projected onto the patch surface created before surgery. This is done using the Project component, where the curves are input as C, the surface as B and the direction of projection as D, set using a Unit Y vector. The result of this projection defines where the curves intersect the surface. This is input into the Patch surface, that is generated by processing the pre-surgery mesh, which serves as the base for further geometric splitting. Next, the Split Brep component is used to divide this surface using the Patch as the cutting tool. This surgical patch was previously generated by processing the post-surgery mesh through Topology and a Patch component. The output of the Split Brep operation is a list of surface fragments, which are sorted and accessed using a List Item component. The correct surface fragment is selected from the Split Brep result using a second List Item. The index for this is controlled via a numeric slider, allowing manual selection of the intended region. The selected piece is converted into a Brep and further processed through Deconstruct Brep, which extracts its edges. A specific edge is isolated using List Item.

In the second part (**Error! Reference source not found.72**), these curve segments are joined using Join Curves Plus to ensure clean boundaries. The resulting curve is then pulled back onto the Patch, that is generated by processing the post-surgery mesh, using the Pull Curve component, aligning it with the actual surgical geometry. This pulled curve is then used to split the post-surgical patch using the Surface Split component. From the result of that split, the correct region is selected using another List Item with index 1 and finally combined with the original brep using Brep Join Plus. The result is a continuous geometry that merges part of the original structure with a new post-operative surface region.

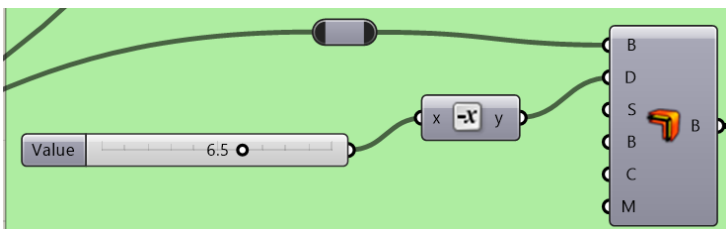


Figure 73: Group 6 of the overview of the final code

This section of the script (**Error! Reference source not found.73**) processes the final geometry created in the previous step. The geometry is first passed through a Relay component and then into the Offset Brep component. This operation creates an inward offset of the original Brep, intended to serve as the base geometry for generating internal hole structures. The amount of offset is controlled by a Numeric Slider labelled "Value", which is set to 6.5. This value is passed through a Negative

component to ensure the offset is directed inward, forming a hollow internal layer within the prosthesis.

This Offset Brep acts as the foundation for the three different hole structures that are developed and explored further in this chapter. Each hole structure is shown using overview images (**Error! Reference source not found.**⁷⁴, **Error! Reference source not found.**⁷⁵ and **Error! Reference source not found.**⁷⁶) for clarity, but the technical breakdown of each version is presented in the respective detailed sections:

- The lattice structure filling the prosthesis volume is described in section 4.1.2.1.

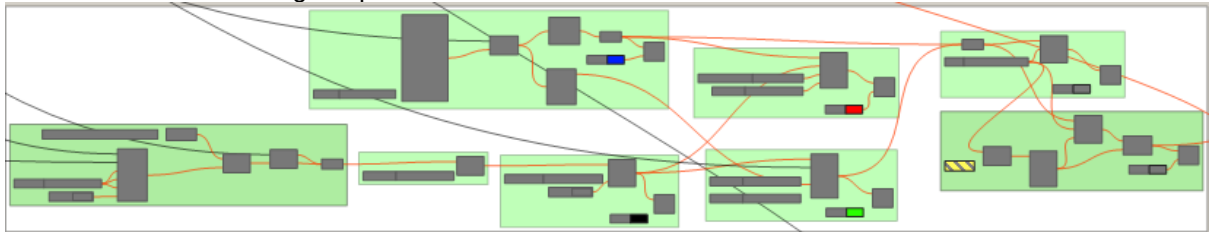


Figure 74: Group 7 of the overview of the final code

- The Voronoi structure applied to the full volume is further explained in section 4.1.2.4.



Figure 75: Group 8 of the overview of the final code

- The lattice skin logic is discussed in section 4.1.2.5.

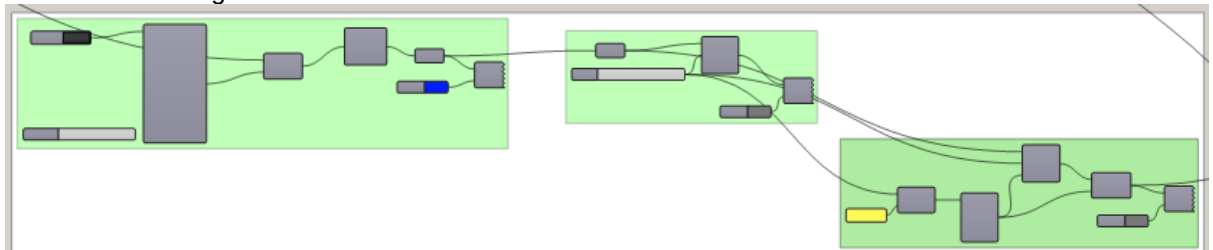


Figure 76: Group 9 of the overview of the final code

During the experimentation process, I also attempted to implement the Voronoi structure with offset (described in Section 4.1.2.2) and the Voronoi structure on the surface (discussed in Section 4.1.2.3) into this Offset Brep. However, these implementations resulted in errors or caused the Grasshopper file to become too computationally heavy, which led the program to crash. Therefore, these options were not included in the final setup but are acknowledged here as part of the design exploration and may be worth investigating further in future work.

4.1.1.2 Removable nipple

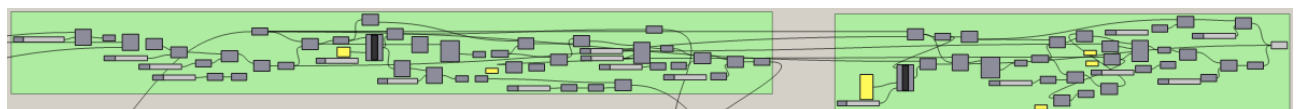


Figure 77: Overview of all the code for the removable nipple

The removable nipple feature (Figure 77) was introduced to provide both aesthetic customization and a practical solution for removing internal support material (hydrogel) from the hole structure of the prosthesis (as mentioned in section 4.6). The idea emerged from a discussion with a fellow student and was positively received by Yannick, promoter and external supervisor at Anita. It was developed through experimentation in Grasshopper, followed by STL export and 3D printing. The design includes an opening in the prosthesis and a rounded, detachable nipple element, both created using parametric modelling.

Opening prosthesis

This section of the Grasshopper script (**Error! Reference source not found.8**, **Error! Reference source not found.9** and **Error! Reference source not found.80**) is dedicated to creating a functional opening on the surface of the prosthesis. This opening is designed to serve as a connector or access point for later structural integration or removable elements. The process is split into several steps, illustrated across three reference photos.

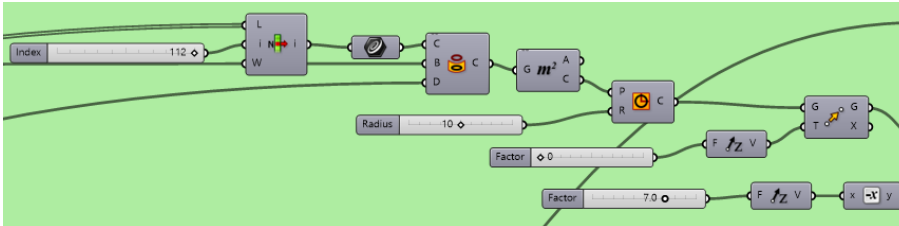


Figure 78: Group 10 of the overview of the final code, part 1

In **Error! Reference source not found.8**, the process begins with a List Item component that selects a specific curve from a Linear Array using a numeric slider (index 112). This curve is passed into a Project component, which projects the curve onto a Patch surface that was previously generated from the pre-surgery mesh. The projection occurs in the Y-direction, guided by a Unit Y vector. The projected curve is used to find its center point using the Area component. A Circle is then drawn around this point, with the radius defined by a numeric slider (value 10). This circle is moved vertically using the Move component and a Unit Z vector, where the translation distance is controlled by a slider set to 0.

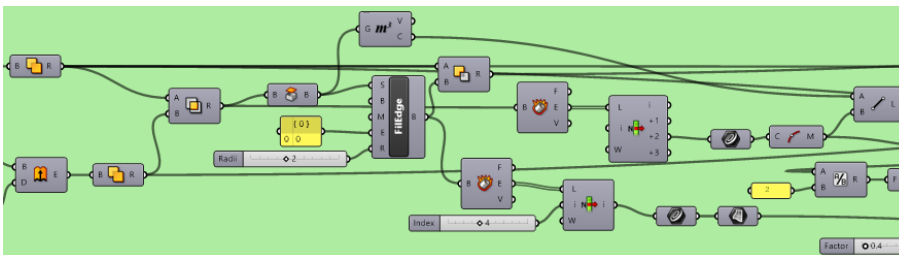


Figure 79: Group 10 of the overview of the final code, part 2

In **Error! Reference source not found.9**, the circle is extruded downward using a Negative Unit Z vector with a value of 7.0, creating a cylindrical volume. This extrusion is then combined using Solid Union and later intersected with the existing prosthesis geometry using a Solid Intersection operation. This step does not subtract geometry but identifies the shared volume between the prosthesis and the extrusion—effectively isolating the intersected region for further use. The result of this intersection is processed in two different ways: one output is passed through a Cap Holes component to close any gaps, then filleted using Fillet Edge, which smooths the edge transitions with a radius slider (value 2). A specific edge (index 4) is selected using List Item, converted to a Curve and rebuilt into a Surface. This surface is used in later detailing steps. The other output is analysed by using Deconstruct Brep to extract its edges. A specific edge (offset +2) is selected using List Item and converted into a curve. The midpoint of this curve is identified using the Curve Middle component. A Line is then created between two key points: the center point of the capped surface, calculated using the Area component, and the midpoint of the selected curve.

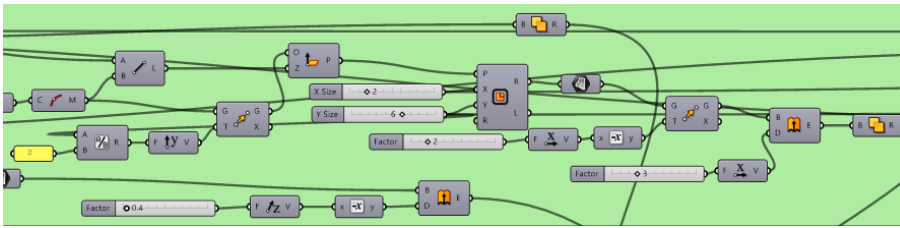


Figure 80: Group 10 of the overview of the final code, part 3

In **Error! Reference source not found.80**, the center point from the previous geometry is moved in the Y-direction using a Move component. The movement value is determined using a Division A/B component, where the Y-size of a rectangle (value 6) is divided by 2 to ensure the new shape remains centered. From this new point, a Plane Normal is constructed using the previously generated Line as the Z-direction reference. A Rectangle is then drawn on this plane, with X and Y dimensions set using sliders (values 2 and 6). This rectangle forms the base of a new Surface, which is moved in the negative X-direction (value 2) and then extruded in the positive X-direction (value 3). To create a solid block it is connected with Solid Union. Lastly, the surface selected from the Fillet Edge is also extruded downward in the Z-direction using a small negative value (0.4), creating a closing element that completes the design of the functional opening.

Nipple

This section of the Grasshopper script (**Error! Reference source not found.81** and **Error! Reference source not found.82**) focuses on constructing the rounded nipple-like feature for the prosthesis. The process is split into several steps, illustrated across two reference photos.

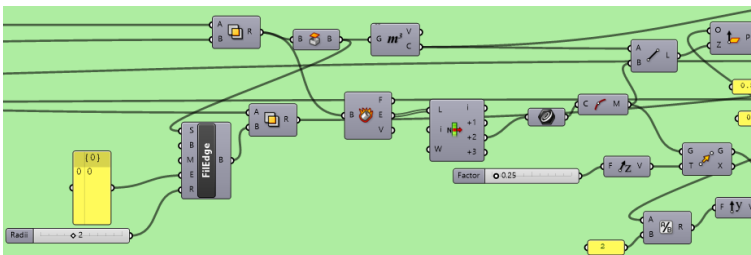


Figure 81: Group 11 of the overview of the final code, part 1

In **Error! Reference source not found.81**, the process begins with a Solid Intersection between the previously created solid geometry and an extrusion. This intersection identifies only the overlapping volume, which serves as the base region for the nipple design. The intersected geometry is passed through Deconstruct Brep, from which edges are extracted. A List Item component selects a specific edge (output +2), which is then converted into a Curve. The center point of this curve is located using the Curve Middle component. This point is vertically translated using a Move component and a Unit Z vector, controlled by a Numeric Slider set to 0.25. This new point becomes the origin for further operations.

Simultaneously, the same Solid Intersection result is passed into a Cap Holes component to create a closed volume. The Area component calculates the center point of this capped surface and a Line is drawn between this center point and the earlier midpoint of the curve. This line serves as the direction input for the Plane Normal component, which defines a local plane for the upcoming nipple geometry. At the same time, another Solid Intersection from the same input is capped and sent through Fillet Edge to soften the transitions. The fillet is applied with a radius of 2 using a slider and a panel index value of 0. The result of this smoothed geometry is then intersected again with the overall solid using Solid Intersection, helping to cleanly isolate and preserve only the overlapping region.

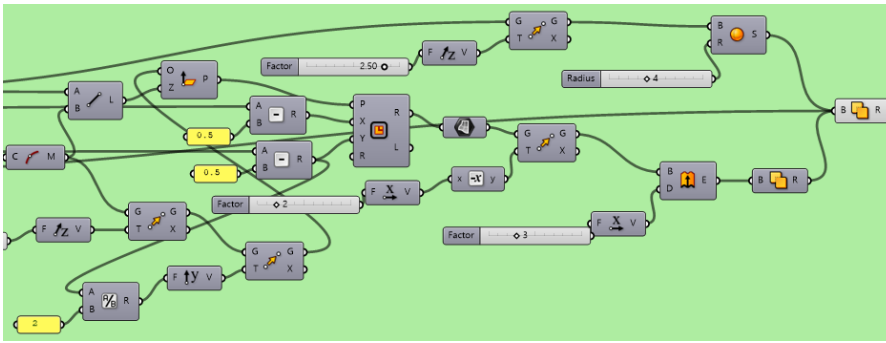


Figure 82: Group 11 of the overview of the final code, part 2

In **Error! Reference source not found.82**, the nipple geometry is added. First, the center point from the Area component is moved vertically by using a numeric slider with a value of 2.5 units in the Z-direction. A Sphere is generated at this location, with a radius set to 4 via a numeric slider. This creates the rounded shape of the nipple. This sphere is later merged into the final nipple model.

To support the nipple geometry in the opening of the prosthesis, there is an additional block generated based on the projected midpoint of the selected curve. This point is first moved in the Y-direction using a Move component, where the shift distance is determined by a Division A/B operation. The input for this division is calculated by subtracting 0.5 from the Y-size value of the rectangle (set to 6), and then dividing the result by 2, effectively centering the upcoming geometry. At the new location, a Plane Normal is constructed using the previously generated line as the Z-direction input. On this plane, a Rectangle is created with dimensions set by sliders (X = 2, Y = 6), each reduced by 0.5 using Subtraction components to fine-tune the proportions. The rectangle is then converted into a Surface, moved in the negative X-direction by a value of 2, and extruded positively along the X-axis by a distance of 3 to create a solid support volume. Finally, all geometry—the extruded block, the filleted intersection from the earlier step and the sphere representing the nipple—is combined using Solid Union.

3D prints

To reduce the printing time and allow for quicker prototyping, I looked for ways to shorten the duration of the 3D printing process. The most efficient solution was to cut the prosthesis model into smaller parts so that only the relevant sections were printed. This approach helped to test specific features without the need to print the entire model each time.

Two different iterations were printed for both the nipple and the opening of the prosthesis. For the nipple, the first version was a simple cylindrical shape (**Error! Reference source not found.83**). In the second version, a Fillet Edge was added at the bottom of the cylinder to make the transition smoother (**Error! Reference source not found.84**). This helped to test which version would better connect with the opening and provide a more natural appearance.



Figure 83: Nipple in cylinder shape



Figure 84: Nipple with fillet edge

For the opening, the same strategy was applied. One version consisted of a basic cylindrical cut-out (**Error! Reference source not found.85**), while the second version included a filleted edge at the bottom to match the rounded shape of the nipple (**Error! Reference source not found.86**). These

variations were created to see if the shapes would align correctly and to evaluate the visual and functional quality of the connection between the two parts.



Figure 85: Opening cylindrical cut-out



Figure 86: Opening with fillet edge

To verify the fit between the nipple and the opening, I first tested the insertion using only a partial section of the prosthesis model (**Error! Reference source not found.87**). After confirming that the fit was successful, I repeated the test on the full prosthesis model (**Error! Reference source not found.88**). This step was important to ensure that the geometry worked in both isolated and complete contexts, and that the removable nipple could be reliably integrated into the overall design.



Figure 87: Fit nipple and opening on partial prosthesis



Figure 88: Fit nipple and opening on full prosthesis

4.1.1.3 Final 3D model prosthesis

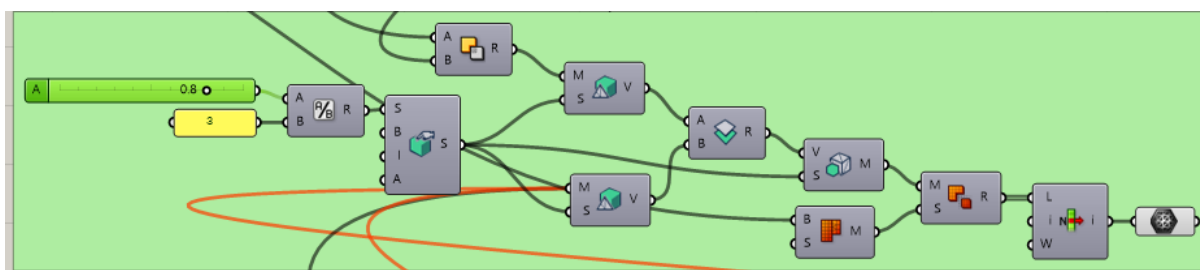


Figure 89: Group 12 of the overview of the final code

This part of the Grasshopper script (**Error! Reference source not found.89**) focuses on combining and subtracting key components of the prosthesis using volumetric Boolean operations to produce the final model. The process starts with a Solid Difference operation, where the geometry of the prosthesis (including the nipple opening) is used as input A and the volume representing the removal system is used as input B. The result is a unified prosthesis shape with the necessary subtracted cavity. This resulting mesh is then converted into a volumetric representation using the Mesh to Volume Prosthesis component, part of the Dendro plugin. The voxel resolution for this conversion is controlled by the Create Settings component, which receives input from a Division A/B operation. This division is based on a numeric slider set to 0.8 and a fixed note panel value of 3, providing consistent voxel sizing.

In parallel, the selected hole structure, taken from one of the three variations discussed earlier, is also converted into a voxel-based volume using the same resolution settings to ensure compatibility. These two volumetric models are then processed with a Volume Difference component, where the internal hole structure is subtracted from the prosthesis body. The result is then converted back into a mesh using the Volume to Mesh component. To isolate the region of interest, a Mesh Split is performed using a Brep generated from the Extrude operation for the opening surface. The correct part of the split mesh is selected using a List Item component and is passed into the final Geometry output.

This workflow produces a clean and integrated final mesh with embedded hole structures, ensuring precision and consistency across all design elements. The geometry is fully prepared for baking and, subsequently for STL export and 3D printing.

4.1.1.4 Final output

The final prosthesis design is shown in **Error! Reference source not found.90**. This model is the result of combining the prosthesis body, which includes the internal structure and the opening, with the removable nipple component. This combination creates a complete and functional design that integrates all previously developed elements into one unified geometry.

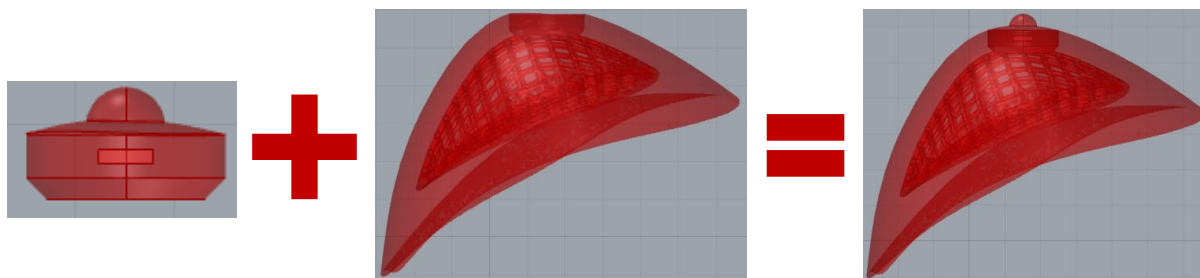


Figure 90: Final result breast prosthesis

Once all components were properly aligned and finalized, the entire geometry was baked in Grasshopper. Baking refers to the step where parametric geometry is converted into fixed Rhino geometry that can be exported. After baking, the result can be visualized as a shaded model, as shown in **Error! Reference source not found.91**. This view gives a clear representation of how all elements—such as the outer shell, the internal structure, and the nipple—fit together and form one integrated prosthesis. This final model is now ready for STL export and can be sent to the 3D printer for production (**Error! Reference source not found.92**). After the production it is ready to use (**Error! Reference source not found.93**).

