Multi-objective design optimization and robotic fabrication towards sustainable construction

The example of a timber structure in actual scale

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This paper attempts to reconsider the role of advanced tools and their effective implementation in the field of Architecture, Engineering and Construction (AEC) through the concept of sustainable construction. In parallel, the paper aims to discuss and find common ground for communication between industrial and experimental processes guided by sustainable criteria, an area of investigation that is currently in the forefront of the research work conducted in our robotic construction laboratory. Within this frame, an ongoing work into the design, analysis and automated construction of a timber structure in actual scale is exemplified and used as a pilot study for further discussion. Specifically, the structure consists of superimposed layers of timber elements that are robotically cut and assembled together, formulating the overall structural system. In order to achieve a robust, reliable and economically feasible solution and to control the automated construction process, a multi-objective design optimization process using evolutionary principles is applied. Our purpose is to investigate possibilities for sustainable construction considering minimization of cost and material waste, and in parallel, discussing issues related to the environmental impact and the feasibility of solutions to be realized in actual scale.

Keywords: *Multi-objective optimization, robotic fabrication, cost and material waste minimization, sustainable construction, timber structure*

INTRODUCTION

Recently, efforts towards the establishment of alternative strategies and solutions that will lead to smarter, more sustainable and inclusive economy are coming to the fore (European Commission, 2010), directions that are intrinsically connected within the broader notion of circular economy (Hebel et al, 2014). Although, the concept of sustainable design and construction (Abeer, 2012) is currently gaining significant attention in other disciplines including Architecture, Engineering and Construction (AEC), when the discussion refers to the way such principles are applied within the area of computational design and robotic fabrication, less focused examples can be found. On the other hand, integrated computational design and robotic fabrication processes are currently in the forefront of the research undertaken in architecture and engineering field, mostly in experimental level, with little impact in the broader field of AEC. This is due to various reasons including the expensive technology and the low expertise among constructors. As a sequence, their implementation is observed partially, preventing the establishment of robust and reliable methodologies in the wider construction industry. In the literature, the implementation of optimization techniques is mainly focused, either on the design investigation of conventional forms influenced by sustainable criteria or on experimental studies, where advanced computational design and robotic fabrication techniques are used in the development of complex morphologies, but with little consideration about the sustainability of solutions.

In the first direction, examples can be mostly found in the area of multi-objective analysis using genetic algorithms in order to optimize solutions by minimizing their environmental impact, for instance in example for minimizing the life carbon footprint and life cycle cost of residential complex (Schwartz et al, 2015), building envelope (Barg et al, 2015), etc. In the second direction, advanced computational design and robotic construction techniques are applied, in most of the cases, in experimental studies considering timber as a material with high sustainable potential. Examples like the work on robotic timber construction of non-standard forms (Willmann et al, 2016) or the work on robotic fabrication of wood plates morphologies (Schwinn et al, 2012) demonstrate the potential of timber to be used as an ecological material, followed by other studies where robotic construction of timber is combined with topology optimization techniques for design and robotic construction experimentation (Søndergaard et al, 2016).

This paper implements a multi-objective design optimization strategy towards an automated construction process in the case example of a timber structure driven by cost and material waste objectives. Moreover, issues related to the robot-human intervention within the workflow, the robotic constructability and the applicability of other mechanisms involved in the construction process are examined. Next chapter describes the research methodology that includes a multi-objective optimization strategy based on evolutionary principles. This is integrated with an automated construction process, which involves an industrial robot and a parallel intervention of manufacturers. Then, the case study example of a timber construction is described followed by discussion in regard to the effectiveness of the process to be implemented within the broader area of construction industry. Finally, general conclusions in regard to the role of computational design and multi-objective optimization, integrated with robotic fabrication and driven by sustainable criteria are drawn.

