TECHNOLOGY TRANSFER FROM AUTOMOTIVE TO ARCHITECTURE: INTEGRATING WAAM AND GRC WITHIN DFMA FOR COMPLEX DESIGN STRATEGIES

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Architectural and construction practices have evolved in response to shifting societal, cultural, technological, material, and economic conditions. Within the context of climate change, the introduction of Design for Manufacturing and Assembly (DfMA) strategies in the AEC (Architecture, Engineering and Construction) sector has shown its potential to support more sustainable building practices. However, the emphasis on performative aspects leads to oversimplifications of construction processes, while the application of guidelines and frameworks that prioritise modularity and prefabrication can compromise design ambition and geometric complexity.

This study aims to restore the centrality of design by integrating DfMA principles with cutting-edge technologies to expand the boundaries imposed by conventional prefabrication. In doing so, the research explores how to leverage the concept of technology transfer from the automotive industry, which is driven by highly competitive market dynamics and can embrace new technologies rapidly. The implementation of cross-functional management tools capable of aligning design objectives and functional performance, combined with Wire Arc Additive Manufacturing (WAAM) technologies, can guarantee formal freedom and address sustainability by reducing the weight of the components and emissions during production. In parallel, the study examines the use of Glass Reinforced Concrete (GRC), a material known for its versatility, strength, and capability to create complex geometries. Building on these technologies, we propose a robotic automated manufacturing process to streamline the production stages of a façade component.

INTRODUCTION

In the Architecture, Engineering, and Construction (AEC) sector, the demand for innovative solutions that balance design, sustainability, and scalability has never been more critical. This study utilises technology transfers to enhance construction processes, drawing insights from the automotive industry, where advanced technologies and design tools are closely integrated.

In particular, the automotive sector has been used as a source sector of complex frameworks and optimisation methodologies, which, through several stages –from the initial concept to final production- incorporate engineering and design into new product development.

Design for Manufacturing and Assembly (DfMA), the approach that integrates design and engineering to address customer needs while optimising cost, quality, and performance, is key to improving collaboration among departments, aiming to lower costs, accelerate innovation cycles, and boost competitiveness. The industry's lean approach minimises non-value-adding activities, cycle time, and effort, thereby improving efficiency and quality [1]. Additionally, the integration of the supply chain and long-term relationships between OEMs (Original Equipment Manufacturers) and suppliers ensure cost-effectiveness, reduced time-to-market, and improved sustainability.

This research incorporates these strategies to redefine the interaction between design and manufacturing processes in façade construction to enable the creation of lightweight components while reducing material usage and emissions related to production processes; the study integrates WAAM (Wire Arc Additive Manufacturing) because it offers formal freedom and aligns with the principles of mass customisation [2], allowing the production of bespoke components without compromising scalability. Since WAAM requires significant time for layer-by-layer deposition, the research focuses on lattice structures. This approach reduces the area of application and production time while preserving structural efficiency. The choice to analyse WAAM is twofold. On the one hand, the process provides a certain degree of design freedom because it is suitable for manufacturing large components with medium geometric complexity. On the other hand, its recent advancements in both the automotive and construction industries position it as an enabling technology that can facilitate the knowledge transfer that this research ultimately seeks to achieve. Glass fibre-reinforced concrete (GRC) enhances this technology with its versatility and capacity to achieve complex geometries.

INTRODUCTION TO WIRE ARC ADDITIVE MANUFACTURING (WAAM)

WAAM (Wire Arc Additive Manufacturing) is an advanced manufacturing technology that utilises arc welding tools and wire materials to produce metal components [3]. It falls under the category of Directed Energy Deposition (DED), one of the Additive Manufacturing technologies identified by ISO/ASTM 52900:2021 [4]. The WAAM process is widely used in aerospace, automotive, shipbuilding and mechanical sectors because it can produce large and complex parts with high structural integrity and low material wastage [5]. A new multidirectional WAAM process has been developed to enable the creation of complex geometrical features without the need for additional support structures, thus reducing manufacturing time and cost [6].

In the AEC sector, WAAM attracts researchers because it shows promise to produce customised components with reduced lead times. The HPWAAM project [7], led by a UK consortium, has achieved promising advancements in this technology. The project was funded by Innovate UK (the United Kingdom's national innovation agency) [8] and involved Cranfield University and industrial partners such as Foster + Partners and Weir Group [9]. Qualitative data extracted from structured interviews with researchers and professionals in the field highlight that the current research focuses on hybrid methods that combine traditional structural steel production techniques with WAAM to create complex elements that exceed conventional manufacturing capabilities. In this context, traditional manufacturing can be used to post-process WAAM components; for instance, CNC machining can refine specific areas of a beam that require precision geometry or surface finish, such as the ends, holes, grooves, or threaded sections, thereby achieving high levels of accuracy and surface quality[10].

Additionally, conventional methods can be used to construct most of a structure, while WAAM is utilised to enhance it, allowing for optimised structural components. The application of WAAM to pre-manufactured components for addressing complex nodes demonstrates its potential to exploit structural optimisation, enhancing structural performance and efficiency. This approach leads to material savings, weight reductions, decreased environmental impact, increased automation, and lower costs [11].