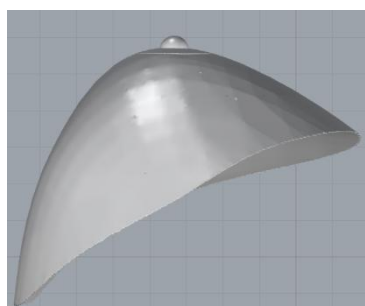


Figure 91: Shaded result of final prosthesis



Figure 92: 3D printed result of final prosthesis

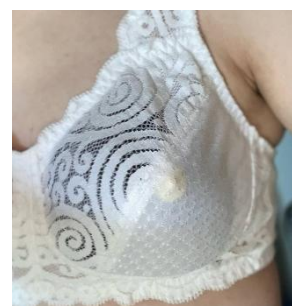


Figure 93: 3D printed prosthesis in context

4.1.2 Hole structure

In this section, the development and testing of different hole structures in Grasshopper are explained. The goal was to reduce the weight of the prosthesis while keeping it stable and comfortable. Many ideas were tested based on YouTube tutorials and self-experimentation. Some approaches failed, but several different structures were successfully created. These structures were generated with visual coding in Grasshopper and were tested in different ways. The code is divided into different groups that each focus on one part of the process. In the next sections, each hole structure is explained step by step, including the purpose and logic behind each group of components in the script.

4.1.2.1 Lattice structure using Crystallon

In this section, the process of generating a three-dimensional lattice structure using the Crystallon plugin for Grasshopper is documented (**Error! Reference source not found.4**). The objective was to create a hemisphere-based lattice geometry that can serve as a lightweight, structurally optimized component for breast prostheses. The workflow presented here was informed by visual coding within the Grasshopper environment and guided by a publicly available tutorial (<https://youtu.be/YvdkZGqwmGk>).

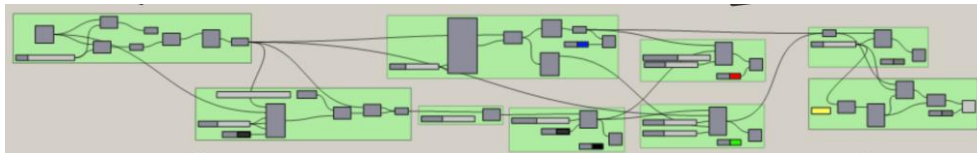


Figure 94: Overview code of Lattice structure using Crystallon

The entire code is composed of different groups of blocks of code, each responsible for a distinct stage of the lattice creation process. The flow of data is indicated by lines between the blocks, allowing for a clear understanding of the transformation steps from input geometry to final mesh output. Each group will be discussed further in detail to have a better understanding of the code.

Input geometry: hemisphere definition

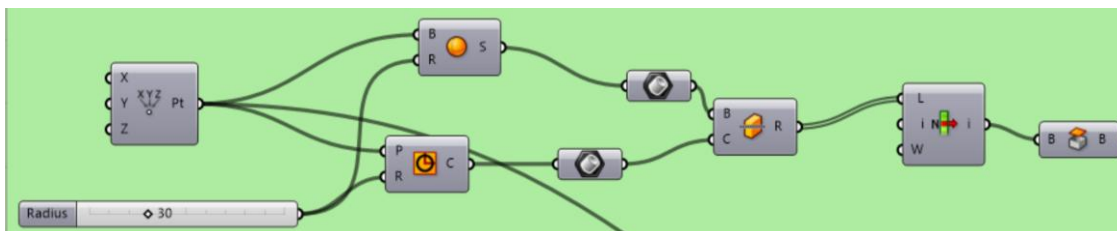


Figure 95: Geometry definition of the hemisphere

The parametric Grasshopper script (**Error! Reference source not found.95**) begins by defining a central point in Rhino, which serves as the base reference for the base plane. A radius slider dynamically controls the hemisphere size. Using this input, the script constructs a complete sphere, processes it with Brep component. For the final input geometry will the upper hemisphere be extracted with a Split Brep by applying a circle component, with the same radius slider as the sphere, as a cutting boundary. For the results there will be a list item used to select to right fragment of the split. To create a closed Brep, there will be used Cap Holes, to cap all the planar holes in the Brep. The following step is to create the unit cell of the Lattice structure.

Unit cell selection

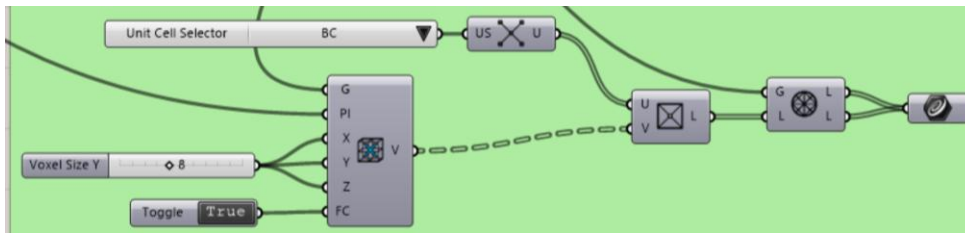


Figure 96: Unit cell selection

Within this process (**Error! Reference source not found.96**), the hemisphere geometry serves as the bounding volume in which the lattice structure is generated. The procedure begins with selecting a unit cell type from Crystallon's "Unit Cell Selector" dropdown menu, part of the "Populate" toolset in Grasshopper. In this case, the "BC" (Body-Centered) unit cell is chosen as the repeating structure to fill the lattice grid.

Next, the voxel size is defined using a numeric slider labelled "Voxel Size Y," set to 8. Despite its label, this value is applied uniformly in all directions (X, Y, Z), resulting in a regular, evenly spaced grid. Smaller voxel sizes create a denser lattice, while larger ones generate a more open structure.

To ensure the entire hemisphere is filled, a Boolean toggle is set to "True" and connected to the "FC" (Fill Completely) input of the voxelization component. This forces the system to generate voxels throughout the entire volume, even if their centers extend slightly beyond the geometry's boundary.

The voxel grid is then generated using the "Voxelize Distance" component, which takes the bounding geometry, voxel size, base plane, and fill toggle as inputs. This results in a 3D array of voxels (V), which serve as containers for the unit cells.

The "Cell Fill (CF)" component then populates each voxel with the selected unit cell (U), aligning and positioning them based on the voxel grid (V). This creates a network of curves (L), representing the beams or struts of the lattice structure.

However, some beams may extend beyond the intended final geometry. To correct this, the "Trim Lattice (TL)" component is used. It removes any curves that fall outside a defined boundary (usually a closed mesh or Brep), resulting in a clean, trimmed lattice confined to the hemisphere. Finally, all trimmed curves are merged into a single output using the standard "Curve" component, producing the final lattice structure ready for visualization or export.

Lattice skin

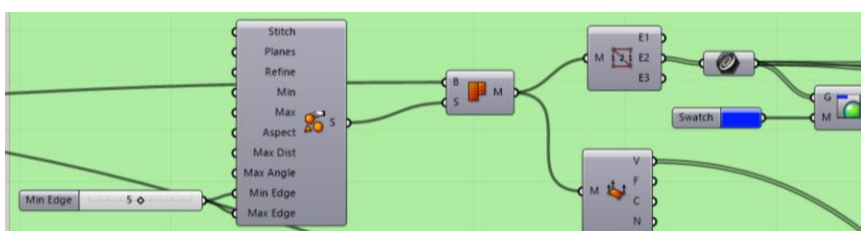


Figure 97: Lattice skin

At the heart of the script lies the process of filling the hemisphere -shaped geometry with a repeating lattice made of unit cells (**Error! Reference source not found.97**). This is done using Crystallon's volumetric grid system, which populates the space with unit cells arranged in a 3D matrix. These unit

cells are repeated throughout the volume and then clipped to fit perfectly inside the defined hemisphere. To achieve this, the setup includes multiple operations such as bounding box calculations, intersection testing, and trimming of curves that go outside the boundary. Boolean logic is used to remove all geometry that extends beyond the hemisphere, ensuring that the lattice remains fully contained and structurally aligned with the outer shell.

The voxel population starts with a numeric slider that sets both the minimum and maximum edge length to 5 units. This makes sure the mesh remains consistent and avoids irregular edge lengths that could deform the geometry. This slider is connected to a component named "Settings (Custom)", where several important mesh parameters are defined. Among these are options like Stitch Seams (for clean edge connections), Simple Planes (to avoid unnecessary subdivisions), and Refine (for improving detail without losing accuracy). Additional parameters such as aspect ratio, max angle, and max distance help control the quality and density of the mesh.

Next, the Brep of the hemisphere is converted into a mesh using the "Mesh Brep" component. This step is important because mesh geometry is easier to work with for visualization and structural analysis than a Brep. Once the mesh is created, it is deconstructed into its elements—vertices, edges, and faces—using the "Deconstruct Mesh" component. Alongside this, the "Mesh Edges" component extracts the edges for use in later steps. Interior edges (those shared by exactly two faces) are specifically selected, as they contribute to a more coherent lattice structure.

These edges are then converted into curves. This conversion opens the possibility to perform geometric operations like extrusion or subdivision. These curves, once extracted, are passed through a "Custom Preview" component for on-screen display. A colour swatch is also connected to this preview, which helps make the different mesh regions visually clear and easy to interpret during the design process. This visual feedback ensures that the structure can be evaluated before moving forward with further transformations.

Connection filtering

The next important stage focuses on improving connectivity within the lattice structure by generating

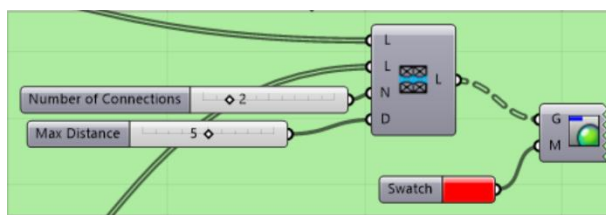


Figure 98: Lattice connection

filtering.

additional struts between nodes (**Error! Reference source not found.**8). This is done using the "Lattice Connections" component, which takes two different sets of lattice curves as inputs—Lattice A and Lattice B. Lattice A represents the existing structure made from the unit cell population and clipping, while Lattice B is the result of later processing steps, including

The Lattice Connections tool introduces a user-defined number of new struts (parameter N) between nearby nodes. The proximity condition is controlled by another parameter D, which limits connections to only those nodes that fall within a certain distance. The goal of this is to improve the overall integrity and appearance of the lattice by connecting disconnected or loosely structured areas. When adjusted, these parameters provide instant visual feedback through the display—often via curve thickness or colour—helping the user to evaluate the connection pattern immediately.

After enhancing the network with new connections, the script moves to the "Morph Lattice to Skin" operation (**Error! Reference source not found.9**). This component morphs or aligns the lattice

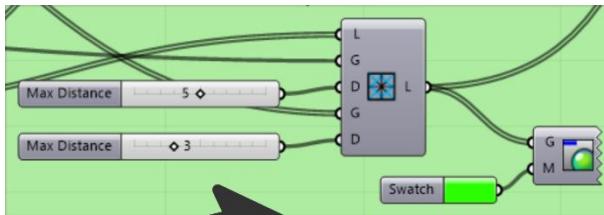


Figure 99: Morph the lattice to the skin

structure to match the shape of an outer skin geometry. It receives as input the modified lattice from the previous step, the hemisphere geometry (Geometry 1), and the lattice skin mesh (Geometry 2). Two distance sliders control how the morphing behaves. The first defines a maximum distance from the skin within which lattice nodes are allowed to be adjusted. The

second controls how much the nodes are actually moved. Nodes that are close enough to the skin are repositioned to align with it, which allows the lattice to blend more smoothly into the shell structure. This results in a hybrid geometry that balances internal structural logic with external design intent.

Valence-based curve filtering

To clean up the lattice and remove unnecessary elements, a filtering process is applied (**Error! Reference source not found.100**). This starts with the



Figure 100: Merge curves

"Merge Curves" component, which combines overlapping or nearly touching curves into single elements. A slider labelled "Max Distance" is set to 4 units, which defines how close two curve endpoints must be in order to be merged. This merging process

helps reduce geometric noise and prepares the network for more precise simulation or export. The cleaned curve network is also easier to analyse and edit in the later stages.

Once the curves have been merged, a valence-based filtering is applied using the "Remove by

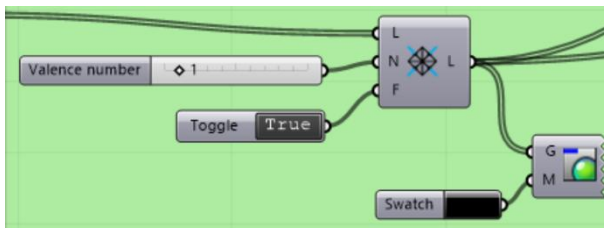


Figure 101: Remove by valence

Valence" component (**Error! Reference source not found.101**). In network structures, the valence of a node is the number of curves connected to it. The tool here is set to remove all nodes with a valence of 1—these are usually stray beams that do not contribute structurally and often appear as floating or isolated lines. Removing them helps create a cleaner, more

efficient network.

A toggle switch (set to "True") gives the user the option to turn this filtering on or off, depending on the phase of the design. When active, the result is a more refined structure where all remaining nodes have meaningful connections. A colour swatch linked to the output provides immediate feedback, allowing the designer to visually check the result of the operation. After filtering, the lattice appears more consistent and structurally logical, ready for further optimization, simulation, or fabrication.

Mesh generation and lattice thickness

In this stage of the workflow, the Grasshopper script employs the Dendro plugin. Dendro is particularly suited for generating complex geometries using voxel-based methods. It enables advanced modelling operations like smoothing, merging, and Boolean operations with high control over mesh density and detail. The script uses Dendro to convert the Lattice pipe structure into a voxel-based mesh suitable for export.

The process begins by defining the lattice thickness using a radius slider connected to the curve geometry (**Error! Reference source not found.**102). The curves represent the skeleton of the lattice

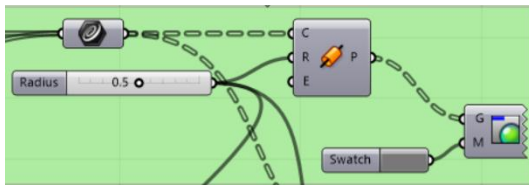


Figure 102: Lattice thickness

framework. A slider, typically set to 0.5, is used to determine the radius of the pipes that will form around these curves. This radius defines the physical thickness of the struts in the lattice. These curves and the radius input are passed into the Pipe component, which generates cylindrical geometry along each curve. The result is a detailed and continuous pipe network that visually expresses the structure's internal connectivity.

To support design evaluation, the resulting pipe geometry is connected to a Custom Preview component. A Colour Swatch is added to enhance visual clarity, allowing the designer to immediately assess the form, thickness, and spatial arrangement of the lattice structure inside the modelling environment.

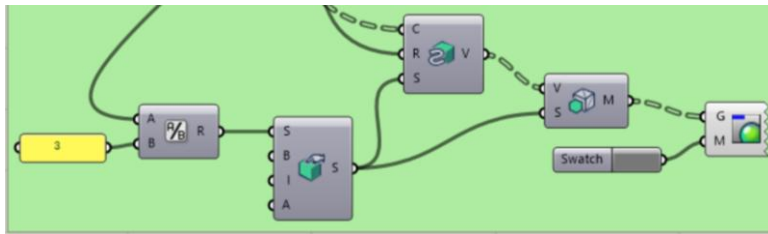


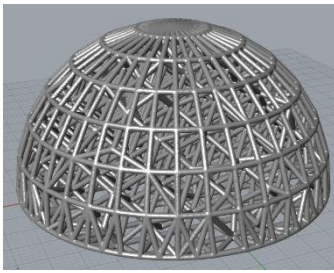
Figure 103: Volume mesh

Following the pipe generation, the second part of the script (**Error! Reference source not found.**103) focuses on creating a volume mesh using Dendro. This step converts the original pipe structure into a voxel-based representation and then into a clean mesh. The process starts with a simple Panel Note, fixed at a value of 3, which defines how finely the radius is divided—essentially a resolution control. This value is combined with the radius input in a Division component, generating a new value that determines the voxel size.

Using this result, the Create Settings component sets the Dendro voxel resolution accordingly. The voxel size directly influences how accurately the final mesh represents the original curve-based geometry. A smaller voxel size results in a higher-resolution mesh, but at the cost of increased computation time.

The next component, Curve to Volume, uses the defined voxel settings (S), the pipe radius (R), and the curve geometry (C) to generate a voxel-based volume. This step essentially converts the visible curves and their thickness into a volumetric field. After the volume has been created, it is passed to the Volume to Mesh component, which converts the voxel data into a watertight mesh. This mesh preserves the general shape of the original pipe lattice but with a resolution determined by the voxel size. Finally, this mesh is connected again to a Custom Preview and Colour Swatch for visualization. This allows for immediate inspection of the mesh quality, surface smoothness, and overall structure.

Final output



The final output of the Grasshopper (**Error! Reference source not found.104**) workflow is a high-resolution, structurally consistent lattice mesh that conforms precisely to the hemisphere geometry. Through a combination of parametric control, voxel-based processing with Dendro, and curve-to-mesh conversion, the model is transformed from a loose network of curves into a clean, fabrication-ready structure. Each strut has a defined thickness, and all elements are trimmed to fit within the specified boundary, ensuring no parts extend beyond the design envelope.

Figure 104: Shaded result of the Lattice structure

4.1.2.2 Voronoi structure using surface offsetting

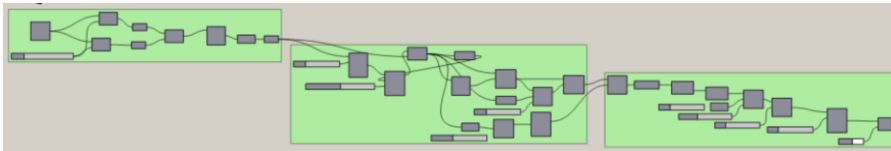


Figure 105: Overview code of voronoi structure using surface offsetting

This part of the thesis explains a second digital model created in Grasshopper using voronoi structure approach (**Error! Reference source not found.105**). Instead of using a unit-cell method like in the previous section, this method uses a smooth surface with holes by applying offsetting and Boolean operations. The code was based on a tutorial on YouTube (<https://youtu.be/P0LV6kKftJs>) and modified to explore the visual and structural difference between Offset Type = 0 and Offset Type = 1.

Input geometry: hemisphere definition

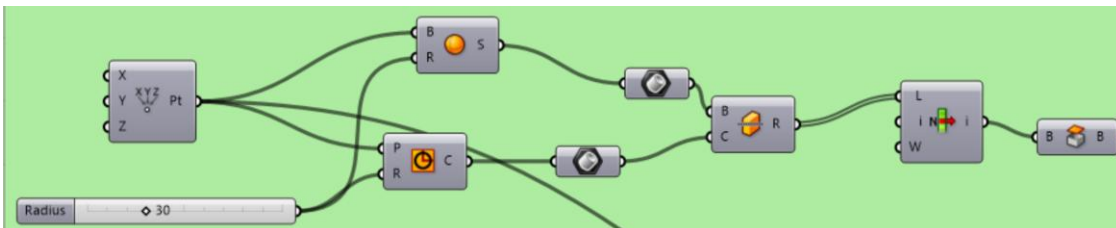


Figure 106: Geometry definition of the hemisphere

The parametric Grasshopper script (**Error! Reference source not found.106**) begins by defining a central point in Rhino, which serves as the base reference for the base plane. A radius slider dynamically controls the hemisphere size. Using this input, the script constructs a complete sphere, processes it with Brep component. For the final input geometry will the upper hemisphere be extracted with a Split Brep by applying a circle component, with the same radius slider as the sphere, as a cutting boundary. For the results there will be a list item used to select to right fragment of the split. To create a closed Brep, there will be used Cap Holes, to cap all the planar holes in the Brep.