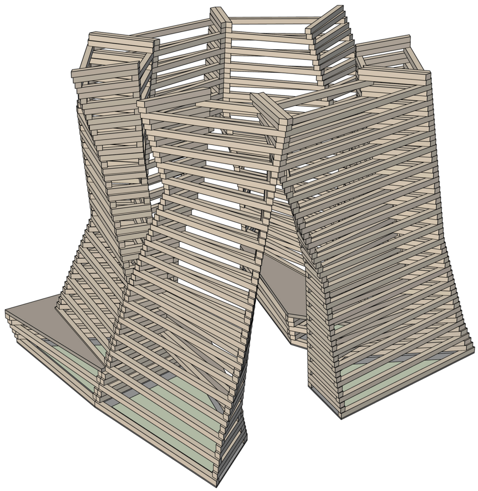


Figure 1
Suggested
structural system

RESEARCH METHODOLOGY

This paper suggests the development of two equally important steps towards the construction of a timber structure in actual scale, the design optimization and the robotic construction process. This is done in an integrated and interrelated manner where the design results derived from digital optimization inform the robotic construction stage and vice versa. The objectives related to the cost and material waste minimization lies within the broader aim of this research, which is the introduction of a sustainable construction process using advanced robotic technology and multi-objective design optimization (Dep, 2002).

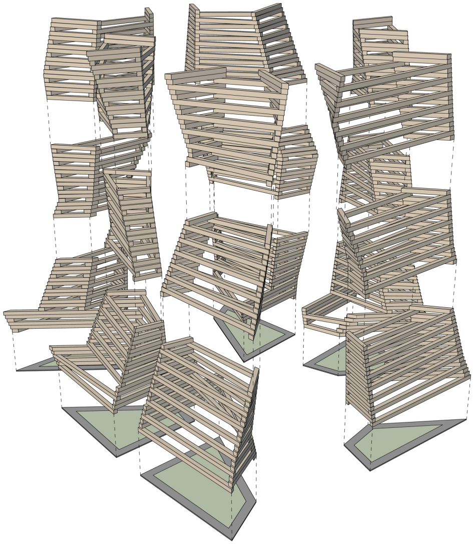


Figure 2
Structural components assembly diagram

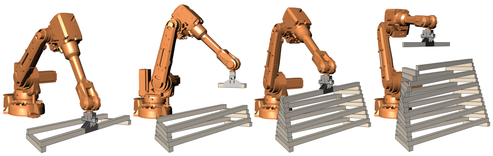


Figure 3
Robotic manufacturing process of an individual structural component

In the design optimization stage, the parametric associative design tool Grasshopper [1] (plug-in for Rhino [2]) and the multi-objective analysis plug-in Octopus [3] based on evolutionary principles are introduced to evaluate design solutions against minimum cost and material waste performance but also against other design performance criteria including maximum area of openings and maximum dimensions of the interior space In addition, the selected design of structural elements and the articulation of the overall structure considers robotic construction criteria, which among others include minimum and maximum length of shortest and longest timber members respectively, aiming to be effectively handled by the custom-made end-effector tool. Also, the investigation is influenced by other criteria related to the capacity of the robot to perform the given tasks and include reach length, payload and working area. In addition, the involvement of the manufacturers during the construction process is taken into consideration since it consists an indispensable part of the process, functioning as an assistive factor for the effective execution of the given structure. Overall, the suggested multi-objective optimization process achieves to generate a pool of solutions that can formulate the range of feasible candidate structural systems to be fabricated, attempting to be materialized in the next stage of experimentation.

Within the framework of this ongoing research work, the design optimization is followed by the robotic construction in 1:1 scale in order to evaluate the selected optimized results but also to validate the performance of current robotic construction scenarios. In order to achieve this, initially, a single structural component is selected to be robotically fabricated, aiming also to observe potential drawbacks or obstacles occurring during the process. These are particularly related to the robotic tool path that might cause singularity and possible collision with the structure.

Firstly, the structural component is robotically executed using foam material as an alternative and low budget choice and secondly, actual timber material is implemented in the construction process to test our hypothesis. In a future stage, the goal is to fabricate the overall structural system that consists of eighteen differentiated components based on the same geometrical configuration and construction logic. This paper demonstrates results derived during the first stage of experimentation that is the robotic construction of a single structural component using foam material.

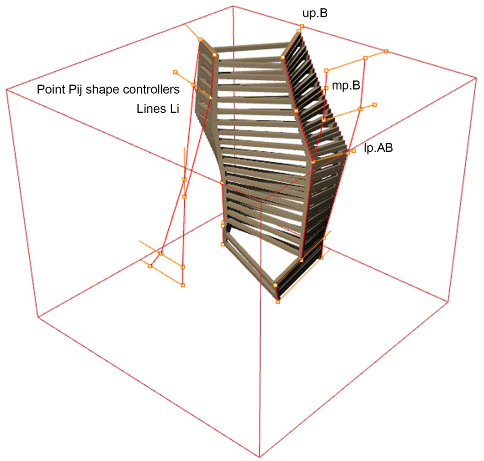


Figure 4
Geometrical configuration and parametric controllers shaping the structural segment SS1