The research started with identifying specific clusters of approaches in the AEC sector to this technology by examining case studies and reviewing papers (Table 1). One cluster focuses on large-scale component fabrication, using WAAM to produce entire structural elements. An example is the MX3D Bridge in Amsterdam, a 3D-printed steel structure which integrates topological optimisation to reduce material usage while enhancing performance [12]. Another approach emphasises the production of complex interfaces and connectors, where WAAM creates bespoke solutions for joining standardised components. This application is particularly valuable in modular and hybrid construction, as it accommodates complex geometries and irregular angles that traditional methods struggle to address [13]. The prototype for the Wire-Arc Facade (2021), developed by Roland Snooks and the RMIT Architecture | Tectonic Formation Lab, investigated a hybrid approach in which metal was directly deposited onto prefabricated steel plates. This method exploits the strengths of WAAM to create intricate geometric components of the facade, while flat elements are produced from folded sheet metal. Additionally, this approach differs from standard procedures because it uses folded metal sheets instead of disposable base plates as a support of the WAAM components [14].

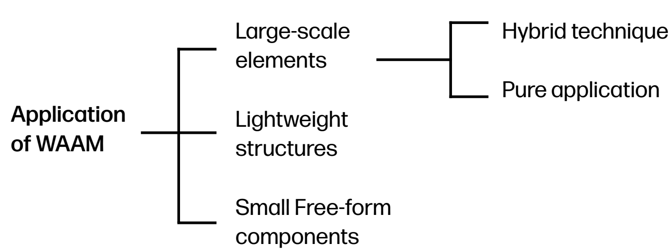

Table 1. Application of WAAM in the AEC sector. Elaboration by the author.

The authors of this research decided to explore aspects of large-scale fabrication, focusing on the application of WAAM where necessary to reduce both cost and production time. Among the different technologies, the "dot-by-dot" printing method has been identified as the most suitable for these types of applications. It requires great attention due to geometrical irregularities [15] but can be used to create lightweight structures, optimising material use and ensuring performance. The manufacturing of lattice structures via WAAM has been facilitated by recent advancements in deposition strategies. Researchers have effectively created pyramidal lattice structures, demonstrating the capability of this method to produce complex geometries [16]. However, the processes of rapid cooling and solidification are relevant factors to consider because they can lead to inconsistencies in the microstructure, resulting in variations in mechanical properties throughout the lattice structure [17]. The microstructural features of WAAM-produced layers can lead to non-uniform mechanical properties, which need to be evaluated in the early stages of the design to guarantee uniform structural performance in load-bearing applications [17,18]. Understanding these effects is important for optimising the performance of WAAM-manufactured components. Ongoing research focuses on refining process parameters and exploring innovative materials to improve WAAM's ability to produce high-performance lattice structures [19]. This demonstrates that the technology requires iterative testing and implementation to reach the intended outcomes.

The data collected so far seems encouraging and may indicate a good potential for the adaptation of these advancements in the construction sector. In addition to the exploration of advanced fabrication techniques, this research also considers materials that complement and enhance the capabilities of WAAM. One such material is GRC, which has some advantages over the other materials in the construction industry.

GLASS FIBRE-REINFORCED CONCRETE (GRC) IN THE AEC SECTOR

Glass fibre-reinforced concrete (GRC) is a construction material that combines glass fibres with a cementitious matrix, offering enhanced strength, durability, and aesthetic versatility. As a subset of fibre-reinforced concrete materials, GRC was a significant innovation in the realm of modern construction [20]. It is increasingly used in construction for structural and non-structural applications, such as facade panels and cladding in general [21]. Thanks to its adaptability and aesthetic appeal, many leading architectural firms use it for applications ranging from simple to complex geometries [22]. Due to its features, the Elizabeth Line project in London (Figure 1) utilised GRC to create a unified and durable cladding system for its central stations, demonstrating the versatility of GRC in large-scale project applications.

Developed by Bryden Wood and GRCUK, the system spanned 32,000 m^2 and included 27,000 panels, designed to fit the complex geometries of curved tunnels and intersections. The structure was made from laser-cut, folded, and welded stainless steel sheets. Advanced digital tools have been used to ensure accuracy and compatibility with the GRC panels. This project demonstrates how to balance aesthetics and efficiency with the implementation of innovative engineering methods aimed to minimise material use, weight, and the variety of unique moulds. The integration of advanced tools and methodologies such as 5-axis CNC machining and complex management workflows ensured high precision and streamlined fabrication and on-site assembly. The paneling was thoroughly studied to enable faster installation with minimal human intervention, while digital twins and 3D scanning ensured precision within tight tolerances [23].

Achieving this level of efficient design and construction with GRC requires a process of optimisation and standardisation. This involves optimising the base geometry and minimising custom panels to streamline fabrication and reduce costs. The substructure that connects the GRC panels to the building's structural framework can be highly intricate, and that's why one advanced method in GRC applications is the "stud-frame construction", where a prefabricated metal frame, typically made of galvanised steel, is embedded into the panel itself. Within this context, BB Fiberbeton [25], a leading manufacturer specialising in GRC solutions, developed a hybrid system that integrates the steel frame into the cement mix of the GRC. This approach reduces the weight of the substructures, facilitates the installation with minimal mounting points and provides high adaptability for small, medium, and large panels [26]. However, the stud-frame approach, like any other method based on the standardisation of moulds and substructures, has several limitations in addressing the geometric complexity of bespoke designs.

This issue can be overcome with the implementation of Additive Manufacturing techniques, which allow non-uniform material placement and topological optimisation for each panel. The use of standardised steel frames limits the possibility of changing the density of the structural materials precisely where needed, leading to excess weight and decreased flexibility for complex geometries.

To address these challenges, the research explores an automated manufacturing process in which WAAM is used to develop customised sub-structures for GRC panels. While exploring the boundaries of customisation, it is important to consider the application of standards to maintain quality and consistency in manufacturing. The European Standard EN 1169 identifies requirements for prefabricated concrete products, particularly GRC, and outlines key aspects for providing quality, safety, and performance [27]. The Glass Fibre Reinforced Concrete Association (GRCA), the global hub for professionals involved in the design, manufacturing, and application of GRC, is a fundamental source of data [28]. The organisation was founded early 50 years ago in October 1975 to improve GRC quality and comprehension, offering resources and services to architects, engineers, manufacturers, and contractors. The manuals provided by GRCA outline multiple GRC manufacturing techniques that match various application requirements, design specifications, and manufacturing goals.