Point distribution and projection

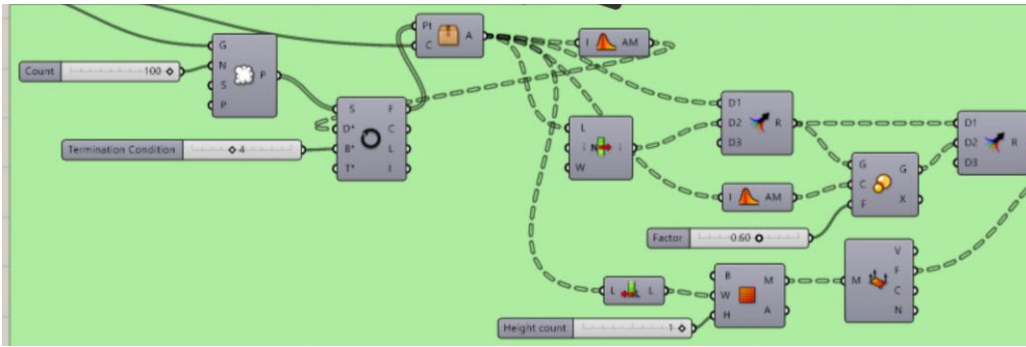


Figure 107: Point distribution and projection

The Grasshopper script (**Error! Reference source not found.107**) follows a recursive logic sequence, starting with a numeric slider labelled “Count”, which defines the number of points distributed within a Brep hemisphere using the Populate Geometry component. These points are fed into Hoopsnake, where a second numeric slider labelled “Termination Condition” acts as the iteration limit, connected to input B+ of the Hoopsnake loop. Within the loop, a self-created cluster receives the current point set (connected to input Pt) and the hemisphere geometry (input C). This cluster processes and transforms the geometry in each cycle. Its output is used in multiple ways: first, it feeds into an Average component that calculates a midpoint or centroid of the processed geometry. The result of this average is routed back into Hoopsnake via input D+, enabling the recursive refinement of the geometry with each iteration. In parallel, specific data is extracted using a List Item component and routed to input D2 of a Merge node. Simultaneously, the List Length of the current point list is calculated and used to generate a Mesh Plane, where the Height Count is set via another numeric slider (input H) and the width is driven by the list length (input W). The resulting mesh is then decomposed using the Deconstruct Mesh component to obtain its vertices, edges, and faces. Meanwhile, the cluster output is also routed to input D1 of the Merge component, combining it with the list item result. An Average value from the geometry is passed to the Scale component (input C), where a user-controlled Factor (via another numeric slider) sets the transformation scale (input F). The merged geometry is then scaled (input G) and re-merged with earlier data through another Merge operation. This final merge combines the scaled result (input D2) and previously merged geometry (input D1), producing a unified dataset that carries the structural logic and transformations from all iterations.

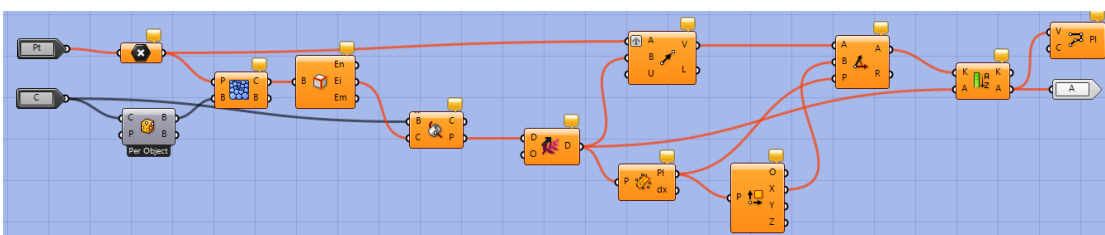


Figure 108: Code behind the self-created cluster

The self-created cluster (**Error! Reference source not found.108**) operates as a central processing system within the iterative Hoopsnake loop, controlling both the internal distribution of geometry and its alignment within a constrained boundary. Rather than functioning as two isolated units, the cluster is designed as an integrated mechanism that transforms raw point data into structured, boundary-aware geometry. It acts as a bridge between abstract spatial input and refined, usable outputs—contributing directly to the overall spatial logic of the script.

At its core, the cluster begins by taking in a set of input points—generated through the Populate Geometry component—and processes them through a 3D Voronoi operation. This partitions space

into distinct cells around each point, establishing a cellular framework that defines the initial spatial organization. From these cells, directional vectors are computed between point pairs, and the resulting vector field is analysed for angular relationships. These relationships are refined using plane fitting and deconstructed coordinate data, allowing the system to maintain consistent spatial alignment even as geometry evolves through multiple iterations. The output is a clean set of sorted polylines, which represent the logical connections between points and reinforce the structural hierarchy established by the Voronoi diagram.

Simultaneously, the cluster applies a boundary refinement logic by enclosing the Voronoi structure within a dynamically generated bounding box. This serves as a spatial limiter that ensures all geometry remains within the defined design envelope. The edges of the Voronoi mesh are extracted, converted into usable curve primitives, and aligned with the same reference planes used for internal organization. These boundary curves are not simply passive constraints—they actively influence how the geometry is structured, scaled, and interpreted in later mesh operations.

Seen as one system, the cluster performs a dual role: it organizes internal geometry through vector- and angle-based logic, while also shaping external form through bounding constraints and alignment. This makes it a critical component in maintaining balance between freedom and control, allowing geometry to grow iteratively while staying readable, aligned, and structurally logical. Its outputs feed directly back into the Hoopsnake loop, enabling a recursive refinement process where each iteration builds upon the last with increasing precision and coherence.

Thickness and mesh output

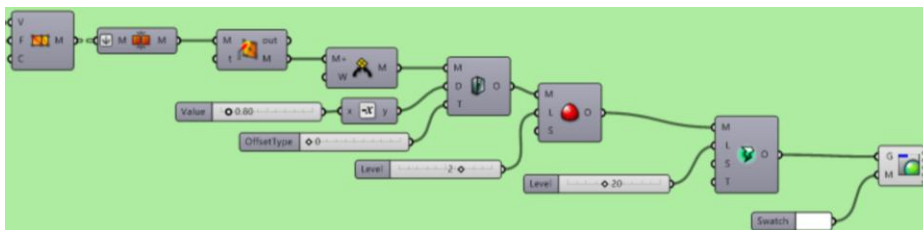


Figure 109: Voronoi thickness with Offset Type 0

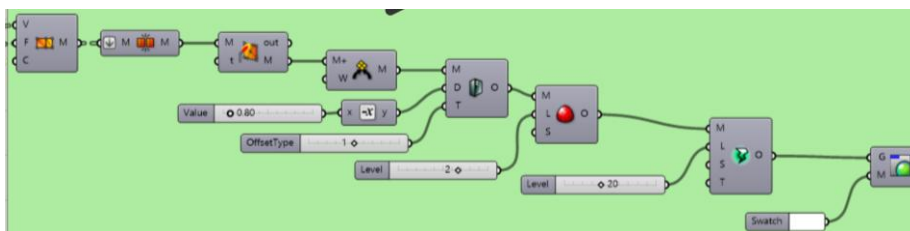


Figure 110: Voronoi thickness with Offset Type 1

In this final modelling phase, the Grasshopper definition processes the Voronoi geometry into a thickened, smoothed, and visually refined mesh using a combination of components from the MeshEdit and Weaverbird plugins. This workflow transforms a skeletal or surface-based mesh into a manufacturable and structurally coherent volume.

The process starts with the Construct Mesh component, where vertices (V) and faces (F) from the previous step are used to generate the initial mesh. This mesh is passed through Mesh Join to combine all parts into a single object, followed by Mesh WeldVertices (from MeshEdit), which ensures that nearby vertices are merged. This operation eliminates gaps and topological errors, preparing the geometry for thickening.

The unified and cleaned mesh is then routed through Join Meshes and Weld (Weaverbird), reinforcing mesh consistency before volume is added using Mesh Thicken. This stage is governed by two key parameters. The first is Input D, which is controlled by a negative numeric slider and defines both the magnitude and direction of the applied thickness—whether it inflates or deflates the mesh. The second is Input T, a numeric slider labelled Offset Type, which determines whether the offset operation is applied at all. If Offset Type is set to 0 (**Error! Reference source not found.109**), the mesh retains its original thickness with no volume added. If set to 1 (**Error! Reference source not found.110**), the mesh is offset and given real depth, transforming it into a volumetric structure.

After thickening, the geometry is passed through Catmull-Clark Subdivision, which smooths and subdivides the mesh for a more organic appearance. A numeric slider controls the level of subdivision detail. The mesh then undergoes Laplacian Smoothing, further polishing the surface by averaging vertex positions, removing sharp edges, and enhancing flow. The final result is visualized using a Custom Preview and coloured via a Swatch, giving immediate feedback on surface quality and overall form.

Final output

The final output of this modelling approach results in two distinct geometric interpretations of the same Voronoi-based hemisphere—one using Offset Type 0 (**Error! Reference source not found.11**) and the other using Offset Type 1 (**Error! Reference source not found.12**). Both are generated from the same base mesh and follow identical logic up to the thickening phase, after which their visual and structural qualities begin to diverge significantly.

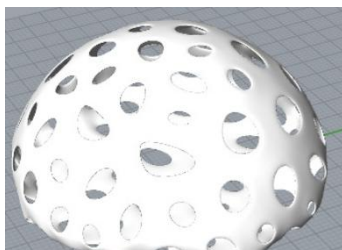


Figure 111: Shaded result of voronoi structure with Offset Type 0

With Offset Type 0, no physical thickness is applied to the mesh. The result is a lightweight, shell-like structure where the Voronoi edges remain flat and surface-based. This version reads more as a pattern mapped onto a curved surface, visually appealing but without true volume. It is ideal for conceptual visualization or for applications where minimal material use is critical. However, it lacks the structural depth required for fabrication methods such as 3D printing, and offers limited mechanical performance if used in load-bearing or physical prototyping contexts.

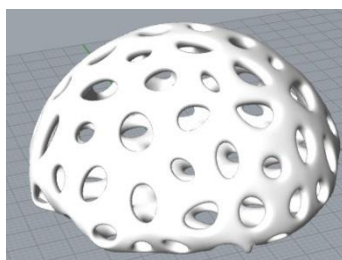


Figure 112: Shaded result of voronoi structure with Offset Type 1

In contrast, Offset Type 1 applies a real offset to the mesh, transforming it into a volumetric structure with continuous wall thickness. This gives the hemisphere a more organic, sculptural appearance and makes it physically manufacturable. The added depth enhances rigidity, supports smoother surface transitions after subdivision and smoothing, and creates a more visually readable form when viewed from multiple angles.

4.1.2.3 Voronoi structure on surface of hemisphere

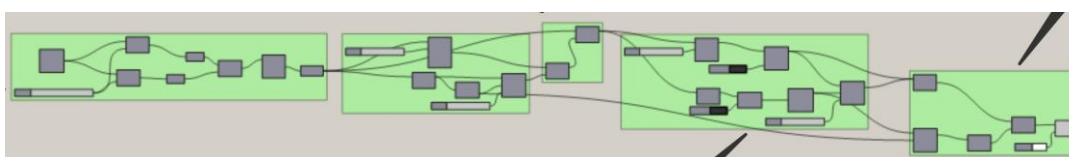


Figure 113: Overview code of Voronoi structure on surface

This section presents a Grasshopper-based modelling approach focused on generating a three-dimensional Voronoi structure directly on the surface of a hemisphere-shaped Brep (**Error! Reference source not found.113**). Unlike previous examples that relied on internal lattices or volumetric grids, this method emphasizes surface articulation by projecting Voronoi logic onto a curved shell. Inspired by a YouTube tutorial (<https://youtu.be/APkNu6uJBXE>) and adapted for this thesis, the script leverages point distribution, 3D Voronoi generation, curve refinement, and directional extrusion to form an organic, porous hemisphere.

Input geometry: hemisphere definition

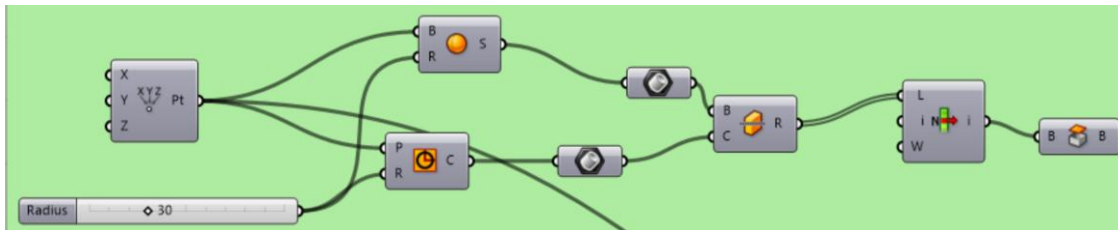


Figure 114: Geometry definition of the hemisphere

The parametric Grasshopper script (**Error! Reference source not found.114**) begins by defining a central point in Rhino, which serves as the base reference for the base plane. A radius slider dynamically controls the hemisphere size. Using this input, the script constructs a complete sphere, processes it with Brep component. For the final input geometry will the upper hemisphere be extracted with a Split Brep by applying a circle component, with the same radius slider as the sphere, as a cutting boundary. For the results there will be a list item used to select to right fragment of the split. To create a closed Brep, there will be used Cap Holes, to cap all the planar holes in the Brep.

Point distribution and voronoi generation

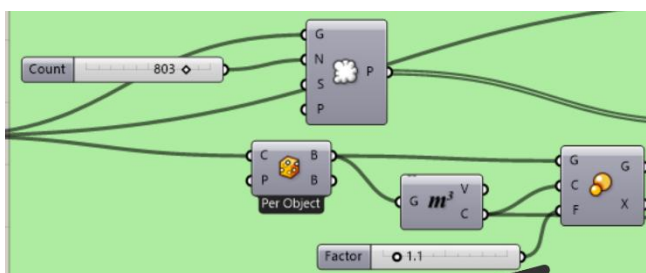
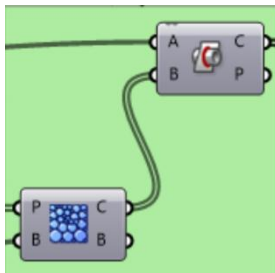


Figure 115: Populate geometry

The process (**Error! Reference source not found.15**) begins with a numeric slider labelled “Count”, which controls the number of points distributed across the interior of the hemisphere. These points are created using the Populate Geometry component, where the hemisphere Brep serves as the input domain and the count value determines the number of randomly positioned points inside that volume.

Parallel to this, a secondary operation prepares the bounding context for the Voronoi generation. A Bounding Box is created around the hemisphere Brep to serve as a reference volume. This bounding box is converted into a Volume to compute its dimensions. The result is passed to a Scale component, which enlarges the bounding volume slightly to ensure that the Voronoi cells fully extend across the space. The scaling transformation is controlled by a numeric slider labelled “Factor”, allowing users to fine-tune the spread and size of the Voronoi cells relative to the hemisphere.



The output from the Populate Geometry component is then used as the point input for a Voronoi 3D operation (**Error! Reference source not found.116**). This generates a 3D cellular pattern, with each point serving as a seed from which a spatial cell is grown. To ensure the resulting Voronoi geometry is confined to the original hemisphere, the Voronoi output is intersected with the Brep using the Brep|Brep component. This trims the Voronoi structure so that only the cells within the hemisphere remain.

Figure 116: Voronoi 3D generation

Refining voronoi geometry

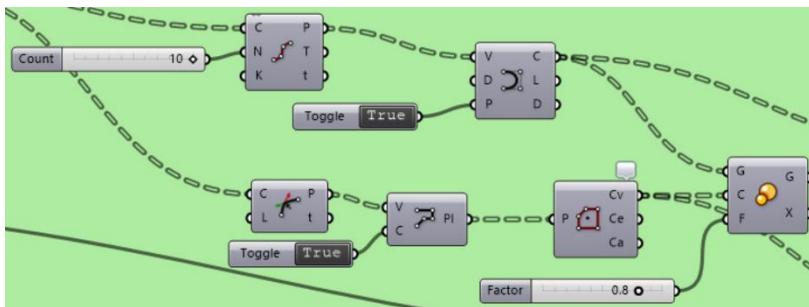


Figure 117: Refining voronoi geometry

This step in the Grasshopper script (**Error! Reference source not found.7**) focuses on refining the Voronoi geometry by identifying and selectively manipulating curves. The goal is to reduce redundant or unwanted curves and subtly reshape the network.

The process begins with a numeric slider labelled “Count”, which defines the resolution used in the Divide Curve component. Here, the output Brep from the Voronoi trimming operation in the previous step is used as the input curve (C). The curve is divided into a number of points based on the slider value (N), generating evenly spaced divisions along the geometry. These division points are then fed into a NURBS Curve component, which reconstructs a smooth curve from the point list. A toggle set to True enables the interpolation option, ensuring the resulting curve flows continuously through the division points and approximates the original shape.

At the same time, the original Voronoi-trimmed Brep is processed through a Discontinuity component to detect sharp changes or corners along the curves. The output from this component is used as input for the Polyline function, with another toggle (set to True) controlling whether the points are connected directly or interpolated. This generates simplified polyline representations of the original geometry. The resulting polylines are then analysed for their spatial center using the Polygon Center component, which computes the central coordinate for each closed shape.

These polygon centers are used as reference points in a Scale operation. The NURBS curves created earlier are scaled relative to the centers of their corresponding polygons. The center coordinates act as the pivot points (C), the original curves as the geometry to be transformed (G), and the scaling magnitude is controlled by a numeric slider labelled “Factor” (F). This scaling operation allows for subtle deformation or reduction of the curve network based on its internal hierarchy, helping to remove unnecessary complexity while preserving the underlying spatial structure.

Voronoi thickness

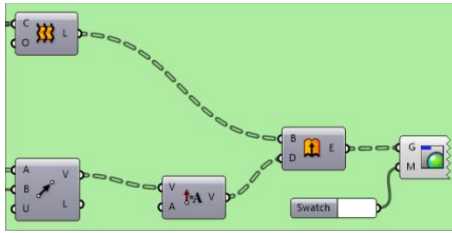


Figure 118: Voronoi thickness

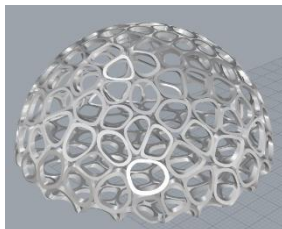
In this final step, the Grasshopper script (**Error! Reference source not found.8**) adds thickness to the refined Voronoi structure. This is achieved by lofting, vector-based extrusion, and a controlled directional transformation to create a volumetric effect from the 2D or surface-based geometry developed in the previous steps.

The process starts with the Polyline output from the earlier curve simplification phase. These polylines are passed into a Loft component (input C), which generates surface geometry by connecting the curve segments along their path. The resulting lofted surfaces are then processed through an Extrude operation to add physical depth and thickness.

The extrusion is driven by a direction vector, which is calculated using the Vector 2Pt component. Here, input A receives the center point of each polygon (output Cv from the Polygon Center), and input B uses the center of the overall bounding volume from earlier in the workflow. This generates a directional vector pointing outward from the geometric core toward the center of each individual polygon.

To control the length and impact of the extrusion, this directional vector is passed into the Amplitude component. This lets the designer scale the vector to a specific magnitude, effectively defining how far each surface should extrude. The result of the Amplitude is connected to input D of the Extrude component, producing individualized thickness for each Voronoi cell based on its spatial orientation and distance from the volume center. Finally, the extruded geometry is visualized using a Custom Preview, with a Colour Swatch applied to enhance contrast and improve visibility.

Final output



The final output of this Voronoi-on-surface approach is a lightweight, organic hemisphere structure, characterized by a smooth distribution of rounded, cell-like openings. As shown in **Error! Reference source not found.9**, the geometry preserves the curvature of the original hemisphere while transforming it into a porous, skin-like shell.

Figure 119: Shaded result of voronoi structure on surface

4.1.2.4 Voronoi structure on whole volume of

hemisphere



Figure 120: Overview code of voronoi structure on volume

This section describes a Grasshopper-based modelling approach aimed at generating a Voronoi 3D structure that fills the entire volume of a hemisphere-shaped Brep (**Error! Reference source not found.20**). Unlike surface-based Voronoi patterns, this method constructs a fully spatial cell network that occupies both the interior and exterior zones of the geometry. The process involves volumetric point generation, selective trimming, edge refinement, and mesh construction. The script integrates plugins like Kangaroo 2 and Weaverbird to enable mesh thickening, smoothing, and topological optimization. The setup is based on a YouTube tutorial (<https://youtu.be/226ESXK5tHg>).

