Customized Mass Production in Modular Design Approach for Lightweight Structures Using Bent Metal Pipes.

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This research paper explores the potential and practical applications of automation in the field of robotic construction, with a focus on metal pipe bending. The study investigates the use of automated robots as supplementary team members in construction projects, aiming to achieve NetZero construction by reducing on-site manufacturing and emphasizing on-site assembly for improved efficiency and safety. The integration of 3D printing technology into key structural components is also examined to address complex construction challenges.

In the modern era, the development of automated and robotic construction systems is essential for achieving competitive, market-driven, and rational building practices. These systems encompass various stages of the construction process, including the manufacturing of building materials, prefabrication of construction components, on-site construction, facility management, rehabilitation, and recycling. By leveraging automation and robotics, construction projects can achieve accelerated design and construction phases, high-quality standards, and cost-effectiveness.

Flexible automation, supported by computer-assisted planning, engineering, and construction management techniques, offers solutions to overcome challenges in the construction industry. The implementation of automated and robotic construction technology can effectively address the increasing demand for building projects, especially in regions with high labor costs. Automation has the potential to reduce the labor cost share by 40% or more, leading to increased productivity and year-round operation. Moreover, the adoption of robotic technology in construction enhances working conditions, promotes better health and safety standards, and requires advanced mechatronics knowledge and skills.

By optimizing construction processes through automation, shorter construction periods can be achieved, resulting in faster real estate availability and improved returns on investment. The integration of automation and robotics in construction is crucial for the rationalization of the industry and holds great potential for enhancing productivity, cost-efficiency, and overall project outcomes.

Keywords
automation, robotic construction, metal pipe bending, 3D printing, NetZero construction, efficiency, safety, productivity, cost-effectiveness.

1. Introduction

The concept of off-site construction, deeply rooted in architectural history, has emerged as a transformative solution to housing and non-domestic construction challenges. From the innovative practices of ancient Rome, where pre-fabricated components were meticulously crafted off-site (Redshift, 2021), to the industrial revolution's impact on construction techniques, this approach has continuously evolved. However, it was during the tumultuous period of World War II that off-site construction methods, (Ovando Vacarezza, 2014) particularly modular construction, experienced a momentous breakthrough. The pressing need for expedited housing construction in the aftermath of the war prompted the widespread adoption of modular techniques. Entire housing units were fabricated in controlled factory environments, introducing standardization, reduced construction timelines, and cost efficiencies. Although modular building has grown in popularity in recent years, it is not a wholly innovative method. Prefabricated homes were brought from New York to California in the nineteenth century, when huge segments of the population began to migrate west, such as during the 1849 California Gold Rush. (Wilson, 2019). The concept of flexible structures can be traced back to the early 20th century with the emergence of architectural movements like De Stijl and Constructivism. These movements emphasized adaptability and flexibility in design and construction. In the 1960s and 1970s, architectural experiments with modular and adaptable structures, such as the Metabolism movement in Japan, showcased the potential of flexible architecture. (Hilde Heynen, 2002) (JENCKS, 1997) This significant historic juncture exemplifies the profound impact of off-site construction in addressing critical societal needs. Today, propelled by technological advancements, including digital design tools, robotics, and automation, off-site construction continues to redefine the architectural landscape. By embracing innovation and fostering continuous improvement in the construction industry, the full potential of off-site construction can be unlocked, transcending the limitations of traditional on-site methodologies.

In the realm of architecture and construction, an enduring challenge of the past was the customization and intricacy of building components. Traditional methods often imposed limitations on the creation of unique architectural features, and bespoke elements demanded significant time, expense, and skilled craftsmanship. (Pye Tait, 2008) However, the advent of digital manufacturing and 3D printing technologies has ushered in a transformative solution to this age-old predicament. Architects and designers now harness the power of computer-aided design (CAD) software to conceive intricate digital models, seamlessly translating them into precise instructions for the 3D printing process. (Menna Hazem, 2007) (Jovanovic, 2013) (Paritala, 2017) (Peter s. p. Wong, 2017) By employing these technologies in off-site mass manufacturing, the production of complex components and modules with customized features becomes a reality. (Boychenko, 2017)The integration of digital manufacturing and 3D printing not only enables architectural boundaries to be pushed, but also yields cost and time efficiencies. Automated precision reduces waste and human error, streamlining production processes and lowering material costs. Furthermore, fabricating components off-site and transporting them to the construction site significantly expedites on-site construction while minimizing disruptions. This remarkable advancement addresses historical challenges, underscoring the transformative potential of digital manufacturing and 3D printing in the construction industry. (JANE BURRY, 2020) However, in 2019 COVID-19 pandemic had a huge global impact, notably on the building industry. Short-term production, supply capacity, and worldwide growth were reduced, resulting in economic issues. In the long run, however, the pandemic has spurred the use of digital technologies, resulting in greater cooperation, improved value chain management, and data-driven decision-making processes such as Digital Twins. (United Nations Environment Programme,