Among the various techniques, sprayed GRC is the most commonly used and versatile production approach in the construction sector, particularly in complex construction. This technique is preferred because it produces high-performance lightweight GRC components with aesthetic appeal. A further development of this method is the Auto Spray, which improves manual hand-spray techniques by adding automated systems that enhance manufacturing speed and material consistency. The process delivers excellent results when manufacturers need to produce large quantities of flat or moderately complex GRC components such as facade panels. The introduction of automatically sprayed Ultra-High Performance GRC (HPGRC) builds upon this innovation by using advanced materials together with CNC spray technology to achieve exceptional precision and efficiency [29]. The CNC GRC spray station uses a Cartesian-coordinate robotic system with a 5-axis servo drive, allowing accurate spraying on intricate mould geometries. Automated production lines streamline the process by integrating mixing, spraying, curing, and finishing, all controlled through a PLC-based system. These lines are designed for large-scale output, offering enhanced consistency and scalability for modern architectural applications [22].

RESEARCH METHODOLOGY AND FRAMEWORK DEFINITION

Following the principles of the Design Science Research (DSR) methodology, a problem-solving framework that creates innovative artefacts while enhancing theoretical knowledge, this research proceeds through iterative problem identification, artefact creation, evaluation, and refinement cycles [30]. To develop a new perspective on DfMA, the study explores the design and construction of complex architectural geometries, particularly façade components, by balancing cutting-edge technologies with well-established techniques. This balance defines the scope of the research while ensuring that the study remains forward-thinking and practical, aligning the design process more closely with the requirements and constraints of the industry. Aiming for the technological transfer from the automotive to the AEC sector, the SHAPE process, a structured framework designed to execute automotive projects (Figure 2) and developed by Pininfarina, is utilised in this research to enhance the feasibility and efficiency of the design process for the proposed prototype. This approach, found in manufacturing processes, applies a consistent planning procedure [31].

The stages are the following:

- S0: Product Exploration -> Is the idea worthwhile to be explored further in-depth?
- S1: Concept Evaluation -> The ideas have been explored enough to start their detailed development.
- S2: Concept Definition and Evaluation -> Progress against specific delivery targets
- S3: Development -> Progress against specific delivery targets
- S4: Tooling and Process Validation -> Progress against specific delivery targets
- S5: Pre-Series -> Progress against specific delivery targets
- S6: Ramp-Up -> Retrospective on project successes and failures to improve the next project.

In addition, each project will contain checkpoints, such as milestones, design reviews, etc., which will be determined during the concept definition stage.

DfMA strategies aim to optimise the design process to enhance manufacturing efficiency and streamline assembly. The integration of SHAPE in the research allows production-oriented strategic decisions to be made early in the design stage.

In particular, the following DfMA principles are central to this research:

- **Integration with standardisation of Components:**
  Standardisation will affect the interfaces of envelopes, addressing complexity where needed and guaranteeing compatibility with existing façade technologies.
- **Minimisation of Parts:**
  Building upon systematic complexity, the integration of different functional systems reduces the number of components required to support panelling.
- **Ease of Assembly:**
  Assembly guides, as in the automotive sector, support construction teams for an easy to assembly
- **Material Efficiency:**
  The combination of Additive Manufacturing and topological optimisation focuses on material placement only where needed, reducing material waste. As said, standardisation can sometimes increase inefficiency; integrating subsystems enhances material distribution and efficiency.
- **Design for Recycling:**
  Facade components are designed to allow for disassembly and reuse following the principles of Design for Disassembly (DfD). Further integration of circularity can enhance these components toward a more circular life cycle.
- **Collaboration with Manufacturers:**
  The involvement of manufacturers from the early stages of the design ensures that the research brings novelty both on the academic and the

Figure 1: Aesthetic and functional testing of full-scale prototype elements. Image Courtesy of Bryden Wood UK.