Input geometry: hemisphere definition

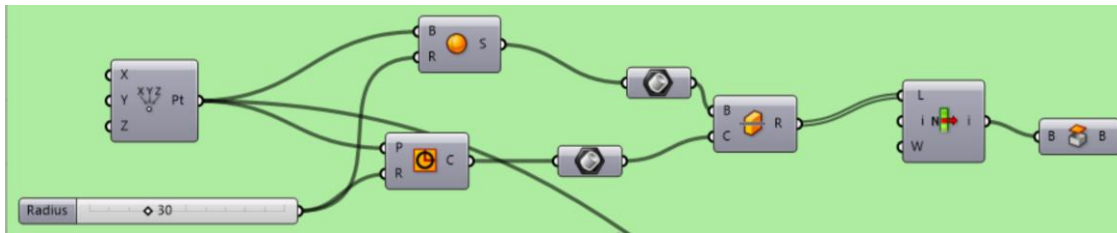


Figure 121: Geometry definition of the hemisphere

The parametric Grasshopper script (**Error! Reference source not found.21**) begins by defining a central point in Rhino, which serves as the base reference for the base plane. A radius slider dynamically controls the hemisphere size. Using this input, the script constructs a complete sphere, processes it with Brep component. For the final input geometry will the upper hemisphere be extracted with a Split Brep by applying a circle component, with the same radius slider as the sphere, as a cutting boundary. For the results there will be a list item used to select to right fragment of the split. To create a closed Brep, there will be used Cap Holes, to cap all the planar holes in the Brep.

Point distribution

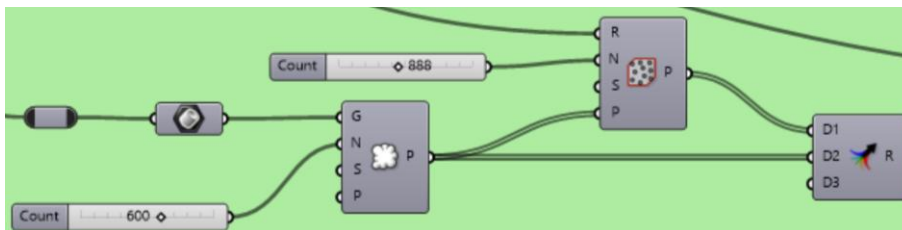


Figure 122: Point distribution

This step establishes the foundational point cloud for the Voronoi structure by combining both surface and volumetric point distribution methods (**Error! Reference source not found.22**). The process begins with a Relay component that passes the Brep hemisphere from the previous step to a Brep component, ensuring proper data flow and compatibility. A numeric slider labelled “Count” controls the number of points to be generated, which is used to populate the hemisphere’s surface through the Populate Geometry component. This creates a set of randomly placed points across the hemisphere’s Brep surface.

In parallel, the same hemisphere geometry is input into a Populate 3D component, which fills the interior volume of the hemisphere with additional points. The Populate 3D takes three inputs: the hemisphere Brep (R), the point count (N), and the previously generated 2D points (P). This layering ensures that the internal point distribution is informed by the surface conditions, improving spatial cohesion and cell uniformity during the later Voronoi generation.

The outputs from Populate Geometry and Populate 3D are merged into a single, unified point cloud covering both the interior and surface of the hemisphere. This balanced dataset supports the creation of complex 3D Voronoi structures that align with the hemisphere’s form and boundaries.

Voronoi generation

This stage of the script (**Error! Reference source not found.23**) refines the spatial logic of the Voronoi diagram by ensuring that only relevant, internal points contribute to the final geometry and that the resulting cells conform tightly to the hemisphere's shape. The process begins with a Point in

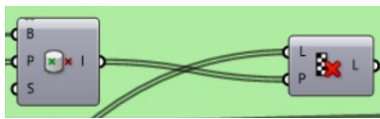


Figure 123: Remove points outside brep

Brep operation, which checks whether each point from the previously merged point set lies within the Brep hemisphere. This filtering step ensures that only points inside the design boundary are used to generate Voronoi cells. The filtered points are passed through a Cull Pattern component, which removes all points outside the hemisphere.

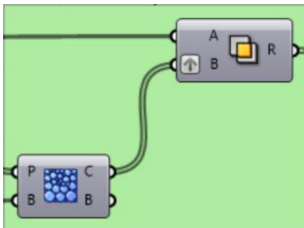


Figure 124: Voronoi 3D generation

The resulting set of valid points is then used as input for a Voronoi 3D operation (**Error! Reference source not found.24**), where the hemisphere Brep is used again as the bounding context. The raw output of this operation is a set of Voronoi cells that may still extend beyond the hemisphere's surface. To strictly confine the cells to the hemisphere volume, the output is intersected with the original Brep using the Solid Intersection component. This trims the Voronoi geometry, ensuring that only the portions enclosed by the hemisphere remain.

In parallel, the script prepares a set of reference curves to assist in later filtering steps (**Error!**



Figure 125: References curves

Reference source not found.25). The SubD Edges of the hemisphere Brep are extracted and passed into a Member Index component, which is set to identify only those edges tagged as “smooth” or “interior” using a panel input. These selected edges are retrieved using List Item and converted into curve geometry

using the Curve component. These curves serve as a clean structural reference, helping define which parts of the Voronoi network remain relevant during further filtering and simplification processes.

Remove curves

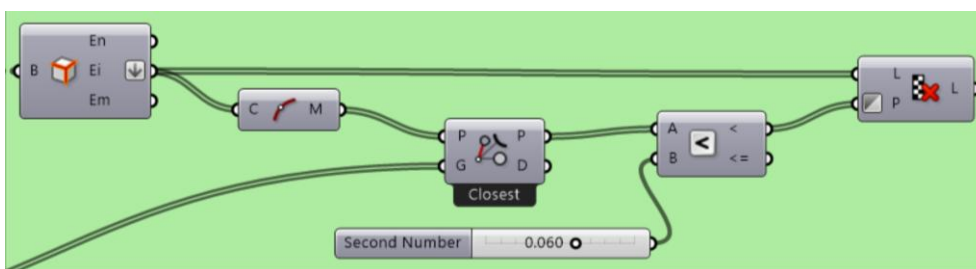
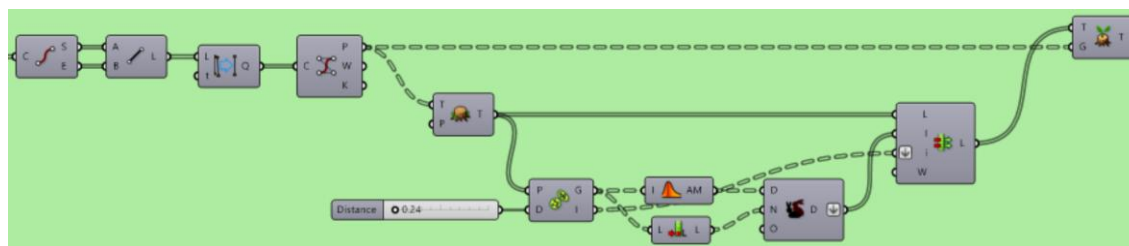


Figure 126: Remove curves

The process starts by extracting Brep Edges from the result of the Solid Intersection performed in the previous step. These edges represent the boundaries of the trimmed Voronoi cells. To evaluate the position of each edge, the Curve Middle component calculates the midpoint of every edge segment. These midpoints are then tested using the Pull Point component, which measures the shortest distance between each midpoint and a reference curve obtained from a previous SubD operation.

Final points



In this stage, the Grasshopper script (**Error! Reference source not found.**27) uses a series of data-cleaning and averaging techniques to refine the final point set, ensuring a clean and structurally consistent Voronoi network. The Kangaroo 2 plugin plays a central role in this process, particularly through the Remove Duplicate Lines component.

Next, Control Points are extracted from the cleaned line geometry and processed through a Flatten Tree operation to remove any hierarchical structure, allowing all points to be treated uniformly. These flattened points are then passed into the Point Groups component, which clusters nearby points based on proximity. The distance threshold for grouping is defined by a numeric slider, giving the user control over how tightly or loosely points should be grouped.

For each group of points, the Average component computes a centroid, which serves as a new unified point for that cluster. The List Length of each group determines how many times this averaged point should be duplicated to match the original structure. These duplicate values are used in the Replace Items component, which substitutes all grouped points with their averaged counterpart while maintaining list integrity. The final result is restructured using Unflatten Tree, restoring the original

data hierarchy but now with cleaned and consolidated points. This step ensures that the final Voronoi geometry is free of unnecessary overlaps or inconsistencies.

Thickness

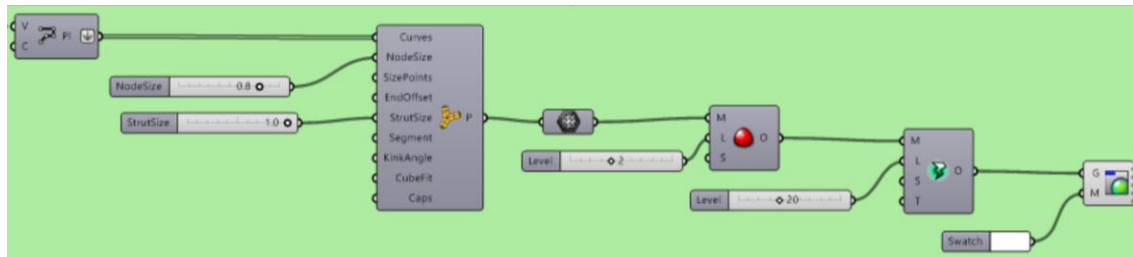
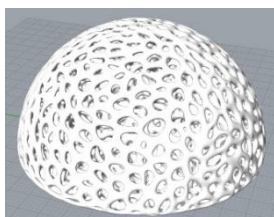


Figure 128: Voronoi thickness

In this final stage, the Grasshopper script (**Error! Reference source not found.28**) transforms the cleaned and organized Voronoi curve network into a smooth, volumetric mesh structure by applying mesh thickening and subdivision techniques. The process begins with the output of the Unflatten Tree component, which holds the cleaned polylines representing the refined Voronoi edges. These polylines are fed into the Multi Pipe component from the Kangaroo 2 plugin. Multi Pipe creates a tubular mesh structure by generating smooth pipes along the input curves, with two parameters controlling the geometry: Node Size, which determines the diameter around junctions or intersections, and Strut Size, which sets the thickness of the pipes between nodes. Both are adjustable through numeric sliders, allowing flexible tuning of the final geometry.

The resulting mesh is then passed into Weaverbird's Catmull-Clark Subdivision component. This algorithm subdivides the mesh, smoothing sharp transitions and generating a more continuous and organic surface. A subdivision Level slider controls how refined the surface becomes, with higher values producing a more polished and rounded appearance. To further enhance surface quality and remove residual angularities, the mesh undergoes Laplacian Smoothing. This step averages vertex positions across the surface, ensuring smooth flow and reducing irregularities. The finished mesh is visualized through a Custom Preview and stylized with a Colour Swatch, making the geometry easier to interpret and assess in real time.

Final output



The final output of this volumetric Voronoi model is a highly detailed, porous hemisphere structure, as shown in **Error! Reference source not found.9**. Unlike the surface-based Voronoi model, this approach fills the entire interior of the hemisphere with a network of three-dimensional cells, creating a fully enclosed geometry.

Figure 129: Shaded result of voronoi structure on volume

4.1.2.5 Lattice skin on surface of hemisphere

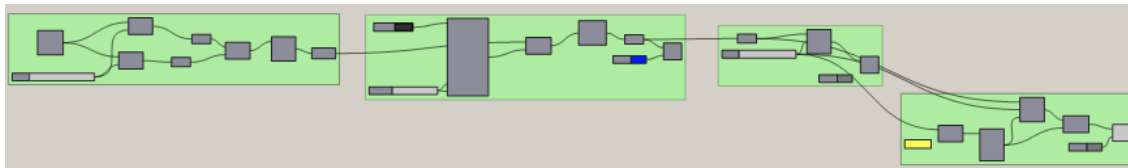


Figure 130: Overview code of lattice skin on surface

This section explains the process of creating a lattice skin on a hemisphere surface (**Error! Reference source not found.30**). The aim is to develop a lightweight yet stable structure that conforms to the dome shape and is suitable for digital fabrication. Using Grasshopper, a parametric model was built to control the lattice's size, thickness, and density. Mesh and Dendro tools were used to enhance design flexibility. The following sections detail each step, from input geometry to the final output.

Input geometry: hemisphere definition

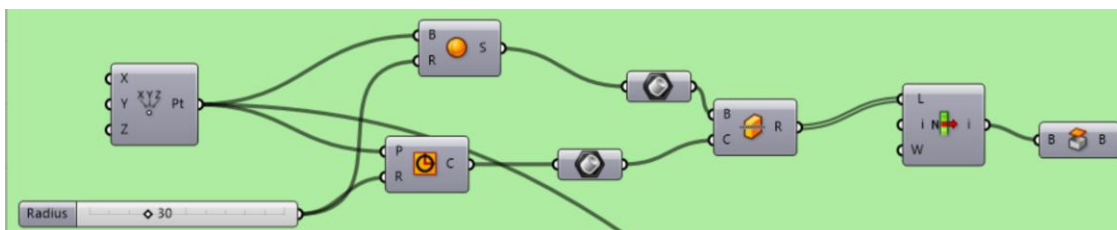


Figure 131: Geometry definition of the hemisphere

The parametric Grasshopper script (**Error! Reference source not found.31**) begins by defining a central point in Rhino, which serves as the base reference for the base plane. A radius slider dynamically controls the hemisphere size. Using this input, the script constructs a complete sphere, processes it with Brep component. For the final input geometry will the upper hemisphere be extracted with a Split Brep by applying a circle component, with the same radius slider as the sphere, as a cutting boundary. For the results there will be a list item used to select to right fragment of the split. To create a closed Brep, there will be used Cap Holes, to cap all the planar holes in the Brep.

Lattice skin

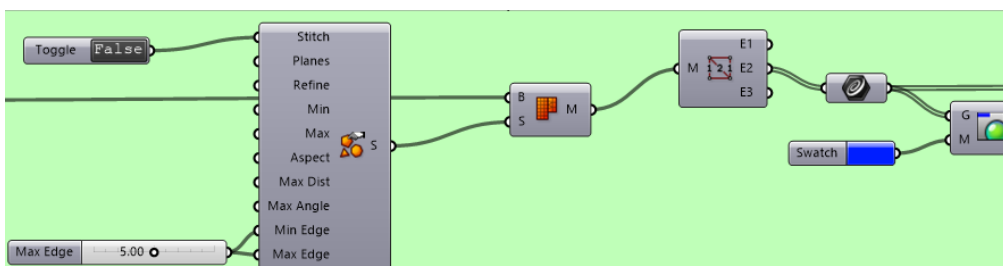


Figure 132: Lattice skin

In the next step of the design workflow (**Error! Reference source not found.32**), the hemisphere's Brep geometry is converted into a mesh using the "Mesh Brep" component. This is crucial, as mesh geometry is better suited for visualization and structural analysis—being lighter, simpler, and faster to process for complex forms like hemispheres. The "Settings (Custom)" input enables manual control over mesh resolution, including the "Stitch" option (for connecting naked edges) and sliders for minimum and maximum edge lengths. In this case, a single slider is used since both values are equal, allowing control over mesh density, which directly influences structural logic and visual clarity in later steps.

Once meshed, the geometry is passed to the "Mesh Edges" component to extract mesh edges. Only interior edges—those shared by exactly two mesh faces—are selected, as they are critical for maintaining structural continuity in the lattice and avoiding unwanted irregularities at boundaries.

The selected edges are then converted into curves, allowing further geometric operations such as extrusion or piping, which are not possible with raw mesh edges. These curves are visualized using the "Custom Preview" component, enabling real-time design evaluation without baking the geometry. A colour swatch is connected to enhance visibility, helping to clearly highlight the mesh structure in the Rhino canvas.

Lattice thickness

The process (**Error! Reference source not found.33**) begins with curves that serve as the skeleton

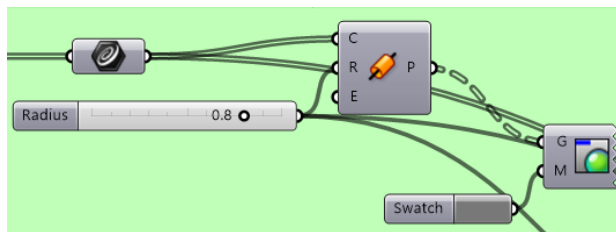


Figure 133: Lattice thickness

of the lattice framework. A slider, set to 0.8, controls the pipe radius, defining the thickness of the lattice struts. These curves, along with the radius input, are fed into the Pipe component, which generates cylindrical geometry along each curve. The result is a detailed, continuous pipe network that reveals the internal connectivity of the structure. To support design evaluation, the pipe geometry is

visualized using the Custom Preview component, with a Colour Swatch added to improve visual clarity.

Mesh generation

Following pipe generation, the final part of the script (**Error! Reference source not found.34**)

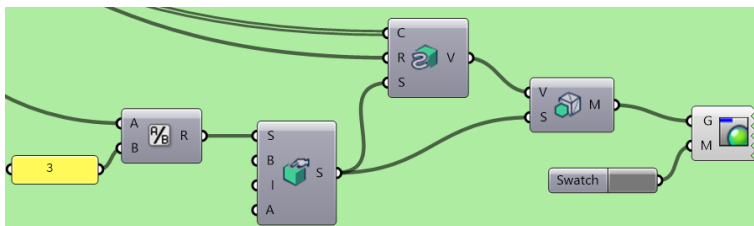


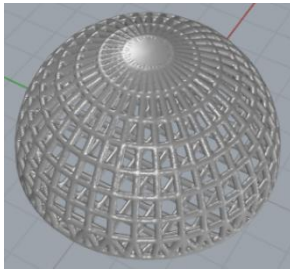
Figure 134: Volume mesh

focuses on creating a volume mesh using Dendro. This step transforms the pipe structure into a voxel-based representation and then into a clean mesh. A fixed Panel Note value of 3 is divided by the pipe radius to calculate the voxel size, which controls mesh resolution. Smaller voxels yield higher detail

but require more processing time.

The voxel size is set via the Create Settings component. Using these settings, the Curve to Volume component generates a volumetric field from the curves and their radius. This volume is then converted into a mesh using the Volume to Mesh component, producing a smooth mesh that reflects the original pipe lattice. For real-time evaluation, the mesh is visualized using a Custom Preview and Colour Swatch, allowing quick assessment of mesh quality and structure.

Final output



The final output of this parametric workflow is a hemisphere structure with a lattice skin, as shown in **Error! Reference source not found.35**. The result presents a well-defined geometric pattern formed by interior mesh edges, creating a continuous framework across the hemisphere's surface. The lattice consists of uniform pipe elements that follow the internal mesh pattern defined earlier in the script. It's important to note that this stage only represents the outer shell—there is no solid lattice volume within the hemisphere. The outcome is a surface-based structure or lattice skin.

Figure 135: Shaded result of lattice skin on surface

4.2 Hole structure testing

This phase of the thesis focused on testing various hole structures to evaluate their suitability for 3D printed breast prostheses. The goal was to explore whether internal patterns could reduce weight without compromising essential properties such as strength, flexibility, and printability.

Several hole structures were designed using parametric modelling and tested on a personal FDM 3D printer (Bambu Labs P1S Combo with AMS). While different from the silicone-based Lynxter S300X to be used later, this printer allowed for quick and cost-effective prototyping. These initial tests offered insights into how different structures affect weight, firmness, print quality, and surface finish.

In total, ten hemispherical and eight breast-shaped models were printed. Hemispheres were used for consistent comparisons, while prosthesis models helped assess real-world applicability. Three materials were used: standard PLA (rigid, high printability), TPU 95A HF (flexible, better simulating prosthetic properties) and Lynxter SIL-001 silicone.

Each sample was evaluated based on weight, firmness (manually assessed), and printability (e.g., support needs, adhesion, print defects). Results were documented in Excel, and a testing protocol (Appendix D) was developed to ensure consistency in future trials.

Table 17 shows that the solid model (100% infill) weighed 66 g and was very firm, while models with 15% infill and patterns like straight-line, gyroid, or Voronoi were significantly lighter—some as low as 3 g. However, thin Voronoi designs proved too fragile. Voronoi volumes and gyroid infills showed a better balance of weight and strength, though some needed support structures. TPU samples showed promising flexibility, though support removal was more complex.

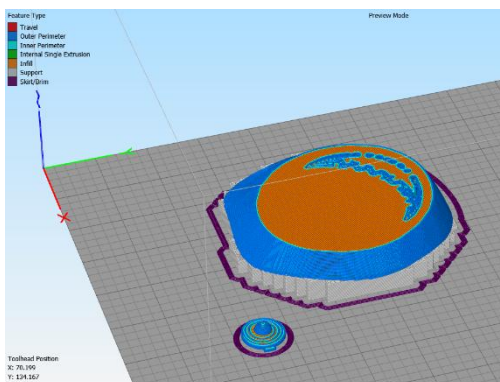


Figure 136: Problem of unintended internal filling

Table 18 summarizes tests on prosthesis-shaped models. Some, like test 17 (internal hole structure), failed due to print complexity and unintended infill (**Error! Reference source not found.36**). Tests 11 and 15 (TPU with internal or solid structures) showed potential, despite minor print issues. Rigid PLA models (tests 12 and 14) were strong but heavy. Tests 13 and 16, which only had lattice skins, were not functional but useful for testing printability. Test 18, a silicone prosthesis with a solid interior and removable nipple, printed successfully and provided a foundation for further development.