2022) (Murray, 2023). There has also been an increase in expenditure in standardizing building rules for safety and sustainability. In addition, the sector is focusing more on industrialization, utilizing modularization, off-site production automation, and on-site assembly automation to boost efficiency and productivity. These themes represent the industry's reaction to the pandemic's issues, as well as the need for resilience, sustainability, and technical innovation. (Cheng Zhuo, 2023) The main advantage of offsite building over traditional construction is assumed to be reduced construction time on site, along with higher quality, a more uniform result, and less snagging and defeasibility.
(Goodier, 2023) (Harrison, 2023)
This research paper explores the enduring legacy of off-site construction and its potential for shaping a sustainable and efficient built environment. It analyzes the current need for mass production in off site construction, emphasizing the concept of growing architecture to fit the surrounding environment and the design requirements. The paper also investigates the use of 3D printing for joints and highlights the reuse of metal pipes to reduce waste and promote comprehensive material utilization. By delving into these topics, the paper aims to contribute to the understanding and advancement of off-site construction in terms of mass production, adaptability, 3D printing, and sustainable practices.

2. Design & Construction Methods

This research paper is based on customization of modular structures using bent pipes and 3d printed joints for design of the train station. To develop the project team focused on methods such as leveraging the specific benefits of analogue and digital fabrication. Methodology also includes several tests around physical model development and then transition to digital model. Techniques, such as 3d printing joint with PLA material using Cura software to slice the model from Rhino in meshes, and reusing of rubber pipes are employed for the test experiments and form finding processes. This iterative approach is represented in the research in a way of learning aspects from an analogue model and then implementing them and changing the digital one. After the first attempt with simple cross sectioned nodes and pipes the team understood the limitations of this specific node. Going back to the digital model, a new set of 3d joint were developed, and new module combinations achieved.
The utilized methodology also includes parametric design strategy using Rhino 7, which has built in Subdivision tools. It allowed the team to reach the digital pipes utilizing Pipe command applied on curves, which represent the structure of the modular train station. The command MultiPipe has been utilized in the project to make 3d joints in the points, where pipes were connecting to each other or to the ground. Digital analyzing tools in Rhino 7 and Scan&Solve plugin helped to compare the behavior of the straight pipe and bent one after applying pressure of 5000 Pa.
Customized modular design involves creating a structure composed of individual modules that can be tailored to specific requirements. This approach offers flexibility, adaptability, and ease of assembly. By allowing customization of modules, architects can meet unique design challenges and create structures that respond effectively to external factors and human needs. Parametric design techniques enable the establishment of rules or parameters that define the geometry and behavior of modules and joints. This approach facilitates efficient customization and variation within the design framework. Architects utilize parametric design to generate and sift through countless design possibilities based on multidimensional aspects. Computational approaches have proven to boost design efficiency by exploring the potential of modular approaches in architecture.
Various digital design tools, such as computer-aided design (CAD) software, are instrumental in creating and manipulating 3D models of the structure, modules, and joints. These tools enable precise design iterations, visualization, and analysis. By leveraging digital design tools, architects can enhance the efficiency and accuracy of the design process, leading to improved outcomes in customized modular architecture. Bent metal pipes serve as the main structural components in customized modular designs. These pipes are typically made of lightweight and high-strength materials such as

materials such as aluminum or steel alloys. The use of these materials ensures structural integrity while minimizing weight, resulting in efficient and resilient structures. Structure flexibility is usually a component of the core conversation when discussing modularity and other adaptability features, which implies that the core discussion section must be flexible to be consistent with adaptable architecture. We used NODES, which are the most economical and sustainable options, to debate this in our design process.

The joints connecting the bent metal pipes are produced using 3D printing technology. Specifically, 3D printed metal joints offer design flexibility, rapid prototyping, and precise customization capabilities. Metal powders and suitable 3D printing processes, such as selective laser melting (SLM) or electron beam melting (EBM), are utilized to create these joints. The use of 3D printing technology enables architects to achieve intricate designs and tailor joints to specific project requirements.

By melting the work piece and adding filler material, welding is a method of joining separate pieces. It is also described as a method of consistently attaching metal components using heat. To create a 3D metal item, 3D welding is characterized as building up metal beads layer by layer. By adopting the welding procedure, it is more affordable and productive to make metal products in large quantities. Ren et AL research has focused on 3D repairing technology, where surface patching has significantly increased accuracy, efficiency, and dependability of component fixing, in addition to producing new 3D objects.

Pipe and tube bending can be done in a variety of ways. The size of the pipe or tube to be bent, the wall thickness, the required radius, and, of course, the material must all be considered. Then there is the equipment and procedures in hand, as well as the machine operator's abilities. A broad range of bends may be created with high precision and attractiveness using a clever combination of material, machines, processes, and experienced operators. The use of a "rotary draw bender" is the most current way of bending pipes and tubes. Round pipe, as well as round, square, and rectangular tubing, is clamped into a form and pulled to the necessary radius over a die. Each die must fit the outer dimensions of the material being bent as well as the required radius. However, once set up, the process can swiftly create high-quality parts. The radii can be as small as half the pipe's diameter.