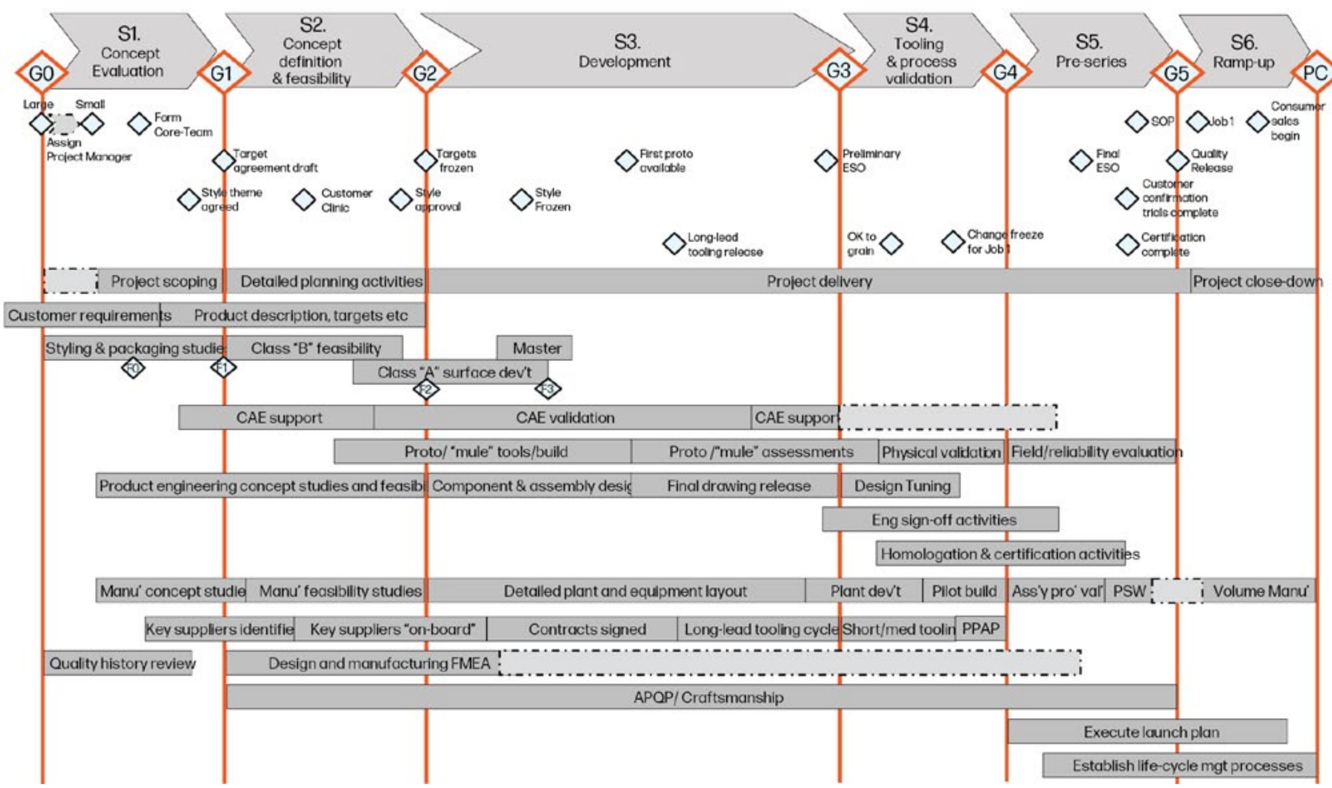

Figure 2: Extract of Shape overview document provided by Pininfarina Spa.

practical side. The study aims to establish a strong network of strategic stakeholders in the development of the process and align design choices with production capabilities.

- **Integration of Mass Customization principles:**
  Additive Manufacturing combined with Automation and Robotic Manufacturing can enable the production of non-standard geometries while maintaining efficiency.
- **Alignment with Sustainability Goals:**
  The integration of substructure and panels minimises material waste and transportation impacts, assessing the embodied carbon of building components. Moreover, as part of a broader DfMA strategy, the components are studied to incorporate Design for Logistics (DfL) principles. In the early design process, logistical constraints- such as component size, weight, and stacking logic- are considered to streamline on-site operations.
- **Reduction of Lead Times:**
  As mentioned, the integration with conventional façade interfaces streamlines the production process, ensuring shorter project timelines.

Recyclability of WAAM metal components, the environmentally responsible production of GRC and other sustainability aspects will be addressed through the “Material Balance” approach. In particular, the investigation into circularity and the use of biobased materials can represent an alternative to cement. However, this direction requires a careful evaluation of structural performance and mechanical properties of the replacement material. The next steps of the research will incorporate these considerations. Moreover, the implementation of these strategies requires manufacturers to participate in design process stages from the beginning. Their expertise can contribute to the development of feasible solutions and, given the industrial orientation of the research, to establish a collaborative network.

Within this context, SHAPE, with its manufacturing-oriented steps, can be used to frame the development of complex components or systems of components. The application of this tool requires appropriate simplification and adaptation. The automotive industry operates at high volumes of production where production lines are optimised to create thousands of identical elements with extremely tight tolerances. In the AEC sector, maintaining the same level of complexity would be impractical since construction projects are generally bespoke. The following six stages simplify the original framework and provide the structure of the research project from conceptualisation to full-scale implementation.

Stage 1: Concept Evaluation

The initial phase focuses on identifying the project’s goals. This stage involves brainstorming sessions between industry and academia aimed at assessing the technical and material feasibility of the research. Architectural and functional requirements are defined, although dimensions are not specified to emphasise the manufacturing process and the materials selection. To support this process, initial 3D models and prototypes of lattice structures in other materials such as ABS and PLA are created using conventional 3D printing. In the exploration of lattice geometries, the authors follow the line of investigation built upon prior research conducted at MaBa.SAPERLab, where studies on similar systems and their architectural potential have been ongoing for several years.

Stage 2: Concept Definition & Feasibility

Building on the initial studies, this phase aims to develop a detailed concept and assess its feasibility through a series of technical simulations, which include structural analysis using parametric tools in the Rhinoceros environment. Considering the context of application in facade systems, both thermal and environmental studies determine the performance of the components. Additionally, the integration of WAAM and GRC is defined, focusing on how these technologies interact regarding material behaviours. At this stage, the collaboration with GRC manufacturers will provide insights into the specific mix to be adopted. In parallel, the first tests on lattice structure made with WAAM will be carried out. The outcomes of this phase also include an initial risk analysis that identifies potential challenges and mitigation strategies.

Stage 3: Development

As the project progresses, the research will optimise the designs for manufacturability and scalability. Based on a digital workflow methodology, tests are conducted to validate the performance of the component. An accurate mock-up is created to assess real-world viability and implement the manufacturing workflow and assembly strategies. During this phase, the research addresses sustainability, optimising material usage, and evaluating the feasibility of recycling. The extraction of the metal embedded within the cement-based composite presents significant technical challenges. To address these issues, on the one hand, the research will rely on Design for Disassembly (DfD) principles, taking inspiration from the automotive industry, where the disassembly of components has been integrated into design strategies to enable maintenance, recycling, and efficient material separation. On the other hand, the study will explore the substitution of the traditional cementitious matrix with a bio-based alternative. In doing so, the research aims to advance the field of circularity.