CASE STUDY EXAMPLE

Construction system review

The suggested structure, which is functioning as a small size shelter for resting, is 9 m2 in area and 2.50 m in height. In pre-design and pre-construction stage, its geometrical configuration is influenced by construction objectives but also by environmental and functional performance criteria that allow an efficient use of space by the visitors. In terms of environmental aspects involved, two openings in the western and eastern part of the shelter provide ventilation and allow the light to enter the interior space. In addition, two other openings in southern and northern part are functioning as the entrances-exits of the structure. The shelter creates a narrow interior consists of benches for resting but also a corridor, which allows visitors to move through the space (Figure 1).

The structural system consists of eighteen individual structural components that are joined in groups of three to create six larger segments that make up the entire structure (Figure 2). Each structural component consists of superimposed layers of timber elements that are robotically cut and assembled together in horizontal layers, formulating closed polygons. Specifically, each layer consists of two long and two short primary beams that create the outline of the closed polygon and the secondary transverse beams that are laid on top of the two opposite short members to support the primary systems but also to achieve larger gaps between layers of timber in the interior and exterior façade of the shelter. The timber elements are in square section of 44x44 mm2. The separation of the overall construction system in individual components allows their manufacturing in the laboratory (Figure 3), their easy of transport and finally their effective assembly in the location.

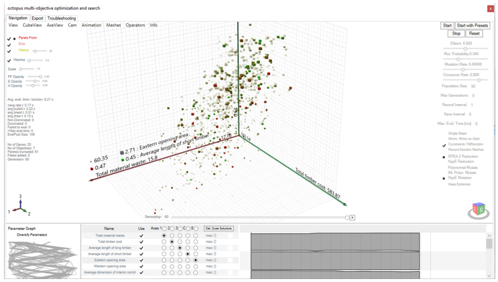


Figure 5
Graph of the distribution of solutions according to the objectives

The overall geometrical configuration together with the arrangement of timber structural elements are parametrically controlled, aiming to adapt their morphology according to the design performance criteria mentioned in previous paragraphs but also according to the robotic construction constrains. The restrictions related to the use of material and the assembly logic of timber elements, lead to the application of a multi-objective optimization strategy so that any changes occur in the entire structure to influence individual construction components and vice versa.

Multi-objective optimization process

As it has been already mentioned in the research methodology part of this paper, the complexity of design tasks as well as the construction process itself lead to the introduction and the implementation of a multi-objective optimization mechanism [3]. This methodology allows the production of a range of possible solutions through generations, aiming to achieve minimum values in the given objectives by

Figure 6
Three selected solutions with minimum values for cost and material waste objectives: case 1. 13.13% of material waste and 553.14 Euros cost of material, case 2. 12.85% of material waste and 557.53 Euros cost of material, and case 3. 12.78% of material waste and 561.92 Euros cost of material

displaying solutions with different combination of parametric variables. The running process is based on the reproduction of two population of solutions that generate a new offspring, leading to the generation of a new population of better solutions. Through the Pareto front, a series of best solutions are selected, mainly the desirable ones, aiming to achieve a feasible construction process.

Initially, the geometrical configuration of the small size shelter is parametrically defined [1] taking into consideration a number of variables that are either constant or flexible. The overall structural system is enclosed in an imaginary square box with dimensions of W=3m (with), L=3m (length) and H=2.5m (height). The overall structure consists of six large structural segments (SSi), each of them parametrically defined by four curves Ci that in turn, are controlled through lines Li and triads of point Pij shape controllers. Figure 4 shows the structural segment SS1 that contains triads of Pij shape controllers responsible for the parametric control of the northern entrance-exit and of the lower point AB, middle point B and upper point B of the eastern opening. Simultaneously, other shape controllers are responsible to control an extension of SS1 on its base, allowing the creation of a bench area. Analytically, in the case of northern entrance-exit, the height of point shape controller is defined as a flexible variable with values range from 1.5 to 2.25m. In the same way, the flexible variable for the height of the lower point AB range from 0.75 to 1.25m and the flexile variable for middle and upper point B is defined as distance from the middle point AB with range 0.2 to 0.65 and 0.2 to 1.1 respectively (the values control parametrically the eastern opening area). Subsequently, each of the four Ci in every SSi is divided in a number of segments to formulate the superimposed layers of timber members. The length of division is fixed and is defined as the height of timber component with value 44mm resulting in the creation of 56 segments that formulate the superimposed layers of the horizontal primary long and short elements as well as of the secondary beams.