3. Results

Based on methodology, the team developed the following experiments and achieved following results.

3.1 Physical Experiments

The form-finding process was conducted in two steps to explore different possibilities and overcome limitations:

The first step involved creating a simple cross connection as a basic configuration for the module (Figure 1). This initial configuration allowed for experimentation and analysis. However, during this stage, it was discovered that the simple cross connection had limitations in terms of the distance it could cover. This limitation prompted further exploration to enhance the module's capabilities. To overcome the limitations identified in the first step, additional connections were designed. These connections had two to four outlets for connecting pipes, enabling the module to cover larger areas, such as train stations. In train station projects, it is essential to minimize the number of columns and supports to ensure the safety and ease of communication for passengers on platforms (Figure 1).

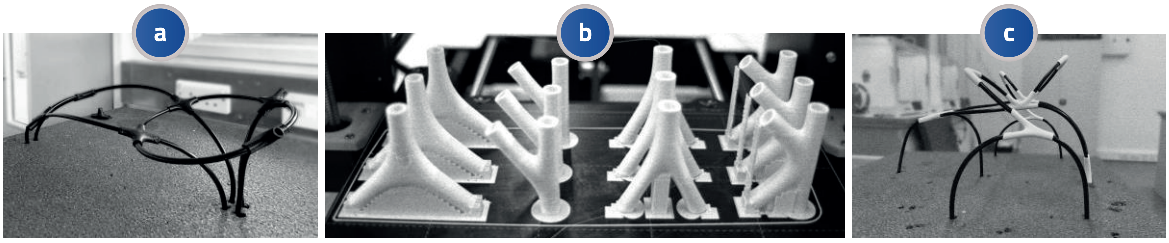
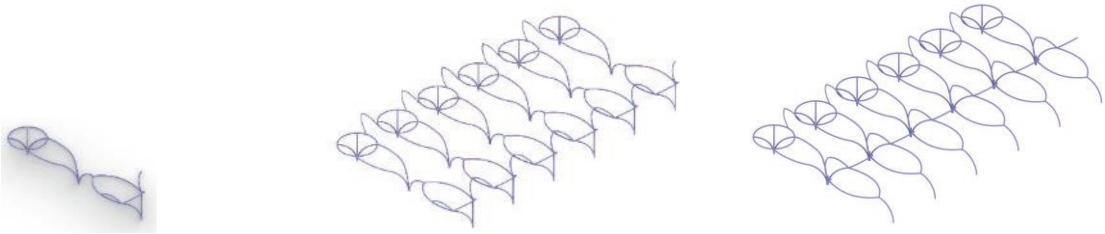


Figure 1. Physical models: (a) Module developed using cross connection and flexible pipes; (b) 3D printed joins with 3 and 4 ends; (c) Module developed using variable connections and flexible pipes.

3.2 Digital Model development

3.2.1. Transition to Digital Model and Customized Mass Production

As the form-finding process using 3D printed joints and reused rubber tubes yielded valuable results, the research then progressed to the next step: transitioning to a digital model. This transition allowed for increased precision and efficiency in the iterative design process. Moreover, it supported the concept of customized mass production, which is crucial in achieving faster results and a variety of outcomes (Figure 2).



(a) (b) (c)

Figure 2. Digital models created from curves in Rhino 7 using subdivision tools: (a) single module; (b) First iteration of arranged module; (c) Final iteration of arranged modules.

Rhino, a powerful computer-aided design (CAD) software, was utilized in this research to create the digital model. With Rhino, the design team could work with curves and orient them in both 2D and 3D space. This flexibility enabled them to experiment and play with different design configurations, generating numerous varieties of outcomes for exploration. The process involved manipulating the curves and adjusting their parameters to create a wide range of module shapes and configurations. By leveraging the digital tools provided by Rhino, the design team could quickly iterate and evaluate the visual and structural aspects of each variation. Working with curves in the digital model allowed for precise control over the geometry and dimensions of the modules. The design team could easily adjust the curvature, angles, and intersections, fine-tuning the overall aesthetics and functionality of the customized modular architecture. Through this iterative process, the design team could test different design possibilities, exploring the potential of the module in various contexts. They could simulate the module's behavior in different environments and assess its performance under different loads and constraints. This digital experimentation provided valuable insights and feedback, guiding the refinement of the design.

The use of Rhino as a digital design tool not only facilitated the exploration of design variations but also enabled efficient customization. By parameterizing the design, the team could easily modify and adapt the modules to specific requirements, such as space constraints and functional needs. This customization capability is a key aspect of the customized mass production approach, allowing for efficient production and assembly processes while maintaining design consistency (Figure 3).