Table 17: Results hole structure tests hemispheres

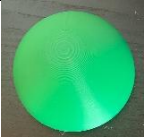
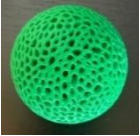
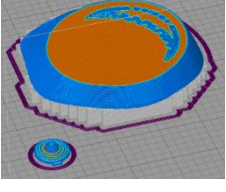
Prototypes	Hole structure	Material	Weight	Firmness	Ease of 3D printing
 Figure 137: Test 1	without & 100 % infill	green PLA	66 g	Very firm	Easy
 Figure 138: Test 2	without & 15 % infill (straight line)	green PLA	19 g	Very firm	Easy
 Figure 139: Test 3	Voronoi volume & 15 % infill	green PLA	24 g	Very firm	With support at the bottom
 Figure 140: Test 4	Voronoi surface & 15 % infill	green PLA	3 g	Very weak → broke	Printable but had my doubts and it is not 100% correct
 Figure 141: Test 5	Lattice BC & 15 % infill	green PLA	8 g	Firm	Printable, other unit cells of lattice is not yet successful

 Figure 142: Test 6	Voronoi surface offset 0 & 15 % infill	green PLA	11 g	Firm	Easy
 Figure 143: Test 7	Voronoi surface offset 1 & 15 % infill	green PLA	11 g	Firm	Easy
 Figure 144: Test 8	without & 15 % infill (gyroid)	black PLA	17 g	Firm	Easy
 Figure 145: Test 9	Voronoi surface & 15 % infill	orange PLA	3 g	Very weak	Printable but had my doubts and it is not 100% correct
 Figure 146: Test 10	Voronoi surface offset 0 & 15 % infill	TPU 95A HF black	11 g	Flexible, Firm	With support at the bottom

Table 18: Results hole structure tests prostheses

prototypes	Hole structure	Material	Weight	Firmness	Ease of 3D printing
 Figure 147: Test 11	inside voronoi	TPU 95A HF black	26 g	Very firm	With support at the bottom, some errors
 Figure 148: Test 12	without structure & 15 % infill (straight line) → shape prosthesis	yellow PLA	46 g	Very firm	With support at the bottom
 Figure 149: Test 13	Lattice skin	TPU 95A HF black	18 g	Flexible, Firm	With specific support, hard to remove and hole in surface due to error
 Figure 150: Test 14	inside structure without holes	white PLA	43 g	Very firm	With support at the top

 Figure 151: Test 15	inside structure without holes	TPU 95A HF black	41 g	Flexible, Firm	With support at the top, some errors now
 Figure 152: Test 16	Lattice skin	black PLA	19 g	Firm	With specific support, hard to remove and support is still inside
 Figure 153: Test 17	inside structure with lattice skin + removable nipple	Lynxter SIL-001 silicone			Too complex, print inside structure full of what is not intended → no time to solve this so I did just test 18
(no photo because it was not printed on time to put in the thesis) Test 18	inside structure without holes + removable nipple	Lynxter SIL-001 silicone			With support First try failed door materiaalwissel Second try will not be finished before that I upload my thesis

4.3 3D scanning

Following the previous discussion on 3D scanning in section 2.5, this section presents the practical outcomes, challenges, and lessons learned from the implementation of 3D scanning within this research. The focus was placed on enabling self-scanning by patients using mobile applications, supported by controlled scans performed on anatomical models when necessary. While the concept of self-scanning holds great promise for democratizing access to personalized prosthesis design, its execution in real-life conditions revealed a number of critical insights.

4.3.1 Self-Scanning Implementation

Patients participating in the study were provided with clear instructions—written in Dutch and tailored to three different post-surgical scenarios—to guide them through the scanning process. These instructions (Appendix F) included step-by-step guidance on setting up the environment, using the recommended mobile apps (xOne, DECAL, 3D Scanner App, and Polycam), and exporting scans in OBJ or FBX format. Despite providing clear instructions and detailed guidance, the quality of the scans submitted by participants proved highly problematic. In practice, none of the scans met the minimum requirements for use in the modelling workflow. Several factors contributed to this outcome:

- **Technical limitations of scanning apps:** Some apps, such as xOne, allowed only one free export per user, which became a critical issue since two scans per participant were typically required. This limitation was overlooked during testing, as only a single scan was performed per app. Other apps had restricted export options or lacked compatible file formats.
- **User challenges:** Some participants had difficulty understanding or following the instructions, particularly regarding exporting and emailing the scans. Limited digital skills and unfamiliarity with 3D scanning technology created additional barriers. One participant shared:

“With Decal, the scanning itself worked fine, but everything went completely wrong after that... With Xone, we were able to do the required scans. However, we can only download one scan for free and possibly share it with you via email...”

A second participant described the challenges of scanning alone:

“I made four scans, but it was difficult... I had to start over several times. I need to stand still, but that’s not possible when I’m doing the scan myself. I also have to switch the device from one hand to the other, which causes more movement. My partner wanted to help, but that doesn’t work, because you have to scan with the screen facing your body, and someone else can’t see what they’re doing. Not easy...”

In another case, a patient sent the files in the wrong format.

- **Low scan quality:** Common issues included low resolution, incomplete surface coverage—especially under the bust and near the armpits—poor lighting conditions, and motion blur from unstable camera handling.

These challenges had a significant impact on the reliability of the dataset. Due to the combination of technical limitations and user-related difficulties, none of the patient-generated scans were usable. As a result, the remainder of the design and development process relied on pre-existing scan files from a patient from the previous year, which were already integrated into the code base provided at the project’s outset. While this ensured continuity and enabled the testing and refinement of the prosthesis design workflow, it also underscored a major limitation of the self-scanning approach.

4.3.2 Alternative Strategies and Supplementary Scanning

To overcome the shortcomings of the self-scanned models, alternative scanning methods were considered and partially implemented to ensure continuity in the design process and to obtain reliable

anatomical reference data. Initially, the idea of conducting 3D scans on a medical mannequin using a professional scanner at the university was explored. This method was intended to provide a standardized baseline for modelling tasks, particularly for bilateral mastectomy cases where no pre-operative data is available.

In contrast, an exclusive scanning session was successfully conducted at the facilities of Anita Dr. Helbig GmbH. Prior to the session, a detailed scanning protocol (Appendix E) was developed to ensure consistency, accuracy, and ethical compliance throughout the process. During the second visit, high-resolution 3D scans were acquired using two professional Artec 3D devices: the EVA and Spider II. The scanning focused on an existing anatomical breast model from Anita, selected to represent a typical unilateral mastectomy case. The model's intact breast was scanned in detail for use in digital mirroring (**Error! Reference source not found.**⁵⁵ and **Error! Reference source not found.**⁵⁶), while the flat side of the chest served as a reference for testing symmetry modelling (**Error! Reference source not found.**⁵⁴).



Figure 154: Result of the scan of the operated side

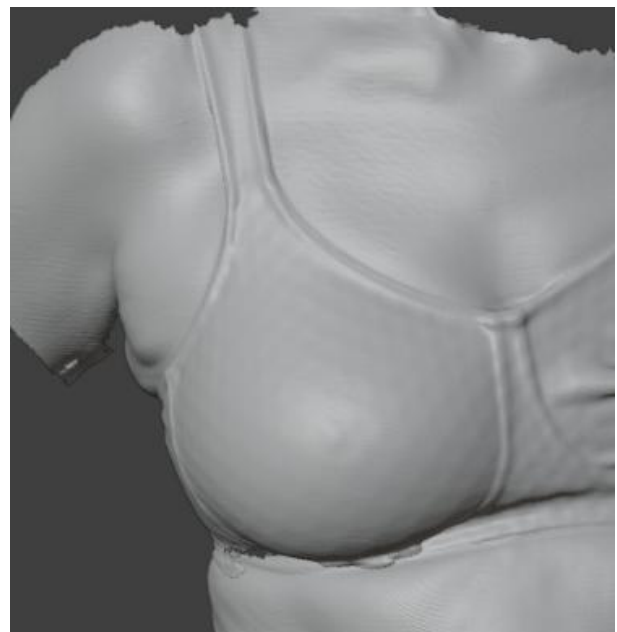


Figure 155: Result of the scan of the receiving side, first try



Figure 156: Result of the scan of the receiving side, second try

The scanning process (**Error! Reference source not found.**7) encountered several technical obstacles, including repeated software crashes, scan errors, and the need to adjust scanner positioning multiple times. In total, the session lasted over an hour. Of the two devices, the EVA scanner produced the most robust and complete results, especially in capturing critical anatomical regions such as the inframammary fold, armpits, and full torso contours. The resulting mesh data was processed in Blender and Rhino, where noise and scan artifacts were removed, the geometry was aligned along anatomical axes, and mirroring operations were applied. This resulted in a clean, symmetrical 3D model that could be used to simulate a custom-fit prosthesis design.



Figure 157: 3D scanning process

4.3.3 Evaluation of Outcomes

While the ideal scenario would have relied entirely on self-scanned data from patients, the practical findings suggest that this approach is still constrained by technical and human factors. The apps for iOS generally outperformed Android counterparts, offering better mesh quality and more intuitive interfaces. However, even with these tools, user performance varied widely.

As a result, this thesis concludes that self-scanning is a promising but currently imperfect solution. It offers a pathway toward accessible and scalable personalization of breast prostheses, especially when supported by good instruction and technical guidance. However, it cannot fully replace professional scanning in situations that demand high anatomical precision.

The dual-track approach—combining self-scans with expert scans of physical models—proved to be an effective strategy. It allowed for patient participation while also maintaining design integrity and data consistency through professional fallback options.

4.4 User feedback

4.4.1 Requirements Analysis Using the MoSCoW Method

To define and prioritize the design and functional requirements of the 3D printed breast prosthesis, the MoSCoW method (Figure 158) was used. This approach organizes features into four priority levels: "Must Have," "Should Have," "Could Have," and "Won't Have," helping to focus development on user needs within practical limits of time, cost, and materials.



Figure 158: MoSCoW analysis

Must Have requirements focus on essential aspects like functionality, comfort, and safety. The prosthesis must be lightweight, water-resistant, easy to clean, anatomically shaped using a 3D chest scan, soft to the touch, and comfortable in a bra without causing skin irritation or being visible under clothing. Odour resistance was also a key concern.

Should Have features enhance the user experience. These include natural and symmetrical shaping, customizable surface textures, breathable materials, ease of replacement, and use of medical-grade silicone. Other desirable traits mentioned were adaptability to body temperature, flexibility, and the ability to hide surgical scars.

Could Have features, suitable for future development, include skin-toned surfaces, artificial nipples, shape adjustability, added weight for better balance, and sustainable or temperature-regulating materials. These were considered non-essential at this stage.

Won't Have features were intentionally excluded to maintain simplicity. These included embedded tech (e.g., sensors), underwires, internal prostheses, and time-consuming maintenance routines—all seen as impractical or unnecessary for this product phase.

4.4.2 User Feedback from Expert Interviews and Cocreation Sessions (2024)

All interviews and cocreation sessions described below were conducted during the previous academic year as part of the *Cocreation* course. The insights gathered were essential for shaping the current prosthesis concept and informed the design requirements using the MoSCoW method. Additional feedback from fellow students, professors and experts during this thesis further refined the direction.

4.4.2.1 Expert Interviews

Medical Expert – Prof. Dr. Philip Blondeel (Plastic Surgeon)

Prof. Blondeel provided crucial input on clinical feasibility, regulatory challenges, and market potential. He emphasized that while full breast prostheses are widely available, innovation is most needed for partial prostheses, especially given that 65% of surgeries are breast-conserving. He recommended 3D photography over scanning for shape capture, highlighted the need for lightweight materials, and pointed to the potential of porous or air-filled 3D printed structures—provided they are hygienic and sealed. He also stressed the need for clear project goals and awareness of the competitive landscape.

Industry Expert – Daniël Meijer (Anita UK/NL)

Daniël Meijer shared practical insights from Anita's experience with prosthesis production and fitting. He noted that 3D printing is not yet adopted due to cost, but a market gap exists between standard (€280) and custom (€3,000) prostheses. Key design factors include comfort, durability, skin compatibility, and integration with bra designs. He stressed the importance of aligning with reimbursement systems in Belgium and the EU for market viability.

Fashion Expert and Patient – Karine Tollenaere

Karine, a breast cancer survivor and fashion designer, highlighted the emotional and practical needs of patients. She advocated for light, non-medical looking prostheses and front-closure bras. She also suggested integrated bra-prosthesis designs and promoted the use of 3D surface imaging. Karine helped connect the project with patient networks and offered strategies for gathering user data anonymously.

4.4.2.2 Cocreation Sessions

Three cocreation sessions with a total of five patients provided essential user-centered insights:

- **Session 1 (2 patients):** Shared experiences with expanders, radiation damage, and prosthesis discomfort. Patients emphasized the need for lightweight, natural, and discreet prostheses that support daily confidence.
- **Session 2 (2 patients):** Explored home scanning, which was firmly rejected. Patients preferred hospital-based scanning, citing professionalism and trust.
- **Session 3 (1 patient):** A silicone prototype was tested. Feedback highlighted issues with size, stiffness, and unclear features. Patients asked for improved softness, fit, and communication.

These sessions helped define both the emotional and technical requirements of the prosthesis. Integrating this feedback into the thesis process reinforced the importance of continuous dialogue with users and experts, ensuring the product remains both functional and empowering.

4.4.3 Scenario Test Design and Challenges

To assess the practical usability of the 3D printed breast prosthesis, a detailed scenario test protocol (Appendix A) was developed. This test was intended to evaluate comfort, weight impact, and daily usability during a one-week trial period. Participants were to wear a custom-made prosthesis during everyday tasks such as working, shopping, and exercising, and to document their experiences in a logbook. They would also complete a standardized EQ-5D-5L questionnaire [67] to provide quantitative data on their health and well-being during the test period.

The test protocol included preliminary measurements of the prosthesis weight, a personal introduction session, daily logging of prosthesis usage and comfort, and a final interview to capture qualitative feedback. Unfortunately, the scenario test could not be carried out as planned. The main reason was the insufficient quality of the 3D scans, which made it impossible to create prostheses that were accurately tailored to individual participants. In addition, the tight timeline of the academic semester did not allow for the production and evaluation of multiple personalized prostheses. It was also considered inappropriate to ask patients to provide feedback on a prosthesis that was not specifically designed for their body.

Nevertheless, the preparation of this scenario test served an important purpose. It clarified the logistical and technical barriers involved in conducting real-life evaluations of personalized medical products and highlighted the need for clinical partnerships that can provide access to higher-resolution scan technology.

4.4.4 User Test Protocol and Technical Validation

A second test protocol (Appendix B), focused on short-term user testing, was also developed. This protocol aimed to gather immediate feedback from participants in a controlled environment. The test session would consist of an introduction, fitting of the prosthesis, simple movement tasks such as walking and bending, and completion of a post-test questionnaire. Participants would provide feedback on the weight, fit, and aesthetic quality of the prosthesis, and the test would conclude with a brief interview.

Despite the test's well-structured design, it was not implemented due to the same constraints mentioned above. However, the framework remains highly relevant for future research and clinical trials.

In place of user testing, valuable expert feedback was obtained from the prosthesis manufacturer Anita and from Yannick, an experienced 3D printing specialist. The feedback from Anita was gathered during company visits, as previously discussed in section 2.3, and following interim presentations. They confirmed the feasibility of using hole structures to reduce weight and validated the selection of silicone-based materials due to their softness, flexibility, and skin compatibility. Furthermore, they emphasized the importance of avoiding oily surface textures and ensuring that the prosthesis remains easy to clean and maintain.

4.5 Material study

For the development of a 3D printed external breast prosthesis, choosing the right material is one of the most critical aspects. The material must be soft and flexible to ensure comfort, but it also needs to be safe for long-term contact with the skin. In addition, it must be suitable for 3D printing using silicone-based extrusion technology. Since this printing technology is still relatively new, especially in the medical field, it was necessary to carry out extensive research to understand which materials could be used and how they behave during the printing process. The goal of this material study was to collect technical knowledge about suitable silicones, test a selection of them, and plan for the use of certified, medical-grade materials in the final product.

4.5.1 Visit to 3D Printer Manufacturer: OMD 3D

An important part of the material research was the visit to the 3D printer manufacturer OMD 3D, together with Yannick Christiaens, lecturer at Ghent University and researcher at Design Nexus, who has extensive expertise in 3D printing, on 31 October. During this visit, I received valuable technical information and practical insights about the requirements and limitations of silicone 3D printing. I learned that the printer works with special cartridges or syringes that contain liquid silicone, and that the viscosity of the material is one of the most crucial parameters. If the silicone is too viscous, it can block the printer system; if it is too fluid, it will not hold its shape during printing. Therefore, it is essential to select a material with the right viscosity for the extrusion process.

At OMD 3D, I also received instructions on basic cleaning and maintenance. For example, after printing, the pump must be carefully cleaned to avoid material buildup, and when using hydrogel, the print head needs to be flushed with warm water. If cleaning is not done properly, residue can stay inside the nozzle and negatively affect the quality of the next print.

The printer uses Simplify3D slicing software and is controlled internally by Duet software. A helpful feature of the machine is its ability to perform automatic calibration, which simplifies the setup process. Parts are printed onto a thermoformed plate, which helps to stabilize the silicone during printing and prevent deformation.

Another important insight from the visit was that for early-stage prototyping, it is recommended to use industrial-grade silicone. This type of silicone is much cheaper than medical-grade silicone but is not safe for direct skin contact. Once the design is finalized and the printer settings are optimized, it is necessary to switch to certified medical-grade silicone for the production of the final prosthesis. OMD 3D also provided us with printed samples (**Error! Reference source not found.**⁵⁹ and **Error! Reference source not found.**⁶⁰) to give a better understanding of the achievable print quality.



Figure 159: Box of samples



Figure 160: Sample of simplified prosthesis made by OMD 3D

4.5.2 Review of Previous Research and Formlabs Resins

To avoid duplicating previous work [45], I reviewed the cocreation project carried out during the previous year. However, I found that the material research was not directly applicable to the thesis. They had intended to use SLA and SLS 3D printers, which work with completely different materials compared to silicone extrusion printers. As a result, the materials they selected were incompatible with the printing process I planned to use.

Even though their findings could not be used directly, studying their work helped me better understand which material properties are important for external prostheses, particularly in terms of flexibility and comfort on the skin. Their best-performing materials were BioMed resins from Formlabs, which were specially developed for SLA and SLS printers. None of these resins were silicone-based, but the comparison still gave useful information about flexibility requirements.

Among the resins they tested, the BioMed Elastic 50A resin (**Error! Reference source not found.**⁶¹) showed the most flexible behaviour, but even it was still considered too stiff for comfortable long-term skin contact. BioMed Durable Resin and BioMed Flex 80A resin (**Error! Reference source not found.**⁶¹) were even more rigid, while BioMed White, Black, Amber and Clear resins (**Error! Reference source not found.**⁶²) were not suitable at all due to their hardness. From this analysis, it became clear that a material softer than 50A Shore hardness was necessary, and that silicone would likely be a better option due to its natural skin-like feel.



Figure 161: BioMed Flex 80A & Elastic 50A Resin



Figure 162: BioMed Amber, Clear, White & Black Resin

4.5.3 New Material Research

After the visit to OMD 3D and the review of previous research, I focused my efforts on identifying silicone materials that are suitable for 3D printing and certified for skin contact. I collected technical data and contacted several suppliers to request detailed information about available materials.

From the printer manufacturers and materials used by Lynxter and OMD 3D, I identified the Copsil 3D silicones, including Copsil 0550, 1050, 4050, and 2550, as potential candidates [68]. Additionally, Lynxter offered materials such as LIQ Sil-001 and LIQ Support-001, which are optimized for their printer system.

Through an internet search and discussions with material suppliers, I also identified other possibilities. Wacker Chemie AG offers the Elastosil P and FX series, which are flexible but not always skin-safe. Their M series is a RTV-2 type but not suitable for skin contact. The LR series is better suited for injection molding rather than extrusion printing, and the Silpuran series, although sticky and good for adhesion, lacks structural strength [69]. Elkem Silicone offers Amsil Silbione materials, which are medical-grade and soft, as well as RTV-2 soft elastomers that are printable [70]. Finally, Avantor Nusil produces the MED 4720, MED 4950, and MED 4840 silicones, which are typically used for implants and are certified for biocompatibility, though I needed to confirm their printability [71].

By collecting datasheets on viscosity, Shore hardness, curing times, and certifications, I created an overview of materials to test further. Some samples were requested, and discussions with manufacturers are ongoing.