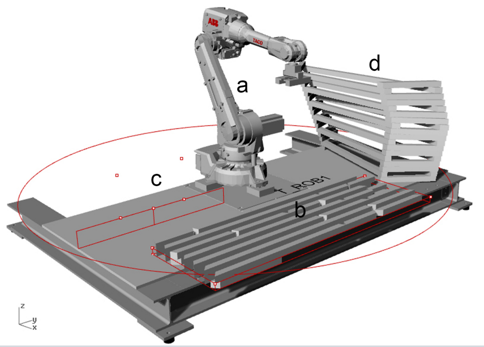


Figure 7
Spatial organization of the working area: a. location of robot, b. containers positioning, c. cutting area, and d. assembling area

Apart from the variables controlling the overall geometrical configuration, the introduction of several objectives are tested during the multi-objective opti-

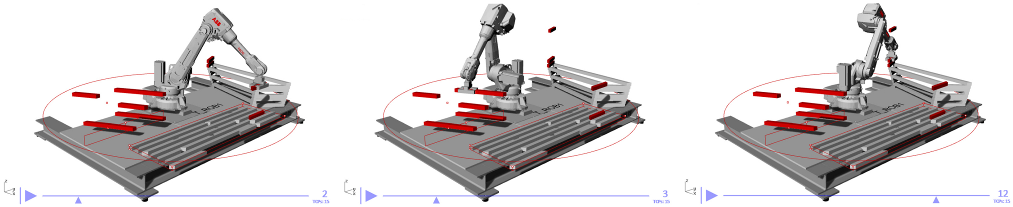


Figure 8
Selected robotic simulation steps in a continue single toolpath that involves picking, cutting and placing

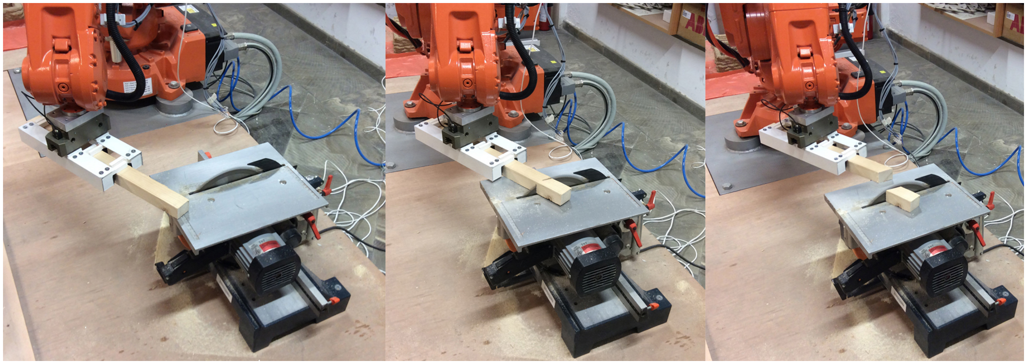


Figure 9
Robotic cutting using circular saw

mization process. These objectives include minimum cost and material waste, minimum average length of the longest timber members, maximum average length of shortest timber members, maximum eastern opening area, maximum western opening area, and maximum average dimension of interior corridor.

Due to the highly differentiated and customized individual timber elements (size, cutting angle, etc.), the cost and material waste minimization are found to be the primary objectives necessary to be considered during the process. Toward this direction, the concept of bin-packing algorithm (Crainic et al, 2007) based on the PackRat platform [4] (plug-in for Grasshopper) is introduced. The specific plug-in offers the possibility for packing rectangular shapes in rectangular containers, an algorithmic procedure that achieves to minimize the used space and hence to achieve less material waste, leading to the reduction of cost and material.