Stage 4: Tooling & Process Validation

After the design optimisation has been achieved, the manufacturing processes and tools need to be validated. This phase involves studies on the application of WAAM deposition and GRC casting workflows within a production line and the integration of robotic systems to support automation and enable a mass customised fabrication process.

Transition toward industrial scalability

Stages 5 and 6 aim at the transition from research to industrial scalability with the goal of testing the feasibility of bringing the prototype into industrial production. Aligned with DfMA strategies, the study is intended to go beyond the experimental phase of digital fabrication and develop a scalable, production-ready system that can be integrated into existing industrial processes and supply chains.

Stage 5: Pre-Series

This stage includes the robotic fabrication of the façade component to complete the validation of the automated workflow and refine both design and production strategies. The final façade mock-up is created and assembled for review, field tests and further refinements. Additionally, this stage produces updated design, manufacturing documentation and installation manuals that offer step-by-step guidance for future implementations.

Stage 6: Ramp-Up

The project's final phase focuses on scaling production to ensure a seamless transition to full-scale deployment. The entire workflow, tools and processes are tested under real production conditions. In line with SHAPE, this stage includes clients' and manufacturers' feedback to evaluate performance and user experience. This feedback loop aims to verify that the final product meets expectations. Ideally, production-ready components are fully realised and implemented by project documentation.

FAÇADE COMPONENT: CONCEPT PRODUCTION PROCESS

Building envelopes require a unique combination of manufacturing, design, construction, and maintenance to perform as expected [32]. Façade design, in particular, represents a complex multi-disciplinary process involving various stakeholders.

This complexity led us to apply a product-oriented framework to streamline the manufacturing process of the prototype, treating it as an independent system within the building structure.

In particular, the production process for the façade component combines advanced technologies such as robotic milling, GRC spraying, and WAAM to deliver a precisely engineered, structurally strong component that corresponds to the design intent. The proposed lattice structure, which is currently in a tentative phase, will be further developed in the upcoming stages of the research to optimise the strength-to-weight ratio and reduce structural loads. The procedure unifies the construction of the entire system within a single, centralised facility (Figure 3).

The following theoretical stages require thorough validation through prototyping, testing, and real-world application to confirm their feasibility and effectiveness. At this stage, specific dimensions are not yet defined, as the initial focus is prioritising the process itself.

Step 1: Milling the Mold

The initial stage implies the creation of a precise mould supporting the following manufacturing processes. Recent research focused on avoiding the use of moulds to reduce costs. In this case, the decision to adopt a mould-based strategy is motivated by the fact that the study is still in the prototyping phase, and the transition to fully industrialised production remains a long-term objective.

Taking inspiration from the automotive sector, where polyurethane moulds are widely adopted, using a robotic arm equipped with a milling tool, the mould is carved according to the panel design (refer to Figure 4). The mould is then treated with a release agent to facilitate the removal of the panel at the end of the next stages.

Step 2: Initial GRC Spray Layer

The first layer of GRC is applied using a robotic arm equipped with a spray nozzle (Figure 5). This uniform layer adheres to the mould and is the base for embedding the metal mesh. Lateral containment depends on the viscosity of the GRC and requires that the mould geometry is specifically crafted to optimise material deposition.

Step 3: Placement of the Metal Mesh

A prefabricated metal mesh (galvanized steel) is placed onto the first layer of sprayed GRC using a robotic arm (Figure 6). The selection of the type of mesh considers factors such as porosity for material penetration, stiffness to resist deformation, and flexibility to accommodate complex