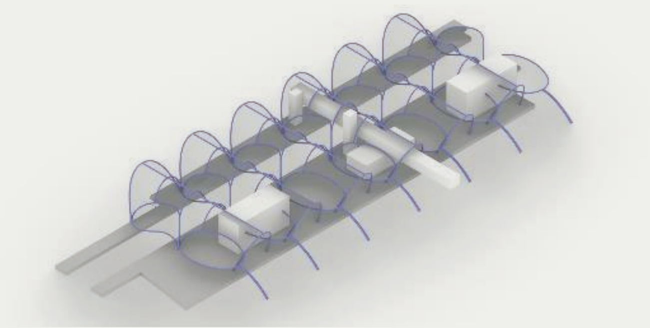


Figure 3. Digital model of the structure applied on the functional diagrammatic arrangement of the functional organization for the train station.

3.3 Stress Analysis

As the next step in the process of delivering the project some stress analysis has been done using Rhino 7 and SnS Pro Evaluation plugin. The pressure of 5000 Pa was applied to both the steel straight and bent pipes diameter of 400mm (figure 4). This pressure represents the load exerted on the pipes during the analysis. The stress analysis provided statistical data on the structural response of the pipes under the applied pressure. This data includes information such as maximum stress values, deformation, and factors of safety, which are important for assessing the structural integrity and performance of the pipes (figure 4). The results of the stress analysis were interpreted and evaluated to determine whether the pipes can withstand the applied pressure without exceeding their structural (Alimits. This step helps in assessing the safety and reliability of the pipes in real-world applications.

a) b) c)

Material Summary (linear pipe)

Property	Value
Description	Steel, Stainless (ferritic)
Density	7.8e-09 Mg/mm³
Elastic Modulus	200000 MPa
Default Failure Criterion	von Mises
Tensile Yield Strength	172.339 MPa

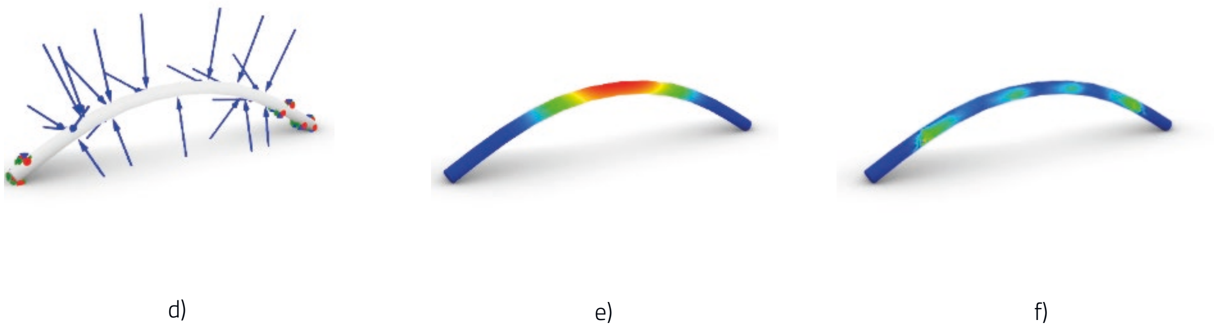
Component Geometry Summary (linear pipe)

Quantity	Unit
Component	0f6aed0c-6645-4be0-91ce-1fef2aa02870
Material	Steel, Stainless (ferritic)
Mass	1.4345e+12 Mg
Bounding Box	{-2500, -107.812, 1915.19}-{2500, 107.812, 2130.81}

Results: (linear pipe)

	Minimum	Maximum
X-Displacement	-3.3827E-004 mm	3.1777E-004 mm
Y-Displacement	-1.9512E-003 mm	2.1193E-003 mm
Z-Displacement	-1.9367E-003 mm	1.9470E-003 mm
Total Displacement	2.0369E-005 mm	2.8359E-003 mm

Von Mises Stress	2.3812E-004 MPa	8.5662E-001 MPa
Max. Principal Stress	-2.6194E-001 MPa	8.1432E-001 MPa
Mid. Principal Stress	-3.4926E-001 MPa	2.5501E-001 MPa
Min. Principal Stress	-1.1434E+000 MPa	2.4978E-001 MPa


d) e) f)

Material Summary (curved pipe)

Property	Value
Description	Steel, Stainless (ferritic)
Density	7.8e-09 Mg/mm³
Elastic Modulus	200000 MPa
Default Failure Criterion	von Mises
Tensile Yield Strength	172.339 MPa

Component Geometry Summary (curved pipe)

Quantity	Unit
Component	8164a156-df42-4c72-a152-88d3dd1324c1
Material	Steel, Stainless (ferritic)
Mass	1.38546e+06 Mg
Bounding Box	{-24.7916, -56.4138, 0.999994}-{-22.9166, -1.89686, 18.6308}

Results: (Curved pipe)