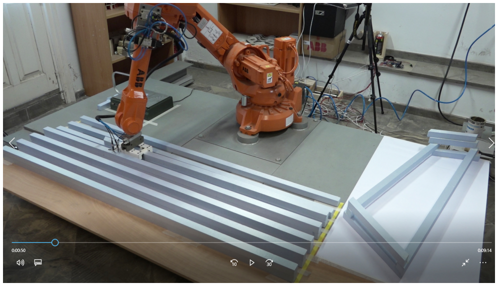


Figure 10
Picking the appropriate rod for robotic cutting

The suggested process determines the material waste as the total volume of used timber members divided by the total volume of available timber members or containers (pieces of 4m length) that take part in bin-packing minimization process. This is described as the used/available ratio U/C with values in percentage (%). Also, the number of available timber members is calculated, providing the total cost in Euros (4.39 Euros/per piece of 4m length).

In addition, the process takes into account limitations occurring during the construction stage (Kontovourkis and Tryfonos, 2016), mainly based on the robotic construction capacity, which includes the dimensions of the end-effector tool for the effective handling of timber elements, and the size of working area that influence decisions in regard to the robotic construction scenario and hence the sequential production of structural components.
Specifically, fitness values control the length of the average longest timber members to be less than L=1.2m and the average length of the shortest timber members to be larger than L=0.40m, values directly related with the capacity but also accuracy of the gripper tool (0.20m length) to handle and control different angles and size of structural elements during cutting and assembling process. Finally, objectives that determine the maximum percentage of opening areas in both eastern and western sides of the shelter are applied. Moreover, a fitness value related to the maximum average dimension of corridor in the interior space is incorporated in the optimization process, targeting on values larger than d=1.0m.

Hence, the multi-objective optimization provides the framework where several objectives are introduced and evaluated simultaneously in a continuously iterated feedback loop process, providing quantitative results related to the environmental impact, architectural qualities and limits of the manufacturing process. These objectives are evaluated against each other, influencing the selection of the best fitting results and therefore are directing the design decision-making. The results obtained during several runs of the multi-objective optimization process shows the variety of solutions over the generations (Figure 5). Figure 6 shows three selected solutions obtained from the optimization process based on minimum values for cost and material waste objectives.

Robotic behavior simulation

Due to the complexity of the tasks involved, which include picking the timber with the appropriate length, placing the timber with the right angle to the circular saw for cutting in both edges and finally assembling the appropriate shape of timber element in the overall structure, initially, a comprehensive installation of the workspace and offline simulation was necessary to be developed in order to capture the robotic behavior. In addition to this, due to the random distribution of the available timbers (containers) that were determined during bin-packing algorithm optimization stage, the appropriate sequence of robotic motion behavior in relation to the construction logic and the chronological placing of timber, were important issues to be investigated in advance.

Equally important factors that influenced robotic simulation process were the technical characteristics of robotic mechanism, particularly the robot reach

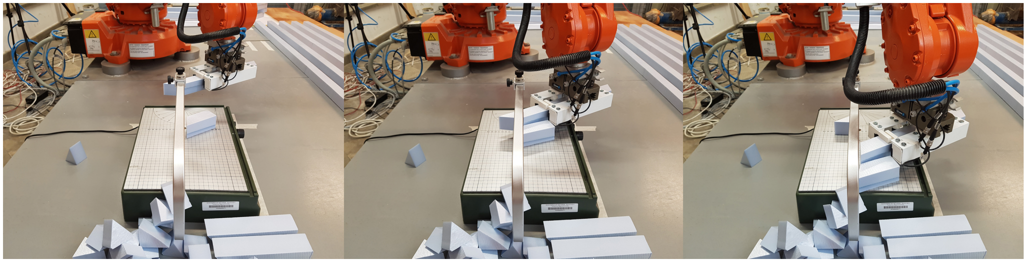


Figure 11
Steps of robotic cutting process using the hot-wire cutter

length as well as the available working area of the laboratory. Towards this direction, attention was given on the right positioning of available timber members (containers) to be inside the range of robot reach length and on the appropriate placing of circular saw in order to avoid collision with timber members but also to effectively cut the members in specific lengths and angles. Also, attention was given on the collision of timber members with the robot itself and with the structure under construction (Figure 7).

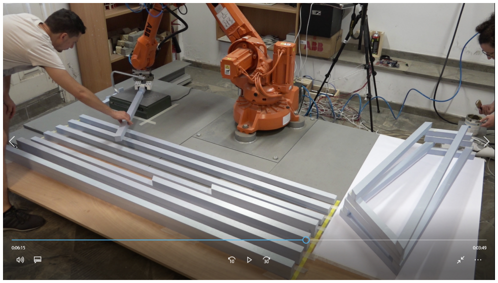


Figure 12
Assistance from the manufacturer during cutting process

Towards this direction, a feasible design solution of a structural component derived from the multi-objective design optimization process was selected and further investigated, focusing on its capacity to be executed by the available industrial robot and within the working area in actual scale. This allows pre-control and pre-testing of construction sequence as well as enables drawbacks and limitations to be observed.