4.5.4 Visit to Medica Fair

To broaden the scope of the material research, I visited the Medica trade fair as part of the Biomedical Product Development course. I took this opportunity to gather additional information for my thesis by visiting booths of companies active in silicone and 3D printing materials. During the fair, I had meetings with representatives from Wacker Chemie AG, Elkem Silicone, and Avantor Nusil.

These conversations provided valuable insights not only into the materials themselves but also into their typical applications, limitations, and costs. I also gained a better overview of the latest developments in the field of silicone 3D printing for medical purposes. Some companies are already experimenting with silicone 3D printing for applications like hearing aids, soft orthotic devices, and other wearable medical products.

From these discussions, I learned that medical-grade 3D printable silicones are still a relatively niche market. Finding materials that are both printable and certified for skin contact is challenging, but there are promising solutions available if budget is not a major limitation.

4.5.5 3D Printer Installation

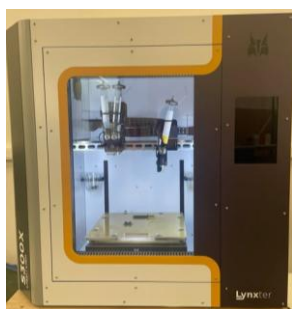


Figure 163: 3D printer Lynxter S300X LIQ21

For this project, the 3D printer model Lynxter S300X LIQ21 (**Error! Reference source not found.**⁶³) was selected, as it is one of the few printers capable of working with soft liquid silicone materials. The printer was delivered on 17 December 2024. The first planned installation was scheduled for 8 January 2025 but had to be postponed due to a problem with the internet cable. The final installation and setup were successfully completed on 17 February 2025.

I will begin with testing and initial prints during the second semester of 2025. At first, industrial-grade silicone will be used to optimize the print settings and test the design iterations. Once the printer is properly calibrated and a good design is confirmed, the process will move on to using medical-grade silicone for the final prosthesis production.

4.5.6 Sample Requests and Communication with Experts

To support material selection, I contacted several companies to request samples and technical datasheets. Formlabs provided resin samples, but as explained earlier, these were not compatible with silicone extrusion printing. No samples or confirmations were received from Wacker or Elkem.

I also shared a compiled file with all relevant material information and datasheets with Yannick Christiaens, who forwarded it to OMD 3D. He asked whether they had experience with the listed materials or could suggest alternatives. Unfortunately, no response from OMD 3D was received before the thesis deadline.

Two materials were available for testing at the university: Copsil 3D 0550 and Lynxter LIQ Sil-001. These were selected for initial testing to evaluate printer behaviour, layer quality, and post-curing performance.

4.5.7 Material testing

Although additional materials were intended for testing, it was not possible to purchase or acquire any beyond the two already available. Even with those, testing could not be fully carried out. Due to technical issues with the slicing software and time constraints, it was only possible to perform one print using Lynxter Sil-001 silicone. As a result, the planned comparative material testing and full protocol (Appendix C) evaluation could not be completed. This limitation will need to be addressed in future development phases.

4.6 Conversation Yannick Christiaens about 3D printing prostheses

On Tuesday, 6 May 2025, I had a valuable meeting during the noon with Yannick Christiaens, lecturer at Ghent University and researcher at Design Nexus, who has extensive expertise in 3D printing. The discussion focused on the silicone 3D printing of the breast prosthesis.

Prior to the meeting, I had sent Yannick an STL file of the prosthesis model. This version featured a lattice-structured surface that forms the outer layer (skin) of the prosthesis. The purpose of sending the file in advance was to allow him to examine the model and attempt slicing it using Simplify3D, the slicing software currently used for the Lynxter silicone 3D printer. This would enable us to assess the technical feasibility of printing the design.

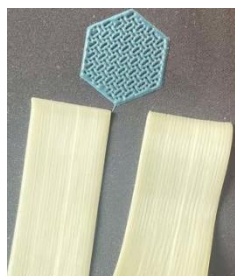
However, several technical challenges arose due to the complexity of the lattice structure. Most notably, the software failed to generate any support structures at the bottom of the prosthesis, which are essential for stable printing. Yannick attempted several strategies to manually add or force the generation of supports, but none were successful. Consequently, he reached out to OMD 3D, the supplier of the printer, to ask whether they had encountered similar issues and could suggest a solution.

OMD 3D responded with a potential workaround, but the proposed solution turned out to be too complex to implement within our current technical capabilities, especially considering Yannick's limited experience with the Simplify3D software. As a result, the slicing and printing of the current design remains a technical challenge.

In addition to the lack of automatic support generation, a second issue emerged: the unconventional shape of the prosthesis makes it difficult to determine the optimal orientation for printing. Even in the most favourable orientation, a significant amount of support material would still be needed. This raises a critical concern—how to remove the support material, which is a hydrogel, without damaging the structure or compromising its functional properties.

1. During our conversation, Yannick formulated three important questions regarding the design and post-processing:
2. Since the support material is a hydrogel, could the prosthesis be designed with an intentional opening or hole that would allow easier removal of the support material after printing?
3. Would adding such a hole present medical risks, for instance, increased risk of infection, especially considering the prosthesis is worn in prolonged direct contact with the skin?

These questions raise important concerns about the design's practicality and medical safety. To address these, I plan to consult the product development and medical experts at Anita Dr. Helbig GmbH. In an initial discussion, the Anita team found the idea of designing the prosthesis with a removable nipple highly promising. This feature could potentially address the first two questions, as it would allow internal access for hydrogel removal while avoiding additional openings in sensitive areas. The team at Anita confirmed that such an approach would not involve significant medical risks.



In addition to answering Yannick's questions, I also had one for him. Previously, he had provided me with a selection of test prints made by OMD 3D using the Lynxter printer. I took these samples with me during the Easter holiday to present to the Anita team. Out of the selection, two samples (**Error! Reference source not found.**⁶⁴) stood out as particularly interesting to Anita. However, I was not sure which specific materials had been used for those prints. After our meeting, I contacted Yannick again via Microsoft Teams and sent him a photo of the selected samples to ask for material clarification.

Figure 164: Two samples interested by Anita team

Lastly, I shared with Yannick my updated breast prosthesis concept, which consists of a complete internal structure with a lattice outer layer and an integrated external skin envelope. I also sent him the STL file of this latest version, and he agreed to review the model to assess whether it would be more suitable for 3D printing.

Meanwhile, I will continue investigating potential solutions for the removal of hydrogel supports, both from a technical and design standpoint. I will also keep Yannick updated on any new developments or findings that could assist in overcoming the current printing challenges.

5 DISCUSSIONS

This chapter reflects on the findings of the research project and aims to interpret them in light of existing knowledge on 3D printed breast prostheses. The discussion provides insight into how the results contribute to the understanding of personalized prosthesis development and highlights both strengths and limitations of the current approach. Furthermore, this chapter returns to the sub-questions from the introduction and provides answers based on the outcomes of the project. The chapter concludes with reflections on the study's limitations and recommendations for future research.

5.1 Interpretation of Results and Contributions to Knowledge

The findings from this thesis contribute meaningfully to the emerging field of 3D printed external breast prostheses by demonstrating how a combination of digital design tools, cocreation-based design strategies, and lightweight structural innovations can lead to more personalized and user-centered prosthetic solutions. Unlike many previous studies that have primarily focused on internal breast implants used in surgical reconstruction, this research shifts the focus toward non-surgical, external prostheses—particularly for women who cannot or choose not to undergo reconstructive surgery. This user-driven perspective aligns with the growing need for inclusivity, accessibility, and comfort in post-mastectomy care.

A major technical insight of this project was gained through the experimentation with hole structures inside the prosthesis. These internal designs, inspired by hole structures, showed clear potential for reducing overall weight—a commonly reported complaint about conventional prostheses. However, the testing also revealed a crucial limitation: when the hole structures became too fine or too densely patterned, the prosthesis lost its structural firmness and risked becoming unstable or uncomfortable during use. As a result, the study found that applying hole structures to the outer shell or surface only can be a more effective strategy for weight reduction without compromising the prosthesis's integrity. This finding highlights the importance of achieving a careful balance between lightness and mechanical support.

The integration of Grasshopper, a parametric design tool within Rhino, enabled early-stage customization and rapid virtual prototyping. Although the script developed during this thesis was not fully optimized due to time constraints and technical complexity, a functional version was successfully implemented. This version allowed for the manipulation of key design parameters—including shape, opening position, and internal structure—based on 3D scan data of the patient's chest. This demonstrates that visual programming environments like Grasshopper can support mass customization of medical devices, reducing the time and cost of iteration while maintaining design flexibility. Such tools are increasingly important in healthcare innovation, particularly in personalized product development where one-size-fits-all solutions are no longer sufficient.

The direction of the design was strongly influenced by insights gathered from patients, 3D printing experts, and industry professionals, particularly through collaboration with the company Anita, which specializes in breast care products. While full-scale user testing could not be performed due to practical limitations, valuable input was gathered through previous interviews (conducted in the Cocreation course), interim presentations, and informal consultations. A MoSCoW analysis was used to prioritize design features based on this feedback, highlighting comfort, secure fit, ease of use, and natural appearance under clothing as essential requirements. These insights helped ensure that the design choices were informed by real user needs rather than purely technical possibilities.

Furthermore, the findings from this research reinforce existing knowledge that conventional prostheses are often heavy, hot, and limited in shape and style, as noted in earlier benchmark comparisons. Many users report discomfort and dissatisfaction with mass-produced prostheses, which are not always adaptable to different body types or activity levels. This project suggests that 3D printing offers a promising alternative by enabling custom-fit, breathable, and lightweight designs that better reflect the anatomical diversity and lifestyle preferences of patients. By combining customization with cocreation, and linking engineering tools with user feedback, the design process becomes not only more efficient but also more inclusive and responsive.

5.2 Linking Back to the Introduction and Research Questions

The central research question of this thesis was: **How can 3D printing technology be used to optimize the design of lightweight external breast prostheses to meet medical standards and user comfort?** This question was addressed through seven sub-questions, each focusing on a specific area of prosthesis development, including material selection, design innovation, user needs and digital modelling. Together, these guided the research process and shaped the design strategy. Below, each sub-question is revisited and interpreted in light of the project's results.

Sub-question I focused on identifying suitable materials for 3D printing that ensure comfort, durability, and safety. Through literature review, online research and basic material tests using PLA and TPU, the study confirmed the need for soft, skin-friendly and biocompatible materials. While medical-grade silicone could not be printed due to technical constraints, it remains a priority for future testing and regulatory compliance.

Sub-question II addressed optimal printing parameters, such as infill percentage, curing time and layer height. This could not be explored in detail because the slicing and printing were partially outsourced. However, the findings stress the importance of conducting systematic testing of these parameters, especially for silicone extrusion, to improve quality and reproducibility in future iterations.

Sub-question III focused on design strategies to reduce weight. Several prototypes with internal and surface hole structures were tested. The results showed that excessive internal holes can reduce stability and comfort, while surface-only hole structures offered the best balance between weight reduction and mechanical integrity. This insight directly supports the project's goal of improving prosthesis wearability.

Sub-question IV explored how user preferences can be integrated into the prosthesis design. A MoSCoW analysis, based on input from earlier user studies and cocreation sessions, helped prioritize features such as a soft texture, discreet appearance, a secure fit and ease of use. These were translated into specific design elements, including the addition of a removable nipple and modular features.

Sub-question V examined how user feedback could inform design improvements. Due to time and scan quality limitations, direct user testing could not be performed. However, meaningful insights were gathered from breast care nurses, Anita representatives and 3D printing experts. These insights shaped the prosthesis requirements and confirmed the importance of integrating structured user testing in future work, using methods such as scenario testing and QAP.

Sub-question VI evaluated the current prosthesis market through a benchmark study of 32 commercial models from Anita, Amoena, Trulife and ABC. The analysis identified limitations in existing products, particularly in terms of weight, personalization and breathability. These gaps informed the innovation direction of the 3D printed design developed in this project.

Sub-question VII focused on the use of Grasshopper for parametric modelling. Although the script was not fully optimized, a functional version allowed for customization based on 3D scan data. Design features such as internal structures and removable elements were incorporated, showing the potential of visual scripting for mass personalization of medical devices.

Taken together, the sub-questions highlight a new understanding: 3D printing, combined with digital modelling, cocreation and structural optimization, offers a powerful approach to creating external breast prostheses tailored to individual needs. To move towards real-world application, future work must address regulatory approval, clinical testing and material certification. Nonetheless, this thesis demonstrates the value of merging engineering and healthcare for more inclusive and user-centered prosthesis design.

5.3 Limitations of the Study

Despite the valuable findings of this thesis, several limitations influenced the scope and outcomes of the project. These limitations should be acknowledged to provide a realistic understanding of the work and to guide future research.

One of the most significant limitations was the absence of real user testing. Although scenario testing and patient feedback were planned, these could not be executed due to the low quality of the 3D scans and limited available time. As a result, the prostheses developed in this project were not evaluated directly by breast cancer survivors, which limited the ability to assess comfort, usability, and emotional impact.

There were also technical and software-related challenges. The slicing software Simplify3D was difficult to operate without prior experience, and a large portion of the time was spent developing and troubleshooting the Grasshopper script. These challenges slowed down the prototyping process and restricted the number of design iterations that could be completed and tested within the timeframe.

In addition, the sample size for feedback was small. Input was gathered mainly from experts, breast care nurses, and representatives from Anita. While these insights were valuable, the absence of direct and diverse patient feedback limits the generalizability of the conclusions.

Although regulatory frameworks such as MDR and ISO 13485 were taken into account during the design process, no formal compliance was pursued, as this exceeded the academic scope of the project.

Lastly, material testing was limited to a few FDM-compatible materials. Future studies should focus on medical-grade silicone extrusion, which is more representative of real-world prosthesis use.

Despite these constraints, this thesis establishes a strong foundation for further development and interdisciplinary collaboration.

5.4 Future Work and Recommendations

Based on the results and limitations of this study, several important directions for future work are identified to further develop and improve the design of 3D printed external breast prostheses.

First, the quality of 3D scans should be improved. In this project, limitations in scan resolution impacted the accuracy of the prosthesis fit. Future research should involve clinical collaborations with hospitals or breast clinics, using professional scanning equipment to ensure high-quality anatomical data for personalized modelling.

Secondly, a full validation protocol is essential. While this thesis collected feedback from experts, direct user testing under real-life conditions was not conducted. Future work should include scenario testing, long-term wear trials and structured feedback using validated tools to evaluate comfort, usability and satisfaction.

In addition, certified medical-grade materials, such as biocompatible silicones, must be tested for safety, softness and long-term wearability. This will support regulatory compliance and improve user comfort. At the same time, a systematic study of print settings—including slicing parameters and curing times—is needed, particularly for silicone extrusion printing, to optimize both production speed and print quality.

The cocreation process should also be expanded. A more diverse group of users with varying body types, activity levels, and personal preferences should be involved in the design process to ensure inclusivity and broader applicability.

From a commercial perspective, pathways for CE marking, reimbursement models, and sustainable production strategies should be explored to make personalized prostheses more accessible.



Lastly, a promising future design direction is the use of hole structures only on the surface, rather than internally. This approach may simplify printing, reduce the weight more and improve breathability while maintaining structural integrity. This concept, shown in Figure 165, was generated using AI for illustrative purposes and could be explored further in future prototyping.

Figure 165: Alternative design idea

6 CONCLUSIONS

This master's thesis set out to explore the central research question: How can 3D printing technology be used to optimize the design of lightweight external breast prostheses to meet medical standards and user comfort? Through a combination of benchmark analysis, cocreation strategies, Grasshopper coding and early-stage prototyping, the study has laid a strong foundation for developing more personalized and user-friendly external breast prostheses.

The thesis confirmed that 3D printing offers new opportunities to improve breast prostheses by allowing for personalization, lighter weight and more ergonomic shapes. Although the use of certified medical-grade silicone was not yet possible in this stage, the research showed that using hole structures in the design—especially on the outer surface of the prosthesis—can reduce weight while preserving shape and structural stability. This aligns with earlier literature about comfort and breathability challenge with traditional silicone prostheses, and offers a new approach that is both innovative and user-oriented.

Another significant contribution of this thesis is the integration of the parametric modelling software Grasshopper. Although the final code was not fully optimized, a working version of the script was built and tested. The code makes it possible to create personalized prosthesis models based on 3D scan data and user-specific design input. This technical tool will be especially valuable for future studies or companies looking to automate prosthesis customization for different body types and needs.

The MoSCoW analysis and stakeholder interviews highlighted the most important needs of users: softness, secure fit, a natural look and comfort during daily activities. While direct testing with patients was not possible due to time and technical limitations, valuable feedback was collected from breast care nurses, industry partners (Anita) and 3D printing experts. These insights supported design decisions such as the addition of a removable nipple, smooth finishes and modular design elements.

The findings also confirmed many of the weaknesses of current commercial prostheses, including limited size options, poor breathability and lack of customization. This thesis supports the claim that additive manufacturing, when used with patient feedback and smart design tools, can address these limitations effectively.

At the same time, the research identified key limitations and areas for future development. The slicing and printing parameters for silicone were not systematically explored and medical-grade material testing remains necessary. Moreover, the lack of large-scale patient testing means that some usability and comfort aspects are still hypothetical and need real-world validation.

Despite these limitations, this thesis contributes to the growing body of research combining medical product design with digital manufacturing. It offers a clear vision for how future breast prostheses could be made more comfortable, adaptable and emotionally supportive. Through a multidisciplinary and cocreation approach, the project brings the development of external breast prostheses closer to the people who wear them every day.

In conclusion, this thesis shows that 3D printing—when guided by cocreation, regulatory awareness, and smart computational design—has great potential to improve the lives of breast cancer survivors. It provides a strong basis for future research and practical implementations that aim to make external breast prostheses more inclusive, functional and emotionally empowering.

7 SOCIAL REFLECTION

The societal significance of this thesis lies in its potential to significantly improve the quality of life for breast cancer survivors, while also challenging existing norms in medical device design through sustainability, inclusivity, and innovation. By focusing on the optimization of 3D printed breast prostheses, this project contributes to a broader conversation about health equity, environmental responsibility, and user empowerment in healthcare innovation.

7.1 Sustainable Development Goals

This thesis sits at the intersection of healthcare, user-centered design and sustainability, aligning with multiple United Nations Sustainable Development Goals (SDGs). Its broader social value is reflected in its emphasis on the physical and emotional well-being of breast cancer survivors and its exploration of innovative, eco-conscious solutions in medical product development.

SDG 3: Good Health and Well-Being is at the core of this project. The creation of anatomically tailored breast prostheses supports not only physical recovery but also emotional resilience. By addressing user comfort, confidence, and body image, the design process recognizes health as a multidimensional concept encompassing both clinical and psychological aspects. Personalized prosthetic care is an essential yet often overlooked component of holistic post-mastectomy rehabilitation.

SDG 9: Industry, Innovation, and Infrastructure is supported through the integration of advanced digital fabrication techniques, including 3D scanning, parametric modelling, and additive manufacturing. These technologies facilitate decentralized, patient-specific production models that can reduce logistical inefficiencies and support agile healthcare delivery systems. They also open doors to democratizing access to high-quality prosthetic care, particularly in settings where traditional manufacturing infrastructure is lacking.

SDG 12: Responsible Consumption and Production is particularly significant in this work. Traditional prosthesis manufacturing often relies on labour-intensive, resource-heavy processes with limited scope for material recovery. In contrast, 3D printing allows for on-demand, localized

production, minimizing transportation-related emissions and reducing surplus inventory. Furthermore, the project investigated biocompatible and recyclable materials to ensure that material health and end-of-life considerations are addressed from the outset. This supports a circular economy approach in medical device design.

The thesis also touches on **SDG 5: Gender Equality**. Breast cancer disproportionately affects women, and the project contributes to gender-sensitive healthcare by acknowledging the specific needs of female patients in prosthetic design. Through cocreation with breast cancer survivors, the project elevates user voices and promotes inclusive innovation. Additionally, by normalizing discussions around body image, post-operative aesthetics and emotional healing, the project challenges societal taboos and fosters empowerment.

7.2 Reflections

During the research period, conversations with friends and family helped clarify the significance and goals of the project. Many were unaware of the challenges associated with breast prostheses and the emotional impact these devices can have. Explaining the thesis in simple terms helped raise awareness about the importance of personalized care after mastectomy and the role of design and technology in supporting recovery and body image.

On an international scale, the topic of this research is highly relevant. Breast cancer is a global health issue, and the need for accessible, affordable and personalized prosthetic solutions spans across countries and continents. Although the research was conducted in Belgium, the methodology and technology have worldwide potential. In lower-resource settings, digital scanning and local 3D printing could provide cost-effective, scalable alternatives to traditional prostheses. This strengthens the global applicability and social impact of the project.

Ethical considerations were carefully addressed throughout the research. All participants gave informed consent (Appendix G-L) and data handling followed GDPR regulations. A key ethical concern that emerged involved the accessibility of self-scanning technologies. While digital tools offer great potential, they can also present barriers for users with limited technical skills. It is therefore important that future implementation includes clear guidance, technical assistance, and possibly hybrid models that combine self-service with professional support. This would help to ensure equitable access and prevent the exclusion of digitally vulnerable users.