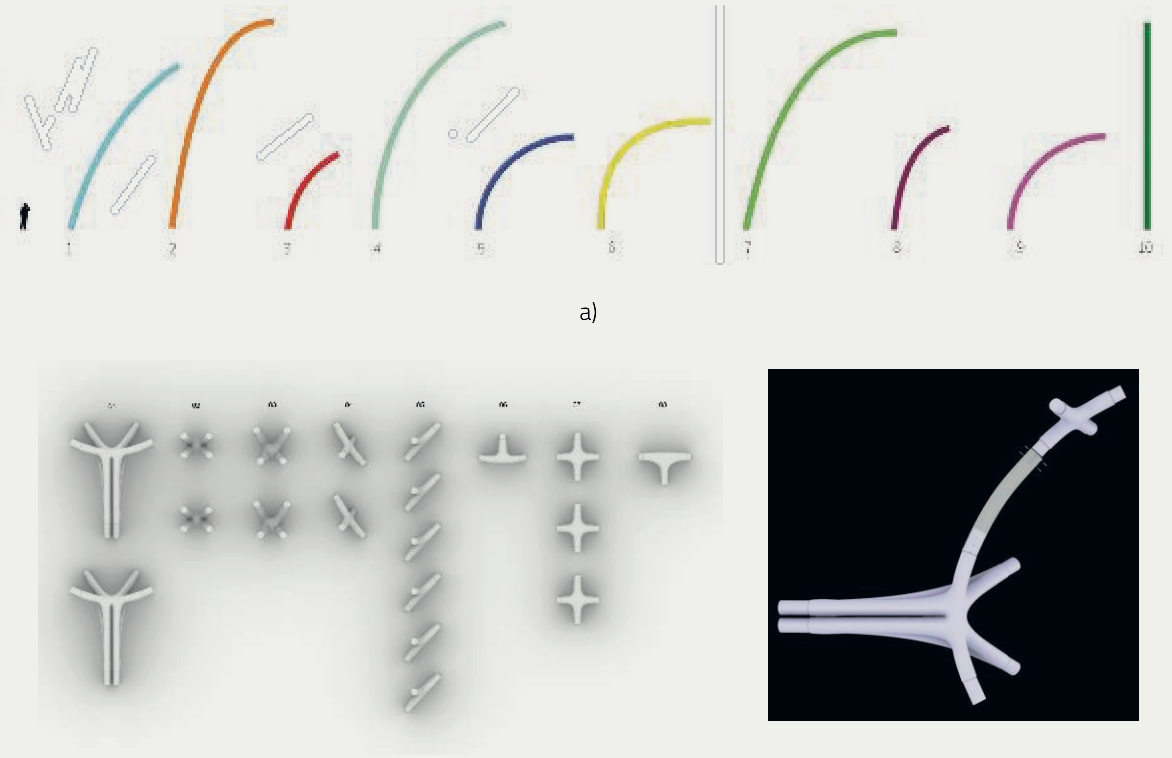
	Minimum	**Maximum**
X-Displacement	-2.7360E-005 mm	2.5705E-008 mm
Y-Displacement	-1.0791E-006 mm	9.2186E-007 mm
Z-Displacement	-2.3685E-006 mm	1.7514E-006 mm
Total Displacement	4.5905E-019 mm	2.7362E-005 mm

Von Mises Stress	1.1158E-007 MPa	8.2612E-002 MPa
Max. Principal Stress	-1.0169E-002 MPa	1.2178E-001 MPa
Mid. Principal Stress	-2.2285E-002 MPa	4.0717E-002 MPa
Min. Principal Stress	-6.5672E-002 MPa	3.7698E-002 MPa

Figure 4. Digital image of preliminary stress analysis and results of displacement on a linear pipe (A, B,C) and curved pipe (D,E,F). Tables are showing the data for respective components and their geometry.

3.4 Components

For the manufacturing strategy, a 1:25 scale model was created using a combination of 3D printing and precise pipe bending techniques. The joints of the model were 3D printed using high-density PLA (Polylactic Acid) filament, chosen for its strength and durability. Rhino 7, a 3D modeling software, was utilized for developing the model, with the subdivision tool employed to refine the detailed geometry. To generate the pipes, the multi pipe command in Rhino was used, enabling the automated creation of pipe structures from specified curves. For the 1:25 scale model, copper pipes with a diameter of 15mm were utilized and carefully bent to match the required angles and curves. This ensured accurate alignment and fit during the assembly process. The combination of 3D printed joints and precisely bent copper pipes allowed for customization and precise fitting, enhancing the overall structural integrity of the module. These manufacturing techniques, coupled with digital modeling and advanced software tools, aimed to expedite construction compared to traditional methods.



a)

b)

c)

Figure 5. The component requirement for one module a) the different radii for pipe bending b) the joints required for assembling of one module c) The joint and pipe connection detail.