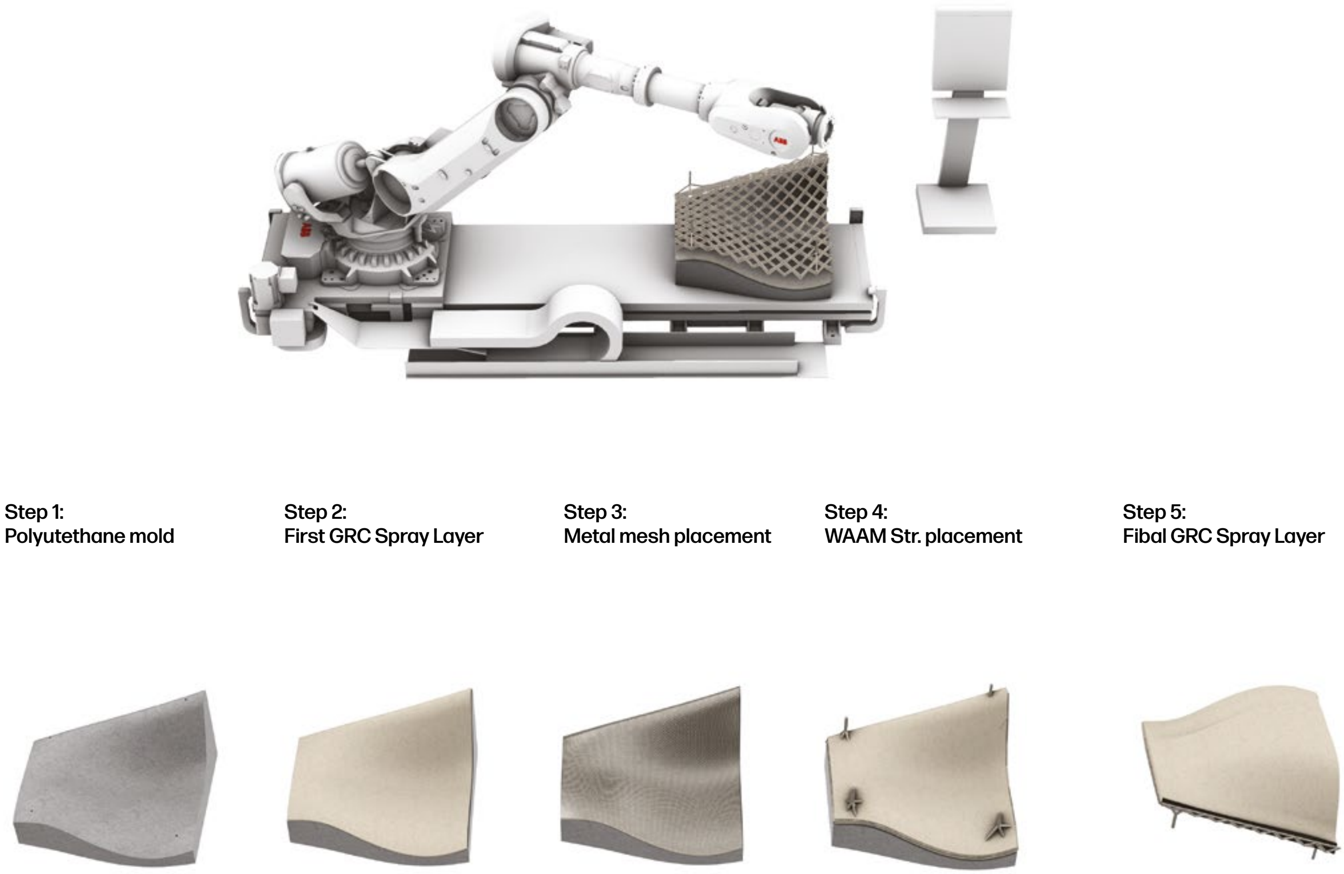

Figure 3: Automated production line. Elaboration by the author.

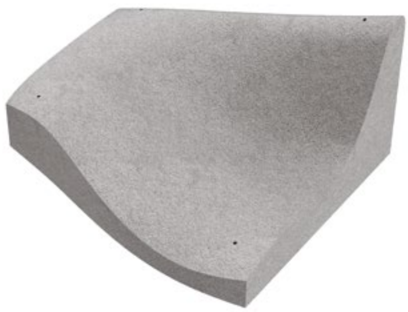

Figure 4: Polyurethane mould. Elaboration by the author.

Figure 5: First GRC Spray Layer. Elaboration by the author.

Figure 6: Metal mesh placement. Elaboration by the author.

Figure 7: WAAM Str. Placement. Elaboration by the author.

Figure 8: Final GRC Layer. Elaboration by the author.

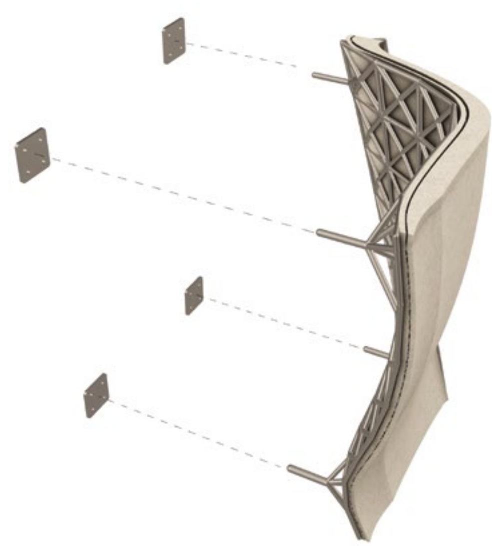

Figure 9: Connection to standard façade interfaces. Elaboration by the author.

geometries. On the one hand, the mesh enhances the tensile strength of the panel; on the other hand, it serves as a stable base for the WAAM lattice structure. The use of a robotic arm within this process aligns with a highly automated workflow where human intervention is minimised, and automation maximised.

Step 4: 3D Printing the Lattice Structure

In this step, a WAAM-enabled robotic arm fabricates the lattice structure onto the metal mesh (Figure 7) using the dot-by-dot technique. The lattice is designed to incorporate connectors for standardised metal plates. From a geometric perspective, the type and configuration of the lattice will be defined using parametric tools, controlling the topology in response to structural loads and performance requirements.

Step 5: Rotating the Components and Applying the Final GRC Layer

A second layer of GRC is sprayed over the lattice to encapsulate the structure, partially embedding it while exposing supports for on-site connection (Figure 8). This stage provides a protective inner finish and prepares the panel for efficient assembly.

Step 6: Connecting to Standard Façade Interfaces

After a specific curing period, depending on the method used, the finished panel, with exposed support points, is transported to the construction site and aligned with the building's façade system (Figure 9). The support points are welded to pre-installed standardised metal plates, following the concept of easy assembly in DfMA strategies.

CONCLUSION AND NEXT DEVELOPMENTS

The research outlined above introduces a methodological shift in how architectural complexity can be approached within a DfMA logic and an industrialised framework. Rather than reducing architecture to repetition and modularity, the study demonstrates how complexity can be structured, scaled, and reproduced by integrating manufacturing processes and cutting-edge technologies. The objective of this study is to go beyond the concept of DfMA based on standardisation to a more advanced understanding of systematic complexity and create a scalable system that balances uniqueness with replicability.