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APPENDIX

1. APPENDIX A: Protocol scenario test

Date: Depending on patient (in semester 2: March, April, May)

Location: Depending on patient (Ursel, Kortrijk, Ghent, ...)

1. Introduction

In the context of my master thesis, entitled "Optimization of the product development of 3D printed breast prostheses", I investigate how advanced 3D printing technology can contribute to the development of breast prostheses that are not only aesthetic and comfortable, but also functional in the daily lives of women who have undergone a mastectomy. Traditional breast prostheses often do not fully meet the personal and practical needs of users. They can be uncomfortable, not fit well, or do not meet the aesthetic wishes of the user. This offers room for innovation through 3D printing, which allows for the production of custom-made breast prostheses.

The concept of this research focuses on the development of a personalization system for the production of custom-made breast prostheses. This is made possible by advanced 3D scanning technology and 3D printing. The approach is personalized: each prosthesis is designed based on the unique anatomical features of the user, including specifications such as embossed patterns for grip and an internal hole structure (lattice structure) to reduce the weight of the prosthesis without compromising its strength or durability. The process starts with the collection of 3D scans, which users can initially make themselves using a smartphone equipped with LIDAR scanning technology or a specific app. In a later phase, these scans are intended to be professionally performed by healthcare providers. The data obtained is processed in the Grasshopper software, where the model of the prosthesis is created. This 3D model is converted into a digital file (STL) that can be printed by a 3D printer.

2. Goal of the test

The aim of this scenario test is to evaluate the performance of the 3D printed breast prosthesis in a realistic usage environment. The following three important aspects are specifically considered:

1. **Comfort:** To assess the wearability of the prosthesis, both physically (comfort on the skin, freedom of movement) and emotionally (how the prosthesis is experienced by the user), during a one-week test period.
2. **Weight:** To analyse the effect of the weight of the prosthesis on the user experience. This is measured both objectively (using a precision scale) and subjectively by the participants, who can share their experience with the weight and comfort.
3. **Practical Applicability:** To collect qualitative feedback on the performance of the prosthesis during daily activities, such as work, household chores, sports, and social interactions.

These insights will be used to make iterative improvements in the design and production of the prosthesis. The research not only aims to test the technical feasibility of 3D printed breast prostheses, but also to understand how these prostheses are experienced in daily life and what adjustments are needed to further optimize them.

3. Test setup

3.1 Preparation

1. **Selection of subjects:** Participants in the test are women who have undergone a mastectomy and are currently wearing an external breast prosthesis or are interested in participating in this study. Recruitment of participants is done via social media (Instagram and Facebook) and through flyers, posters and folders in hospitals. The expected number of participants is between 5 and 15, with variation in age, medical history and lifestyle.
2. **Information session:** Before the test, all participants will receive a detailed explanation of the purpose of the study, the test procedure and expectations. Information about privacy and data protection will be provided so that participants feel comfortable with the use of their personal data. Participants give written consent to participate in the study (informed consent), and are assured that their scans and data will only be used for research purposes and will not be shared with third parties.
3. **Delivery of the prosthesis:** Each participant will receive a custom-made 3D printed breast prosthesis, developed based on previously performed 3D scans. The prostheses come with instructions for use, so that participants can use them optimally. In addition, they receive a logbook to record their experiences and observations during the test period. At the end of the test period, participants must return the prostheses, as they are prototypes. These prototypes will be further tested and optimized in a future work to comply with all medical regulations, including the MDR (Medical Device Regulation) and ISO 13485.

3.2 Test procedure

Phase 1: Preliminary measurements and introduction (Day 1)

1. **Introductory interview:** A personal interview in which the test protocol is explained and the participant is informed about what is expected of her during the test period. The daily activities in which the prosthesis will be worn are also discussed, in order to understand what the participant may encounter.
2. **Objective measurements:** The weight of both the existing used prosthesis and the 3D printed prosthesis is measured with a precision scale. These measurements serve as a reference point for the test period.

Phase 2: Scenario test in practice (1 week)

1. **Daily use:** During the test week, the participant wears the 3D printed prosthesis during her daily activities, such as working, shopping, sports and social interactions. This allows the researcher to evaluate the prosthesis in a realistic context.
2. **Logbook notes:** The participant is asked to keep a daily logbook in which they note how long they have worn the prosthesis, which activities they have performed, the comfort experienced (e.g. pain, irritation or discomfort) and any comments or suggestions for improvement.
3. **Interim contact:** If necessary, a short telephone or digital contact moment is organized to discuss questions or problems that may arise during the test period.

Phase 3: Evaluation and closing (Day 7)

1. **Questionnaire (EQ-5D-5L):** The participants complete a standardized questionnaire, which provides insight into their comfort and well-being during the test period. This is measured using five dimensions: mobility, self-care, usual activities, pain/discomfort, and anxiety/depression.
2. **Closing interview:** A qualitative interview in which the participant shares her experiences. Specific focal points are discussed, such as how the prosthesis behaved during certain activities, the positive and negative aspects of the design, and recommendations for future improvements.

4. Measurement and Evaluation

The measurement is an essential part of the test procedure, as it provides objective data to evaluate the performance of the 3D printed breast prostheses. This section discusses both the quantitative and qualitative measurements, as well as the methodologies used to collect reliable and valid data. The purpose of the measurement is to ensure a thorough evaluation of the effect of the 3D printed breast prostheses on different aspects of the participants' well-being.

4.1 Quantitative Measurements

The quantitative measurements play an important role in objectively assessing the effectiveness of the 3D printed breast prostheses. The main quantitative data sources are:

- **EQ-5D-5L Questionnaire:** The EQ-5D-5L is a standardized questionnaire used to measure the health status of the participants. Participants complete the questionnaire after the test period to gain insight into their comfort and well-being after wearing the custom-made breast prostheses. These dimensions include:
 - **Mobility:** Participants indicate how easily they can move around, which is an important factor in assessing the physical burden of the prosthesis.
 - **Pain or discomfort:** The degree of pain or discomfort that participants experience in their daily lives, specifically due to the prosthesis.
 - **Self-care:** How well participants are able to perform personal care without assistance, which can be influenced by the comfort and functionality of the prosthesis.
 - **Activities of daily living:** Participants indicate the extent to which the prosthesis interferes with their daily activities, such as work, household chores or social activities.
 - **Psychological health:** The mental and emotional state of the participants, including anxiety, depression or contentment, which can be influenced by the use of the prosthesis.

Each of these dimensions is rated using a scale of 1 to 5, with 1 indicating no problems and 5 indicating the most severe problems.

- **Weight measurement:** The weight of the traditional and 3D printed breast prostheses is measured to evaluate the impact of weight on comfort and functionality. This measurement is performed using a precision digital scale and the results are compared to determine whether the 3D printed prosthesis is actually lighter and whether this affects the user experience.
- **Fit measurements:** The fit of the prostheses is measured by the degree of adaptation to the user's body. This is done through 3D scans, which allow the fit of both the traditional and 3D printed prostheses to be compared. The results are used to assess the effectiveness of the design and to recommend adjustments.
- **Usage time:** Participants are asked to record the time they wear the 3D printed prosthesis compared to their usual prosthesis. This helps to assess whether the prosthesis is comfortable enough to wear on a daily basis and whether the usage time has a positive impact on well-being.

4.2 Qualitative Measurements

In addition to quantitative measurements, it is essential to collect qualitative measurements. Qualitative data provides insight into the participants' experiences and helps to provide context to the quantitative results. This is achieved by using a variety of methods:

- **Short interview:** A short interview is scheduled before the participant tests the prosthesis. The purpose of the interview is to gain more insight into their personal background, expectations and any concerns about the prosthesis. This provides an opportunity to understand the participant's experiences and capture their perspective before they use the prosthesis. The interview also helps to collect valuable information about their current situation and needs, which can later be used for analysis and design improvements.
- **Logbook notes:** Participants keep a daily logbook in which they document their experiences with the prosthesis. This can range from comments about pain or irritation to assessments of the comfort and appearance of the prosthesis. The logbooks are used to identify trends in the participants' feedback and to assess the impact of the prosthesis on their daily lives.

5. Reporting and Analysis

After the scenario test is completed, it is essential to systematically report and analyze the collected data to gain insight into the effectiveness of the 3D printed breast prostheses. The reporting and analysis are crucial to draw conclusions about the performance of the prostheses and to make recommendations for possible improvements. The following sections describe how the data from the test procedure are processed and analysed.

5.1 Data processing

All collected data are carefully analysed and presented in a structured report. The main data sources are:

- **Questionnaire results (EQ-5D-5L):** The participants' scores on the five dimensions of the EQ-5D-5L questionnaire are collected after the testing period. These scores are compared to see if there are significant changes in the participants' health status, mobility, pain, self-care, daily activities, and psychological state.
- **Participant logbook entries:** Daily logbook entries, in which participants document their experiences with the prosthesis, are analysed to identify trends and common problems. Reported discomforts, irritations, or other feedback regarding the comfort and practical usability of the prosthesis are examined.
- **Objective measurements:** The weight of both the existing prosthesis and the 3D printed prosthesis are compared to evaluate the effect of weight on comfort and user experience.

5.2 Qualitative Analysis

In addition to the quantitative measurements, qualitative feedback from participants provides an important source of information. Participants are asked to evaluate specific aspects of the prosthesis and make suggestions for improvement. This feedback is analysed through:

- **Thematic analysis:** Participants' comments are categorized into themes such as comfort, weight, ease of use, and emotional well-being. This helps to understand which aspects of the prosthesis worked well and which need to be further optimized.

5.3 Quantitative Analysis

- **Effect of weight:** By comparing the weight measurements of both the traditional prosthesis and the 3D printed prosthesis, the influence of weight on comfort and user experience can be assessed. For example, lighter prostheses can contribute to a higher score for mobility and less physical strain.

5.4 Results and Interpretation

The results are presented using graphs, tables and figures to visually display the EQ-5D-5L questionnaire scores. This allows the researchers to quickly see where significant improvements have occurred and areas for improvement. The main findings are discussed as follows:

- **Comfort:** If participants experience a significant improvement in comfort, this will be evident from both the qualitative feedback and the changes in EQ-5D-5L scores, particularly on the dimensions of pain/discomfort and self-care.
- **Weight:** The impact of weight is assessed by looking at both objective weight measurements and subjective feedback from the participants on range of motion and physical strain. A slight reduction in weight can contribute to improved comfort and ease of use, resulting in higher scores for mobility and activities of daily living.
- **Practicality:** The practicality of the 3D printed prosthesis is evaluated based on the participants' logbook notes and feedback from the interviews. This provides insight into how the prosthesis performs in different contexts, such as work, social interactions, and sporting activities.

5.5 Conclusions and Recommendations

Based on the data analysis, conclusions will be drawn about the effectiveness of the 3D printed breast prostheses in practice. These conclusions will provide insight into how well the prostheses meet the needs of the users in terms of comfort, functionality and aesthetics. Recommendations will also be made for possible improvements in the design and production process to further optimize the prostheses.

2. APPENDIX B: Protocol user test

Date: Depending on patient (in semester 2: March, April, May)

Location: Depending on patient (Ursel, Kortrijk, Ghent, ...)

1. Introduction

In the context of my master thesis, entitled "Optimization of the product development of 3D printed breast prostheses", I investigate how advanced 3D printing technology can contribute to the development of breast prostheses that are not only aesthetic and comfortable, but also functional in the daily life of women who have undergone a mastectomy. Traditional breast prostheses often do not fully meet the personal and practical needs of users. They can be uncomfortable, not fit well, or do not meet the aesthetic wishes of the user. This offers room for innovation through 3D printing, which allows for the production of custom-made breast prostheses.

The concept of this research focuses on the development of a personalization system for the production of custom-made breast prostheses. This is made possible by advanced 3D scanning technology and 3D printing. The approach is personalized: each prosthesis is designed based on the unique anatomical characteristics of the user, including specifications such as relief patterns for grip and an internal hole structure (lattice structure) to reduce the weight of the prosthesis without compromising its strength or durability. The process starts with the collection of 3D scans, which users can initially make themselves using a smartphone equipped with LIDAR scanning technology or a specific app. In a later phase, these scans are intended to be professionally performed by healthcare providers. The obtained data is processed in the Grasshopper software, where the model of the prosthesis is created. This 3D model is converted into a digital file (STL) that can be printed by a 3D printer.

2. Goal

Primary goal:

Gaining insights and feedback on the design of the 3D printed breast prosthesis to implement improvements that meet user needs.

Secondary goals:

1. Evaluate the wearability and comfort of the prosthesis during daily activities.
2. Obtain qualitative feedback on aesthetics and practical usability.
3. Analyse objective data (such as weight and fit) and subjective satisfaction through questionnaires (such as the EQ-5D-5L).
4. Understand how the prosthesis contributes to the emotional and psychological well-being of the participant

3. Test setup

3.1 Target audience

Participants in this user test are women who have undergone a mastectomy and are currently using an external breast prosthesis or have experience with such devices. The inclusion criteria are as follows:

- Willingness to test a custom-made 3D printed breast prosthesis for a specific period.
- Signing an informed consent form.

Recruitment of participants takes place via social media (Instagram and Facebook) and through flyers, posters and folders in hospitals. The aim is to recruit 5 to 15 participants, so that a diversity of experiences, lifestyles and preferences is included.

3.2 Test method

This test combines qualitative and quantitative evaluation methods:

- **Qualitative:** Interviews and observations to gain in-depth insights into participants' experiences.
- **Quantitative:** Questionnaires (e.g. EQ-5D-5L) and objective measurements, such as weight and duration of use.

3.3 Duration

The test session per participant lasts approximately one hour and includes:

- Introduction and explanation (10-15 minutes).
- User test, including fitting and performing activities (30-45 minutes).
- Completing questionnaires and closing interview (5-10 minutes).

The entire test period can be extended to one week if the participants feel comfortable testing the prosthesis in their daily lives, then they perform the scenario test.

4. Test protocol

4.1 Preparation

1. **Test environment:** Provide a quiet, clean and comfortable space, with sufficient privacy for participants.
2. **Equipment and Materials:** Check that all equipment (e.g. recording devices) is functioning properly and that all necessary materials are present.
 - 3D printed breast prostheses (prototypes).
 - Questionnaires, including the EQ-5D-5L.
 - Notepads and recording equipment (with permission).
3. **Instructions:** Prepare a clear explanation and any visual aids to explain the procedure.
4. **Planning:** Ensure a realistic schedule, allowing participants sufficient time for each step of the test.

4.2 Introduction to the participant

Duration: 10 -15 minutes

- **Introducing:** Introduce yourself and the project. Explain the background and objectives of the test.
- **Voluntariness and Confidentiality:**
 - Emphasize that participation is voluntary and that participants may stop at any time.
 - Indicate that all data will be treated confidentially and used solely for research purposes.
- **Session overview:**
 - Short interview to understand the participant's background and experiences.
 - Fitting and testing the prosthesis.
 - Completing questionnaires and final interview.

4.3 User test

Duration: 30 - 45 minutes

1. **Fitting prosthesis:**
 - Provide clear explanation of how the prosthesis should be fitted.
 - Check if the participant feels comfortable.
2. **Simulate daily activities:**
 - Have the participant perform simple activities such as walking, sitting, and picking up a light object.
 - Ask questions along the way, such as:
 - How does the fit feel during movement?
 - Are there any pressure points or discomfort?
3. **Feedback collect:**
 - Ask about specific aspects, such as:
 - Experience with the weight and material.
 - Possible areas for improvement.

4.4 Observations and Feedback

- **Observations:** Record behaviors, nonverbal responses, and any adjustments the participant makes.
- **Feedback:** Collect direct feedback, supplemented with data from the questionnaires.

4.5 Completion

Duration: 5 - 10 minutes

1. Thank the participant for their time and input.
2. Ask if they have any additional comments or suggestions.
3. Provide information about how the results will be processed and what the next steps in the project are.
4. If desired, offer to keep the participant informed of future developments.

5. Measurements and Evaluation

5.1 Quantitative Measurements

The quantitative measurements are aimed at collecting objective data that provide insight into the functioning and impact of the 3D printed breast prostheses.

1. **EQ-5D-5L Questionnaire:**
 - The EQ-5D-5L is a standardized questionnaire used to measure the health status of participants. This standardized questionnaire is completed by participants after testing the prosthesis to gain insight into their comfort and well-being after wearing the custom-made breast prostheses.
 - The five dimensions of the EQ-5D-5L are:
 1. **Mobility:** Participants indicate how easily they can move around, which is an important factor for assessing the physical burden of the prosthesis.
 2. **Pain or discomfort:** The degree of pain or discomfort that participants experience in their daily lives, specifically due to the prosthesis.
 3. **Self-care:** How well participants are able to perform their personal care without assistance, which can be influenced by the comfort and functionality of the prosthesis.
 4. **Activities of daily living:** Participants indicate to what extent the prosthesis hinders them in their daily activities, such as work, household chores or social activities.
 5. **Psychological health:** The mental and emotional state of the participants, including anxiety, depression or contentment, that may be affected by the use of the prosthesis.
 - Each dimension is rated on a scale of 1 (no problems) to 5 (very serious problems).

2. **Weight measurement:**

- The weight of both the existing prosthesis and the 3D printed prosthesis is measured with a precision scale.
- This data is used to evaluate whether the weight of the new prosthesis offers a significant improvement.

3. **Fit measurements:**

- The fit is assessed by means of 3D scans and feedback from the participants.

5.2 Qualitative Measurements

In addition to quantitative measurements, collecting qualitative feedback is crucial to understand the subjective experiences of the participants.

1. **Interviews:**

- Semi-structured interviews are conducted prior to and after the test period.
- Examples of questions:
 - If you feel comfortable doing so, can you tell us a little bit about when you had breast cancer and what your experience was like?
 - Can you tell us about your experience with breast prostheses?
 - What do you currently like or dislike about the breast prosthesis you are using?
 - What aspects are most important to you (e.g. weight, fit, comfort, aesthetics)?
 - Have you experienced any specific challenges with previous prostheses? If so, what are they?
 - What would be an ideal breast prosthesis for you?

6. Processing

6.1 Data collection

All collected data is carefully and systematically documented to ensure that it is complete, reliable and traceable. The different types of data are categorized and stored in a secure location with compliance with privacy guidelines (such as GDPR). The data includes:

- **Questionnaire responses:**
 - The completed EQ-5D-5L questionnaires are digitally recorded, with each participant receiving a unique code to ensure anonymity.
 - Responses are scored and prepared for statistical analysis.
- **Session observations and feedback:**
 - Detailed notes are taken on non-verbal responses, behaviors, and spontaneous comments of participants.
 - Observations are linked to specific activities (e.g., walking, sitting, picking up an object).
- **Interview transcripts and summaries:**
 - Recorded interviews are transcribed verbatim.
 - Key quotes and themes are noted and provided with a contextual analysis (e.g., a link to age, experience, or personal preferences).
- **Measurement results:**
 - Weight measurements of the traditional and 3D printed breast prosthesis are recorded using a precision scale.
 - Fit is assessed by comparing the 3D scan models with the user feedback.

6.2 Analysis

The analysis focuses on obtaining both objective insights and in-depth interpretations of subjective experiences.

1. Quantitative Analysis

The quantitative data are analysed using statistical software, applying specific methods:

- **Analysis of EQ-5D-5L results:**
 - Each dimension of the questionnaire is assessed separately and summarized in graphs.
- **Statistical comparison of weight and fit:**
 - The average weight of traditional prostheses is compared to that of the new prototypes to determine if there is a significant reduction in weight.
 - Fit measurements are coupled with comfort and mobility scores to find correlations between objective and subjective data.

2. Qualitative Analysis

The qualitative data is analysed using a structured approach, such as thematic analysis:

- **Interview analysis:**
 - Positive comments and complaints are reported separately, with sample quotes that capture the essence of the feedback.

3. APPENDIX C: Protocol material test

Date: In semester 2: March

Location: Ursel (home) of Kortrijk (university)

1. Introduction

The development of breast prostheses through 3D printing technology offers significant advantages in terms of personalization and user-friendliness for women who have undergone a mastectomy. Compared to traditional manufacturing methods, 3D printing allows for the design of breast prostheses that not only meet medical requirements but are also tailored to the unique anatomical features and personal needs of the end-user.

The choice of materials plays a crucial role in this process, as it directly affects the functionality of the prosthesis, including weight, comfort, durability and safety.

This test protocol focuses on evaluating different materials suitable for 3D printing breast prostheses. The aim is to select materials that meet both medical requirements and user preferences. The research focuses on developing a personalized system for custom-made breast prostheses enabled by advanced 3D scanning and printing technology.

Each prosthesis will be designed based on the user's unique anatomical features, incorporating features such as relief patterns for grip and internal hole structures to reduce weight without compromising strength or durability.