3.5 Transition from digital model back to physical

3.2.1. 3d joints

In this research paper, the team presents a comprehensive and detailed guide to the 3D printing process utilizing PLA filament, accompanied by widely utilized slicer software applications Cura. There are specific requirements and steps listed to achieve the willing result. The model should be watertight or solid, avoiding double surfaces and intersections. It must be clear what is the interior and what is the exterior. In Rhinoceros there is a tool to check it out: ShowEdges. This tool can show any Naked and Non-manifold edges. Those are usually a big issue for 3D printing as the way a computer reads these files may not be as they are designed. By default, Rhinoceros does not allow the creation of non-manifold edges. The model should be in the right scale and in millimeters. The physical prototype model has been designed in scale 1:25.

- Exporting modeled joints in right scale your file from your program of choice as an. STL (mesh and save as Binary if prompted).
- Importing the model into Cura slicer software.
- Selecting the appropriate printer profile for compatibility. In the case of this project the team used Ultimaker S5 printer with Fast profile template for using Left Extruder with PLA material.
- Orienting the model to optimize print quality and adhesion.
- Choose print quality settings such as layer height (0.2mm) and infill density 50% and structure – gyroid.
- Generate the G-code by clicking "Slice". Right after slicing the model software provides printing time and the weight of used material. For the joints team approached for the project, time varies between 4-7 hours per one joint. To optimize printing time of 23 joint required by the project team used 3 printers and arranged several nodes at one printing bed.
- Save the G-code file to an SD card or transfer it to the 3D printer.
- Load PLA filament and heat the printer bed to the recommended temperature.
- Start the print job and monitor the process for any issues.
- Adjust settings or troubleshoot if necessary.
- Allow the printed object to cool before removing it from the print bed.
- Remove support structures if applicable.

3.6 Bent Pipes

Once the team developed a digital model of the train station module, is it possible to make precise curvature of the pipes. The team simulated the automated process using an analogue approach, employing a rotary bender to develop structural elements from copper pipes with a 15mm diameter at a 1:25 scale. Each pipe schedule had a specified wall thickness, and although there was a tolerance, a small variation in wall thickness was possible. This variation needed to be considered, especially when using precise tooling for bending with short radii. To account for this difference, the team carefully took into consideration the tolerances during the bending procedures. The exact and snug fitting tooling was utilized to achieve the desired bends while accommodating any potential variations in the wall thickness. The pipes were marked at equal intervals of 25 mm, ensuring a linear
curvature by keeping them on a straight line to avoid double curvature and keeping the marks in template. Figure 6. Using a mobile manual pipe bender securely fixed to a vice, the team followed the marked points while bending the pipe. This approach allowed for precise bending while accounting for potential variations in wall thickness, ensuring accuracy and quality in the final structural elements.

Figure 6. Analog pipe bender and using a segmental making to bend pipe to template and individual radius.