Traditional industrial logic aims to achieve economies of scale by creating identical standardised components that lower production costs per unit with quantity increases [33]. However, this model has created challenges for architectural practice because uniqueness and contextual factors often conflict with mass production. Additive manufacturing introduced a radical change due to its ability to produce geometrically complex, customised components at costs that did not rise with fabrication complexity. The main barrier to scalability exists because the process depends on manual assembly and requires extensive labour to synchronize different stages. The research proposes combining Additive Manufacturing with Robotic Fabrication to develop an automated workflow that unites component production and assembly functionality. This methodology creates conditions for mass customisation transitions through process and form intelligence integration.

The proposed production process draws qualitative data from literature reviews, case studies, and expert insights. However, this conceptual foundation requires quantitative data to optimise the process and ensure its real-world applications. A thorough knowledge of the material properties, together with mechanical properties and procedural characteristics of the hybrid system, is essential for this project.

The project will gather data during the prototyping phase by analysing digital simulations and physical tests focused on WAAM and GRC interactions. The analysis of mechanical behaviour between these materials at their interface is a crucial requirement. The cement-based matrix of GRC contains fine aggregates as its primary composition, yet its interaction with WAAM metal lattice structures needs to be investigated concerning the matrix-substructure connection. WAAM generates surfaces through its dot-by-dot and layer-by-layer deposition, which creates irregularities that produce micro-ridges along with textural roughness. This characteristic suggests potential benefits instead of becoming a weakness. Moreover, WAAM surface irregularities share similar features with traditional steel bars in concrete, which could enhance mechanical bonding with the matrix material. The analysis of WAAM lattice and sprayed GRC composite behaviour is needed to investigate their bond strength and shear transfer properties. The validation of this hypothesis requires exact measurements of the adhesion strength and crack propagation patterns at the point where the GRC matrix meets fibres and WAAM structures. Geometric and dimensional parameters will require an iterative process of adjustments. The performance of the system depends on three main factors: the GRC layer thickness, WAAM lattice geometry and spacing, and the entire component's dimensions.

At this point, the potential partnership between Pininfarina and a GRC manufacturer can ensure that the production process follows industrial requirements. In parallel, the research benefits from the Material Balance approach, which has long been involved in experimental research that merges physical prototyping with digital modelling, incorporating material behaviour as an active parameter in the design process. The WAAM prototyping phase will encompass mechanical metrics—including tensile, compressive, and flexural behaviours—and production variables like deposition speed, material consumption, thermal distortions, and energy use. Furthermore, we will evaluate environmental performance metrics, such as the thermal and acoustic insulation values of the composite panel, especially regarding its application as a building envelope system. In addition, issues related to circularity will be addressed, including the potential for disassembly, reuse, and recycling of materials at the end of the component's lifecycle. In conclusion, the approach will consist of working simultaneously on the material and computational sides of architecture, enabling a deeper integration between form, performance, and fabrication.

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REFERENCES

[1] P. Tuli and R. Shankar, "Collaborative and lean new product development approach: a case study in the automotive product design," *Int J Prod Res*, vol. 53, no. 8, pp. 2457–2471, Apr. 2015, doi: 10.1080/00207543.2014.974849.

[2] R. Naboni and I. Paoletti, "SPRINGER BRIEFS IN APPLIED SCIENCES AND TECHNOLOGY POLIMI SPRINGER BRIEFS Advanced Customization in Architectural Design and Construction." [Online]. Available: http://www.polimi.it

[3] C. Xia *et al.*, "A review on wire arc additive manufacturing: Monitoring, control and a framework of automated system," *J Manuf Syst*, vol. 57, pp. 31–45, Oct. 2020, doi: 10.1016/J.JMSY.2020.08.008.

[4] A. Shah, R. Aliyev, H. Zeidler, and S. Krinke, "A Review of the Recent Developments and Challenges in Wire Arc Additive Manufacturing (WAAM) Process," *Journal of Manufacturing and Materials Processing 2023, Vol. 7, Page 97*, vol. 7, no. 3, p. 97, May 2023, doi: 10.3390/JMMP7030097.

[5] M. Chaturvedi, E. Scutelnicu, C. C. Rusu, L. R. Mistodie, D. Mihailescu, and S. Arungalai Vendan, "Wire Arc Additive Manufacturing: Review on Recent Findings and Challenges in Industrial Applications and Materials Characterization," *Metals 2021, Vol. 11, Page 939*, vol. 11, no. 6, p. 939, Jun. 2021, doi: 10.3390/MET11060939.

[6] L. Yuan *et al.*, "Fabrication of metallic parts with overhanging structures using the robotic wire arc additive manufacturing," *J Manuf Process*, vol. 63, pp. 24–34, Mar. 2021, doi: 10.1016/J.JMAPRO.2020.03.018.

[7] "HPWAAM." Accessed: Jan. 06, 2025. [Online]. Available: https://www.waam3d.com/project/hpwaam

[8] "Innovate UK - GOV.UK." Accessed: Jan. 05, 2025. [Online]. Available: https://www.gov.uk/government/organisations/innovate-uk

[9] J. Burry *et al.*, "FABRICATE 2020 MAKING RESILIENT ARCHITECTURE."

[10] E. M. Sefene, Y. M. Hailu, and A. A. Tsegaw, "Metal hybrid additive manufacturing: state-of-the-art," Aug. 01, 2022, *Springer Science and Business Media Deutschland GmbH*. doi: 10.1007/s40964-022-00262-1.

[11] X. Meng and L. Gardner, "Hybrid construction featuring wire arc additive manufacturing: review, concepts, challenges and opportunities," Mar. 01, 2025, *Elsevier Ltd*. doi: 10.1016/j.engstruct.2024.119337.

[12] "MX3D | Architecture & Construction." Accessed: Sep. 14, 2024. [Online]. Available: https://mx3d.com/industries/architecture-construction/

[13] A. Ridings *et al.*, "A Literature Review of WAAM and Future Application in Buildings," pp. 54–61, 2023, doi: 10.35483/ACSA.AM.111.8.