The process begins with the collection of 3D scans, which users can initially perform themselves using a smartphone app. Later, these scans will be carried out by professional healthcare providers. The obtained data will be processed in software like Grasshopper, creating a digital 3D model of the prosthesis, which will then be 3D printed.

2. Goals of the tests

The primary goal of the material test is to identify the most suitable materials for 3D printing breast prostheses, with a focus on the following four aspects:

1. **Weight:** Determine the weight of prototypes made from various materials to ensure the prostheses are lightweight for daily use without compromising strength.
2. **Comfort:** Obtain subjective feedback from users about the tactile experience of the materials. This includes how the material feels against the skin and its comfort during different postures and activities.
3. **Durability:** Assess the structural properties of the materials through visual inspection, physical stress simulation, thermal testing and water absorption tests to ensure the materials are aesthetically appealing and can withstand daily use.
4. **Safety:** Evaluate safety based on the materials' Safety Data Sheets (SDS), as chemical safety testing may be too complex or impractical. The material's safety will be assessed in terms of biocompatibility and potential adverse effects on the skin or body.

The results of these tests will provide insights into which material best meets the requirements for 3D printed breast prostheses, considering both user experience and technical demands.

3. Test setup

3.1 Materials to be tested

The following materials will be evaluated for their suitability in 3D printing breast prostheses:

- **Wacker Elastosil FX serie**
- **Wacker Elastosil P serie**
- **Elkem Silbione RTV 2**

- **Elkem Amsil Silbione 24000**
- **Lynxter SIL-001**
- **COPSIL 3D 0550**

3.2 Test methods

Weight

- Measure the weight of prototypes to understand the material's influence on the prosthesis's lightness.
- **Procedure:** Place the prototype on a digital scale, record the weight in grams (accuracy ± 0.01 g) and repeat three times for each material to ensure consistency and accuracy.

b. Comfort

- Collect subjective user feedback on the material's comfort.
- **Procedure:** Users will wear the prototype in a controlled environment while performing various movements (e.g., walking, sitting, turning). They will rate the material's comfort on a scale from 1 (very uncomfortable) to 10 (very comfortable) and provide additional feedback on warmth, flexibility and skin irritation.

c. Durability

- Test the structural integrity of the material through visual inspection, physical stress simulation, thermal testing and water absorption.
 1. **Visual Inspection:** Place prototypes in environments with increased humidity, heat, or UV light for extended periods, then visually check for cracks, deformation, or damage.
 2. **Physical Stress Simulation:** Apply bending or compression to prototypes, observing material behavior under pressure.
 3. **Thermal Testing:** Expose prototypes to extreme temperatures (both high and low) and check for changes in elasticity, rigidity, or deformation.
 4. **Water Absorption:** Immerse prototypes in water for a set period, then check for swelling, deformation, or damage.

d. Safety

- Assess safety using Safety Data Sheets (SDS) and, if feasible, perform biocompatibility testing.

3.3 Required Equipment

- Prepared prototypes with standard dimensions (e.g., 10 cm diameter hemispherical shapes).
- Precision digital scale (accuracy ± 0.01 g).
- Controlled environments for heat, moisture and UV exposure, including a UV chamber and climate cabinet.
- User feedback forms with standardized scales such as EQ-5D-5L.

4. Test protocol

4.1 Weight Measurement

- **Goal:** Measure the weight of prototypes from various materials to identify the lightest options.
- **Procedure:**
 1. Place the prototype on the scale.
 2. Record the weight (accuracy ± 0.01 g).

3. Repeat for all prototypes three times for consistency.

- **Outcomes:**

- Calculate average weights and identify the lightest materials.

4.2 Comfort test

1. **Goal:** Collect user feedback on material comfort.

2. **Procedure:**

- Have the user wear the prototype in a controlled environment and perform various movements (e.g., walking, sitting, turning).
- Ask the user to rate the comfort of the material on a scale of 1 to 10, where 1 means “very uncomfortable” and 10 means “very comfortable”.
- In addition, collect open feedback on specific experiences, such as heat build-up, flexibility and skin irritation.

3. **Outcomes:**

- Document scores and feedback for each material.

4.3 Durability Test

1. **Goal:** Assess the material's structural integrity.

2. **Procedure:**

a. Visual Inspection:

- Place prototypes in a controlled environment with increased humidity, heat, or UV light for an extended period of time.
- Visually inspect for signs of cracking, deformation, or breakage after exposure.
- Materials that do not exhibit permanent deformation, cracking, or signs of aging are considered more durable.

b. Physical Stress Simulation:

- Mimic physical stress by challenging the prototypes with physical movements such as slight bending or compression, without advanced equipment.
- Observe how the material behaves under pressure or bending through visual inspection and feedback from users.
- Materials that show little or no structural changes are considered more durable.

c. Thermal Testing:

- Place the prototypes in a controlled environment with extreme temperatures (for example, in a humid or dry environment with high and low temperatures).
- Check for changes in elasticity, strength, or ductility due to temperature changes.
- Materials that do not crack, deform, or tear when exposed to heat or cold for extended periods of time show better durability.

d. Water Absorption Test:

- Immerse the prototypes in water or a humid environment for a period of time.

- Check how the material behaves after absorption and whether there is swelling, deformation or other structural damage.
- Materials that show minimal water absorption are likely to remain resistant to moisture for longer and therefore more durable.

3. Outcomes:

- Document observations and identify materials with minimal damage or wear.

4. Data analysis

The data collected from the weight, comfort and durability tests are analysed to compare the performance of each material. The results are processed in tables and graphs, which makes it possible to get an overview of the advantages and disadvantages of each material.

1. **Weight:**
Compare the average weight of the materials to determine which materials are the lightest, without compromising structural integrity.
2. **Comfort:**
Analyze the comfort scores and open feedback to identify the materials that perform best in terms of user experience and wearing comfort.
3. **Sustainability:**
Compare the results of visual inspections, simulation of physical stress, thermal tests and water absorption tests. Select materials that show less structural changes or damage.
4. **Safety:**
Analyze the biocompatibility and the safety data sheets (SDS) to identify materials that are safe for prolonged skin contact.

4. APPENDIX D: Protocol hole structure test

Date: In semester 2: March

Location: Ursel (home) of Kortrijk (University)

1. Introduction

The development of 3D printed breast prostheses offers an innovative and promising solution for women who have undergone a mastectomy. In contrast to traditional prostheses, 3D printing technology makes it possible to produce custom-made prostheses that meet the specific needs of the user, both aesthetically and functionally. One of the main challenges in this process is to optimize the balance between weight, strength and comfort of the prosthesis. This is essential to improve the user experience and minimize the physical burden during daily use.

In this research, the use of hole structures plays a central role. Hole structures are complex geometric patterns consisting of open cells, which make it possible to significantly reduce the mass of an object without compromising its mechanical performance. By means of 3D printing technology, these structures can be created with high precision, creating room for experimental optimization of the breast prostheses. The aim of this protocol is to investigate which hole structures are most suitable to minimize the weight of the prosthesis, while maintaining the required strength and durability.

Testing hole structures provides insight into how different designs contribute to the structural properties of the prosthesis. Specific parameters such as geometry, cell size and density of the structures are varied and tested for their influence on the total weight of the prosthesis. This knowledge is crucial to achieve an optimal combination of lightness and strength, thereby improving both the wearing comfort and the longevity of the prosthesis.

2. Goals of the tests

The primary goal of this test is to determine the impact of different hole structures on the weight reduction of 3D printed breast prostheses. More specifically, the research focuses on the following objectives:

1. **Weight:** To measure and compare the weight of breast prostheses with different hole structures compared to a solid prosthesis without lattice.
2. **Comparison of hole structures:** To investigate the effectiveness of different hole structures and determine the structural efficiency of these geometries with respect to weight reduction.

The goal of this test is to gain insight into the extent of weight reduction that is possible through the use of hole structures and to make a well-considered choice for the most suitable structure that maintains the desired mechanical properties and user comfort.

3. Test setup

3.1 Structures to be tested

For this test, five different hole structures will be tested on hemispheres and 3D models of the breast prosthesis.

- Lattice structure using Crystallon
- Voronoi structure using surface offsetting
- Voronoi structure on the surface of the hemisphere
- Voronoi structure on the full volume of the hemisphere
- Lattice skin on the surface of the hemisphere

3.2 Test methods

a. Weight:

The weight of the breast prostheses will be measured, both for prototypes without hole and for prototypes with the different hole structures. This will be the central aspect of this test and provides insights into the weight reduction of each structure.

1. Sample preparation:

- Print a series of breast prosthesis prototypes, each with a different hole structure.
- One prototype is printed without hole structure (solid design) to serve as a reference point for the weight measurements.
- The other prototypes are printed with the selected hole structures. The dimensions of the prostheses remain consistent between the different tests to allow for a fair comparison.

2. Weighing procedure:

- Use a digital precision scale with an accuracy of ± 0.01 g to weigh the printed breast prostheses.
- After weighing the prostheses without hole and with different hole structures, the averages of the measurements are calculated.

3. Comparison of weights:

- The weights of the prototypes without hole are compared with those of the prototypes with hole structures. This allows us to analyze which structure offers the greatest weight reduction.

4. Test protocol

4.1 Weight measurement (Prosthesis without hole structure)

1. **Goal:** To measure the weight of a solid breast prosthesis without hole structure as a control point for comparison.
2. **Procedure:**
 - Print a breast prosthesis without hole structure (solid design).
 - Place the prosthesis on the digital scale and record the weight.
3. **Outcomes:**
 - The weight of the solid prosthesis is noted and serves as a reference for comparison with the printed prostheses with hole structures.

4.2 Weight measurement (Prostheses with hole structures)

1. **Goal:** Measuring the weight of breast prostheses with different hole structures.
2. **Procedure:**
 - Print breast prostheses with the selected hole structures.
 - Measure the weight of each printed prosthesis and record the values.
3. **Outcomes:**
 - The weight of each prosthesis is recorded and will be compared to the weight of the solid prosthesis without hole structure.

4.3 Comparison of Weights

1. **Goal:** To compare the weights of the different prototypes with and without hole structures.
2. **Procedure:**
 - Compare the weights of the solid prosthesis and the prototypes with the different hole structures.

- Analyze which structure offers the greatest weight reduction and evaluate whether this is at the expense of the strength or functionality of the prosthesis.

3. Outcomes:

- The weight differences are analysed and presented in a clear table or graph.
- The best hole structure is chosen based on the weight reduction and the impact on the strength and functionality of the prosthesis.

5. Data analysis

The results of the weight measurements will be processed statistically to assess which hole structure offers the greatest weight reduction without compromising the strength of the prosthesis. The data will be presented in tables that provide a visual overview of the effectiveness of the different structures. Comparative analyses will also be performed to determine whether the weight reduction maintains the necessary mechanical properties of the prosthesis.

5. APPENDIX E: Protocol 3D scan Model Anita

Goal

Create an accurate 3D representation of the breast and chest region using a high-quality scanner setup in order to:

- Design a **custom-fit external breast prosthesis**
- Ensure compatibility with existing patient scan data for iterative design
- Maintain consistency in shape, scale and anatomical alignment

1. Model Selection & Scan Scenario Definition

Choose from:

- **Real-life model (volunteer)** with known anatomical proportions — ideal for lifelike testing

Determine the scenario to mirror your patient scan situations:

- **Pre-mastectomy:** Both breasts visible
- **Unilateral mastectomy:** One breast present (mirror imaging needed) → model has this scenario
- **Bilateral mastectomy:** Both sides flat (requires reference from standard sizes)

2. Equipment Setup

Use professional-grade scanning equipment available in a lab or production setting:

Ensure software support for **OBJ/FBX/STL** export and alignment tools.

Handscanner Artec 3D EVA

3. Positioning & Environment

Model Posture

- Stand **upright**
- Arms relaxed or slightly abducted (15–30°) to expose the lateral chest
- Neutral spine, no twisting
- Feet shoulder-width apart for stability

Environment

- Bright, **diffuse lighting** (avoid direct light or shadows on the chest)
- Neutral or **monochrome background**
- Clean surroundings to avoid mesh confusion

4. Scanning Procedure

Coverage

Capture:

- Entire torso (neck base to mid-abdomen)
- Full breast contours (incl. inframammary fold and armpits)
- Sternum and clavicle (important for alignment and scaling)
- Both sides, even if one side is flat

Scanning Motion

If using:

- **Handheld scanner:** Move around the subject slowly in smooth arcs, keep ~30–50 cm distance

Scan Duration

- 1 hour
- Multiple passes at different angles for complex anatomy
- Avoid shaky or fast movements (may distort mesh)

5. Post-Processing Workflow

Use professional mesh editing tools:

- **Blender**

Steps

1. **Clean mesh:**
 - Remove background, floor, scanner noise
 - Fill holes under the arms and underbust if needed
2. **Smooth and decimate:**
 - Slight smoothing (avoid losing anatomical detail)
 - Optional: reduce polygon count for usability
3. **Align to a common axis:**
 - Use sternal notch, nipple axis and midline
4. **Mirror intact side** (for unilateral scans)
 - Use symmetry tools in Rhino
 - Export mirrored version as a separate file

6. File Export & Naming

Export Format

- File type: OBJ, STL, or FBX
- Scale: Ensure 1:1 real-world scale (preferably metric, in mm)
- Include texture (optional, for color referencing)

File Naming Convention

Use a consistent, informative naming format:

Date_AnitaModel_name_(left, right or both)Breast.stl

6. APPENDIX F: Instructions 3D scan

Hallo,

Wat fijn dat je meedoet aan mijn masterproef!

Deze korte instructie helpt je stap voor stap om een vlotte en succesvolle 3D scan van je borstzone te maken. Jouw bijdrage is essentieel voor het ontwikkelen van nauwkeurige en comfortabele borstprothesen, die specifiek afgestemd zijn op de behoeften van patiënten. Bedankt voor je medewerking!

Als je nog vragen hebt tijdens het proces, aarzel dan niet om contact op te nemen. Veel succes!

Doel van de scan

Deze 3D scans worden gebruikt als onderdeel van een onderzoek naar de optimalisatie van 3D geprinte borstprothesen.

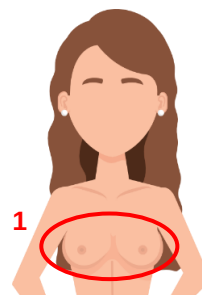
Het volledige proces omvat:

1. Het maken van een 3D scan van jouw borstzone.
2. Het verwerken van deze scan tot een digitaal model voor de prothese.
3. Het produceren van de prothese met behulp van 3D printtechnologie.

Nadien worden gebruikerstests uitgevoerd om feedback te verzamelen en het ontwerp verder te verfijnen.

Assistentie:

Het kan nuttig zijn om assistentie te vragen bij het scannen. Dit zorgt voor een stabielere en nauwkeurigere opname.



Belangrijke algemene richtlijnen

- **Houding tijdens de scan:**
 - Sta rechtop met ontspannen schouders.
 - Blijf zo stil mogelijk terwijl de scan wordt uitgevoerd.
- **Verlichting en omgeving:**
 - Zorg voor een goed verlichte of heldere ruimte zonder schaduwen op de borstzone.
 - Kies voor een egale, neutrale achtergrond om de scan duidelijker te maken.
- **Kleding:**
 - Draag een goed aansluitende beha wanneer dit wordt gevraagd.
 - Maak de borstkas volledig vrij van kleding bij scans zonder beha.
- **Camera beweging tijdens de scan:**
 - Beweeg de camera langzaam en gelijkmatig van links naar rechts en van boven naar beneden.
 - Vermijd snelle bewegingen om verstoringen in de scan te voorkomen.
- **Scanduur:**
 - Voer een scan uit met een minimale duur van 20 seconden en een maximale duur van 2 minuten.

Specifieke scenario's voor de scan

1. Je hebt nog geen mastectomie ondergaan

- **Vóór de operatie:**
 - Maak een scan van beide borsten terwijl je een beha draagt.
- **Na de operatie:**
 - Maak een scan zonder beha om het reliëf van de borstzone vast te leggen.

2. Je hebt een unilaterale mastectomie ondergaan (één borst verwijderd)

- Maak een scan van de intacte borst terwijl je een beha draagt. Deze scan wordt later gespiegeld om een symmetrische prothese te ontwerpen.
- Maak een scan van het reliëf van de borstzone zonder beha, aan de kant van de verwijderde borst.

3. Je hebt een bilaterale mastectomie ondergaan (beide borsten verwijderd)

- Maak een scan van het reliëf van de borstzone zonder beha.
- Omdat er geen preoperatieve scans of scans van de intacte borst beschikbaar zijn, wordt een keuze gemaakt uit standaardprothesematen om een passend model te creëren.

Stappenplan voor het gebruik van apps

Voor Android-gebruikers (Samsung, ...)

1. App: DECAL



- Open Google Play en zoek naar de app "**DECAL**".
- Installeer de app op je telefoon.
- Open de app en log in met je Google-account of maak een nieuw account aan.
- Klik op het scan-symbool .
- Neem een video van minimaal 30 seconden en maximaal 2 minuten. Beweeg hiervoor de camera langzaam van links naar rechts en van boven naar beneden over de borstzone.
- Geef de scan een naam, bij voorkeur met de datum en jouw naam; bvb 20250120 ElineDeRoo.
- Klik op "Upload" en wacht tot de upload is voltooid.
- Klik op het pagina-symbool  en stuur de scan(s) door via e-mail in een **OBJ** of **FBX** bestand naar eline.deroo@ugent.be.

2. App: xOne



- Open Google Play en zoek naar de app "**xOne**".
- Installeer de app en open deze.
- Klik op "**Start Scanning**" of "**Scan**".
- Selecteer "**Proceed with Object Scan**".
- Klik op het videocamera-symbool  linksonder.
- Maak een video van minimaal 20 seconden en maximaal 2 minuten, waarbij je de camera langzaam beweegt.
- Upload de scan met de optie "**Low**" en wacht tot de verwerking is voltooid.
- Ga naar de homepage, klik op het recent gescande model.
- Klik op het "**Wolkje**" en export het bestand naar een **OBJ** of **FBX** bestand
- Ga naar de homepage, klik op library, en vervolgens op downloads.
- Klik op uw scan en vervolgens op Object.
- Als laatste klik op Share symbool en stuur de scan(s) door via e-mail naar eline.deroo@ugent.be.

3. App: Polycam



- Open Google Play en zoek naar de app "**Polycam**".
- Installeer de App en open deze
- Klik op het blauwe plus-symbool
- Selecteer "**Object**" als scanmodus
- Druk op de **witte bol** onderaan in het midden van het scherm om de opname te starten.
- Beweeg de camera langzaam rond het object tot je tussen **20 en 150 foto's** hebt gemaakt (aantal verschijnt rechtsonder)
- Klik op "**Done**" zodra je voldoende foto's hebt
- Zorg ervoor dat bij de instellingen van Process, Photogrammetry en Default geselecteerd zijn
- Klik op "**Upload And Process**"
- Wacht tot het klaar is met Processing
- Klik op Download-symbool rechtsboven in het scherm
- Selecteer onder het onderdeel "**Mesh**" het bestandsformaat **GLTF**
- Tik op "**Export**"
- Verstuur het geëxporteerde bestand per e-mail naar: eline.deroo@ugent.be.

Voor IOS-gebruikers (Apple iPhone)

1. App: 3D Scanner App



- Open de Apple Store en zoek naar de app "**3D Scanner App**".
- Installeer de app op je telefoon.
- Open de app en klik op de rode knop om de scan te starten.
- Scan de borstzone langzaam van links naar rechts en van boven naar beneden.
- Druk opnieuw op de rode knop om de scan te beëindigen.
- Klik op "**HD**" en start de verwerking van de scan.
- Klik op "**Share**" en stuur de scan(s) door via e-mail in een **OBJ** of **FBX** bestand naar eline.deroo@ugent.be.

2. App: xOne



- Volg dezelfde stappen als voor Android-gebruikers.

3. App: Polycam



- Volg dezelfde stappen als voor Android-gebruikers.

Versturen van de scans

1. Zorg ervoor dat alle scans correct zijn geüpload en opgeslagen in een OBJ- of FBX-formaat.
2. Controleer of de bestandsgrootte geschikt is voor verzending via e-mail.
3. Verstuur de scans naar het opgegeven e-mailadres (eline.deroo@ugent.be).

Na het maken van de scan

- De verzonden scan wordt verwerkt tot een digitaal model dat dient als basis voor de productie van jouw borstprothese.
- Na het printen van de prothese wordt deze opgestuurd? En neem ik enkele dagen later contact op om jouw feedback te verzamelen. Jouw ervaring en feedback zijn essentieel om het ontwerp verder te verbeteren en te optimaliseren.

Dank voor jouw medewerking! Jouw bijdrage speelt een belangrijke rol in het ontwikkelen van betere borstprothesen.