3.7 Assembling the model using KIT

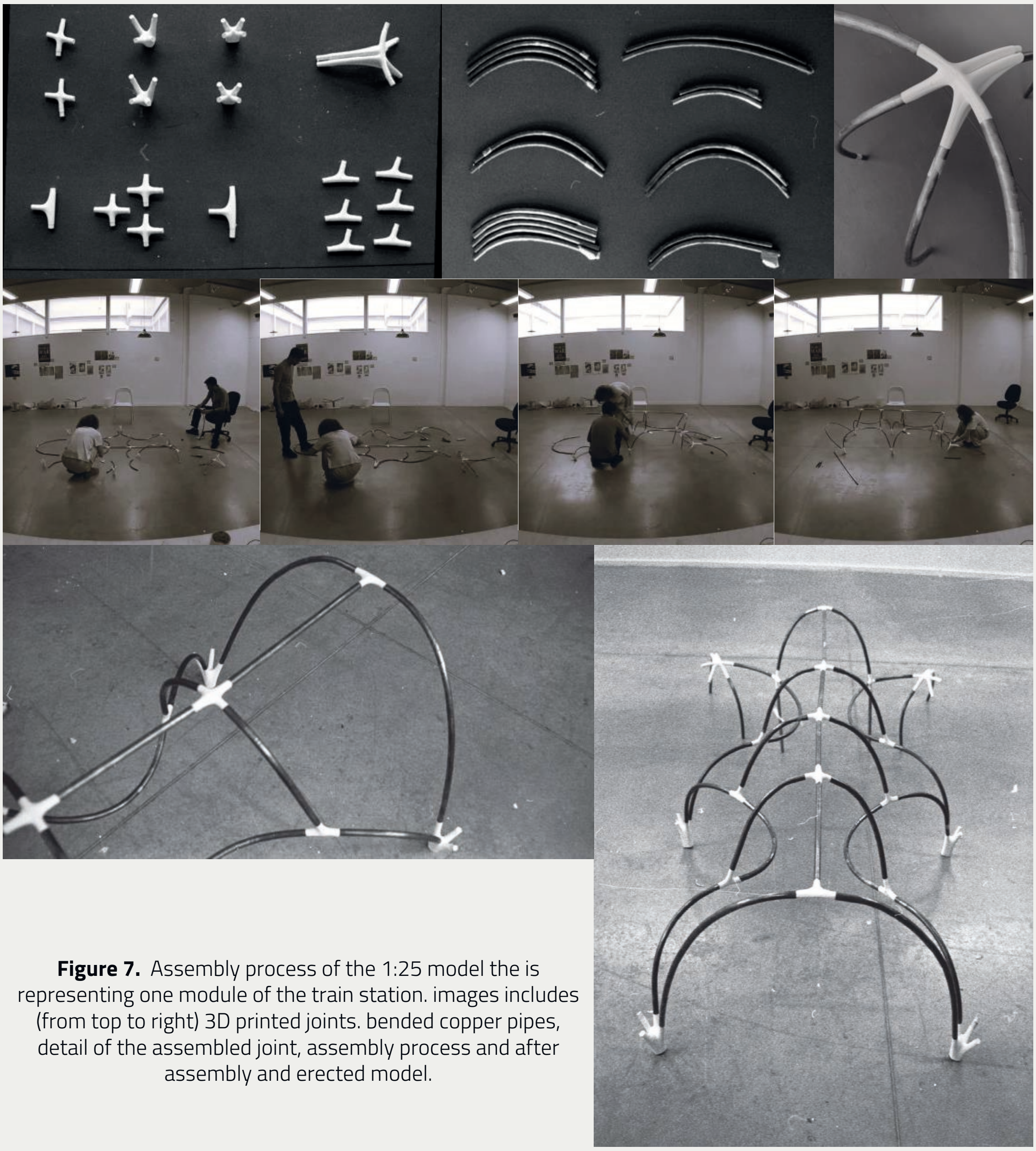


Figure 7. Assembly process of the 1:25 model the is representing one module of the train station. images includes (from top to right) 3D printed joints. bended copper pipes, detail of the assembled joint, assembly process and after assembly and erected model.

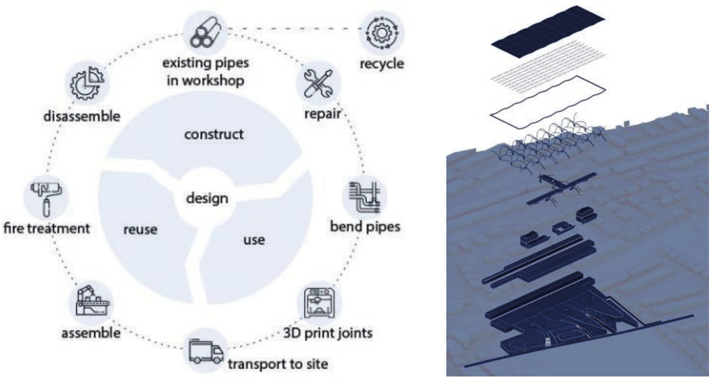
A combination of digital and analogue approaches was used during the assembling process. The pipes were put in their assigned placements, with continual reference to the structure's 3D model. The 3D model gave explicit assembly instructions, directing the proper positioning of each pipe. These meticulously organized pipes were then coupled with their 3D printed joints, which were allocated specified spatial places inside the building model. The inherent flexibility and tension of the pipes became apparent as the assembly continued. This stress in the pipes contributed to the model's self-sufficiency, giving stability and structural integrity. The interaction of the digital representation and the physical assembly enabled a seamless translation of the design idea into a concrete architectural form.

3.8 Environmental and Construction strategy applied for the train station project

To implement the reduction of sources, materials, and waste while construction and demolishing teams approached circular economy as a key aspect of the project. Instead of a permanent design project presents a flexible structure which can change, grow, and shrink. Using recycled steel as a structural element will speed up the project by eliminating the need to wait for the material to be produced. However, to use these recycled materials, they must undergo chemical and thermal treatment to purify the metal and guarantee long-term durability.

To achieve sustainability in the project the team proposes offsite modular manufacturing, which includes repairing existing pipes in the workshop. Thermal - the steel pipe is heated to a feverish temperature. This will remove contaminants from the steel as well as rust from the surface. Chemical – Zinc (zinc chloride) is a chemical that protects the outer surface of steel from rust. The following step is to bend pipes with automated rotary pressure applied by a robotic arm. Simultaneously nodes and connections are being printed using the direct metal laser sintering (DMLS), which utilizes lasers. By layer-wise solidifying metal powder layers in areas of the layer matching to the cross-section of the three-dimensional component in the appropriate layer, complex parts can be created directly from 3D-CAD models. Once all elements are ready, they are delivered to the building site. Assembling process is realized and controlled by robots. Having a digital twin of the physical outcome, robots manipulate with a pick and place approach. The next step is to spray all necessary treatments for the structure, such as fire treatment and anti-corrosion.