[14] R. Snooks, "Behavioral tectonics: agentBody prototypes and the compression of tectonics," *Architectural Intelligence 2022 1:1*, vol. 1, no. 1, pp. 1–14, Aug. 2022, doi: 10.1007/S44223-022-00007-8.

[15] L. Arrè, V. Laghi, M. Palermo, G. Gasparini, and T. Trombetti, "Wire-and-Arc Additive Manufacturing for lattice steel structures: overview of the experimental characterization on dot-by-dot rods," *ce/papers*, vol. 6, no. 3–4, pp. 757–762, Sep. 2023, doi: 10.1002/CEPA.2622.

[16] C. Zhang, M. Gao, and X. Zeng, "Workpiece vibration augmented wire arc additive manufacturing of high strength aluminum alloy," *J Mater Process Technol*, vol. 271, pp. 85–92, Sep. 2019, doi: 10.1016/J.JMATPROTEC.2019.03.028.

[17] A. V. Nemani, M. Ghaffari, and A. Nasiri, “On the Post-Printing Heat Treatment of a Wire Arc Additively Manufactured ER70S Part,” *Materials 2020, Vol. 13, Page 2795*, vol. 13, no. 12, p. 2795, Jun. 2020, doi: 10.3390/MA13122795.

[18] M. Hietala, T. Rautio, M. Jaskari, M. Keskitalo, and A. Järvenpää, “Fatigue Resistance Assessment of WAAM Carbon Steel,” *Key Eng Mater*, vol. 975, pp. 147–153, Feb. 2024, doi: 10.4028/P-C3FGTR.

[19] M. Rauch, G. Pechet, J. Y. Hascoet, and G. Ruckert, “Extending High Value Components Performances with Additive Manufacturing: Application to Naval Applications,” *Solid State Phenomena*, vol. 319, pp. 58–62, 2021, doi: 10.4028/WWW.SCIENTIFIC.NET/SSP.319.58.

[20] F. Micelli, A. Renni, A. G. Kandalaft, and S. Moro, “Fiber-reinforced concrete and ultrahigh-performance fiber-reinforced concrete materials,” in *New Materials in Civil Engineering*, Elsevier, 2020, pp. 273–314. doi: 10.1016/B978-0-12-818961-0.00007-7.

[21] J. G. Ferreira and F. A. Branco, “Structural application of GRC in telecommunication towers,” *Constr Build Mater*, vol. 21, no. 1, pp. 19–28, Jan. 2007, doi: 10.1016/J.CONBUILDMAT.2005.08.003.

[22] L. Zimmermann, P. M. Seiler, and C. Mai, “Glassfibre Reinforced Concrete: a Review,” *IOP Conf Ser Mater Sci Eng*, vol. 246, no. 1, p. 012002, Sep. 2017, doi: 10.1088/1757-899X/246/1/012002.

[23] M. Butcher, T. Nunn, and M. Huber, “GRC Cladding System for the Elizabeth Line Station Tunnels GRC Cladding System for the Elizabeth Line Station Tunnels Public Mass Transit Infrastructure Case Study.”

[24] M. Butcher, T. Nunn, and M. Huber, “GRC Cladding System for the Elizabeth Line Station Tunnels GRC Cladding System for the Elizabeth Line Station Tunnels Public Mass Transit Infrastructure Case Study.”

[25] “BB fiberbeton - GRC manufacturer - Your vision - Our Solutions.” Accessed: Jan. 07, 2025. [Online]. Available: https://www.bbfiberbeton.dk/en

[26] *Specification for the manufacture, curing and testing of GRC products*. International Glassfibre Reinforced Cement Association, 2000.

[27] “Precast concrete products : general rules for factory production control of glass-fibre reinforced cement,” p. 7, 1999, Accessed: Jan. 01, 2025. [Online]. Available: https://www.en-standard.eu/bs-en-1169-1999-precast-concrete-products-general-rules-for-factory-production-control-of-glass-fibre-reinforced-cement/

[28] “Welcome to GRCA | International Glassfibre Reinforced Concrete Association.” Accessed: Jan. 01, 2025. [Online]. Available: https://www.grca.online/

[29] Y. Che and X. Lei Beijing Leinuo Light Cladding Co, “Automatically Sprayed Ultra-High Performance Glass Fiber Reinforced Concrete.”

[30] G. L. Geerts, “A design science research methodology and its application to accounting information systems research,” *International Journal of Accounting Information Systems*, vol. 12, no. 2, pp. 142–151, Jun. 2011, doi: 10.1016/J.ACCINF.2011.02.004.

[31] M. Kagioglou, R. Cooper, G. Aouad, and M. Sexton, “Rethinking construction: the Generic Design and Construction Process Protocol,” *Engineering Construction and Architectural Management*, vol. 7, no. 2, pp. 141–153, Jun. 2000, doi: 10.1046/J.1365-232X.2000.00148.X.

[32] M. K. Parfitt, “Architectural Engineering Approach to Building Façade Design, Construction, and Evaluation,” *Journal of Architectural Engineering*, vol. 13, no. 3, pp. 127–128, Sep. 2007, doi: 10.1061/(ASCE)1076-0431(2007)13:3(127).

[33] Mollie. Claypool, Manuel. Jimenez Garcia, Gilles. Retsin, and Vicente. Soler, “Architecture in the age of automation,” p. 128, 2019, Accessed: Apr. 05, 2025. [Online]. Available: https://www.archidiaries.com/publications/robotic-building-architecture-in-the-age-of-automation/