Thinking about long-term use of the train station, the team had in mind that the population of the town is growing, and the station should be able to provide service for bigger amounts of passengers. Structure of the train station can be changed by using the same construction technology – robotic manipulated and controlled. Some parts can be oriented in a different way, some of them can be reused in another project, some of them which can't be used anymore can go back to the workshop to be treated and / or recycled.



(A) (B)

Figure 8. (A). Life cycle of the project and econometric diagram of the train station, (B) components of train station.

3.8.1. Net-Zero structure

- Sustainability
- By reusing pipes, the demand for new raw materials is reduced, minimizing the environmental impact associated with metal extraction, processing, and manufacturing. This approach promotes resource conservation and contributes to a more sustainable construction approach.
- Reduced Waste
- Reusing pipes eliminates the disposal of old or unused pipes, thereby reducing construction waste. This waste reduction strategy helps minimize the amount of waste sent to landfills and aligns with the principles of a circular economy, where materials are kept in use for as long as possible.
- Design Consistency
- Reusing pipes ensures design consistency and maintains a unified aesthetic throughout the structure. This is particularly relevant in architectural projects such as train stations, where architectural coherence and visual harmony are essential considerations.
- Growing Buildings and Surrounding Adaptability
- The concept of growing or adaptable buildings refers to structures that can accommodate future expansions or changes in use. Research can explore the feasibility and implementation of off-site construction approaches, including the use of metal pipes, for creating flexible and adaptable buildings that can easily accommodate modifications or expansions over time.
- Improved Construction Efficiency
- Studies consistently demonstrate that off-site construction can significantly improve construction efficiency, reduce project duration, and enhance on-site safety. Researchers have employed methodologies such as case studies, simulations, and data analysis to evaluate and quantify these efficiency gains.
- Quality Control and Standardization
- The literature emphasizes that off-site construction allows for greater control over quality assurance through standardized manufacturing processes and controlled environments. Researchers have used quality assessment tools, inspections, and comparative studies to evaluate the quality performance of off-site construction compared to traditional on-site methods. + circular economy
- Cost Analysis
- Cost considerations have been a focal point in many studies. Findings indicate that while off site construction can require higher upfront investment, it offers potential cost savings in terms of labor, material waste reduction, and schedule compression. Researchers have employed life cycle cost analysis, cost modeling, and comparative studies to assess the economic viability of off-site construction.
- Repurposing and adapting existing pipes instead of purchasing new ones significantly reduces material costs in construction projects. This cost-saving measure allows for efficient allocation of resources and maximizes the budget for other aspects of the project.

4. Conclusion

In conclusion, this study presents an architect's perspective on the utilization of customized mass production and modular design principles in the development of lightweight structures using bent metal pipes. By incorporating cutting-edge technologies such as 3D printing, digital modeling, and precise pipe bending techniques, the project demonstrates the immense potential of off-site manufacturing and on-site assembly processes. The seamless integration of digital tools and analog methods during the assembly phase enabled architects to precisely arrange the pipes according to the 3D model, ensuring accuracy and spatial coordination. The inherent flexibility and tension observed in the pipes further enhanced the structural stability and self-supporting nature of the final assembly, showcasing the architectural prowess in utilizing materials effectively. Furthermore, this research underscores the architectural community's response to the challenges presented by the COVID-19 pandemic. The incorporation of digital tools has not only facilitated improved collaboration and data driven decision-making processes but has also empowered architects to exercise greater control over the construction value chain. Additionally, the emphasis on standardized building codes for safety and sustainability, coupled with the exploration of industrialization through modularization and automation, highlights the commitment to advancing the field. By successfully implementing this project, architects are poised to contribute to the creation of sustainable, efficient, and adaptable buildings that address the evolving needs of society.

Moving forward, continued research and development will play a crucial role in refining processes and pushing the boundaries of architectural innovation in the construction industry. Specifically, it addresses the pressing challenge of modular architecture. By utilizing digital design and fabrication tools, this approach enables the creation of structures that are both flexible and durable. This advancement in design has far-reaching implications for the construction industry, as it opens new possibilities for creating efficient and adaptable buildings. This research provides a new perspective on sustainability by promoting the adoption and reuse of existing structures instead of constructing new ones. This approach significantly reduces costs and minimizes the resources associated with the process of demolishing and rebuilding. By embracing the principles of adaptive reuse, this innovative design and construction methodology contributes to the preservation of resources and the reduction of environmental impact. It offers a more efficient and sustainable solution to the ongoing challenges of urban development and construction practices.

However, further research is needed to explore the mechanical properties and long-term performance of 3D printed metal components and to optimize the bending processes for different pipe materials and wall thicknesses. The results and findings of this study demonstrate the potential of combining metal 3D printing and precise pipe bending techniques in architectural applications, paving the way for future advancements in the field of customized mass production and modular design in lightweight structures.

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