The simulation of robot is achieved by using the Taco ABB [5], a plug-in applied for offline programming simulation of ABB industrial robots for Grasshopper (plug-in in Rhino). Final output is the generation of a Rapid program, read by the ABB controller IRC5 that is used to execute the robotic movement in each case. In addition to this, custom commands controlling the opening and closing of the gripper are added to the algorithm. In total, the overall behavior of the robot includes pick the available material, cut using the saw and finally placing in the appropriate position on the structural component. This is done in continues single toolpath that includes 15-17 targets, depending on the construction sequence and type of timber member. Also, the algorithm involves waiting time period in order to give the necessary time to the manufacturers to assists the robot during the process or to allow enough time to the manufacturers to proceed more effectively with the assistive of working tasks like gluing and repositioning of the leftover timber/container for next robotic execution (Figure8).

Automated construction process

The fabrication in actual scale is conducted in the robotic construction research laboratory (directed by the author), which is equipped with an industrial ABB robot, model IRB2600-20/1.65. The robotic arm is used for cutting and assembling each timber beam in the correct position. In this research a custom-made end-effector gripper tool mounted on the edge of the robotic arm is used for material handling. As it has been already stated, in the final phase of this ongoing research where the cutting of timber material will be executed, a circular saw will be used (Figure 9).

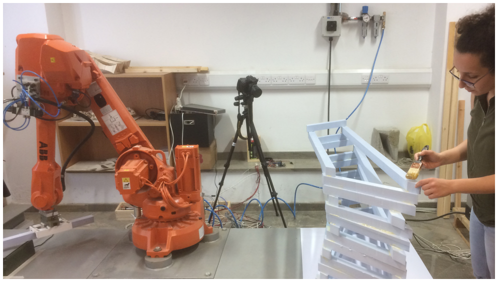
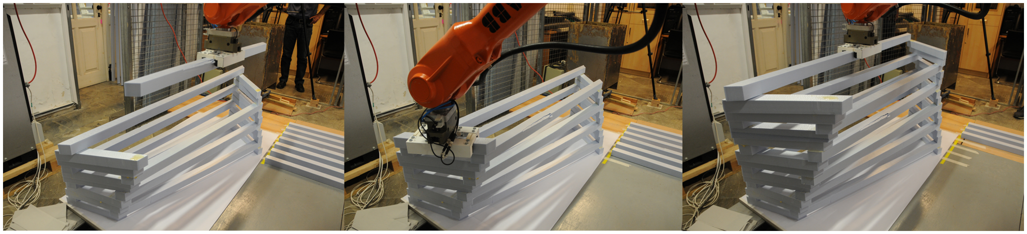


Figure 13
Gluing by the manufacturer

However, in this phase of experimentation where foam material is applied, the robotic demonstration involves the use of a vertical hot-wire cutter. All the other automated principles and set-up configurations that are involved in the construction process remain the same, including size and behavior of custom-made gripper, toolpath trajectory, position of available timbers (containers) and assembly

Figure 14
Steps in the process of structural components layering

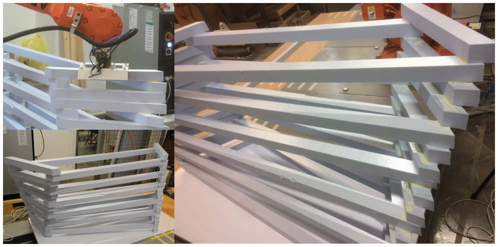


logic. Hence, following paragraphs describe the process through the use of rods made of foam material and include three main steps: a. pick the rod with the appropriate length from the material container, b. place the rod in the right angle to the vertical hot-wire machine for cutting in both edges, and c. assembly the appropriate shape of rod in the structure.

Analytically, in the first step, the robot picks the appropriate rod from the material container. The choice of suitable rod is based on the dimensions of the existing leftover rods and the dimension of the next rod to be placed (Figure 10).

In the second step, the robot places the rod in the right angle for cutting in both edges of the structural component keeping the cutting machine in constant direction XZ (Figure 11). In this step, the manufacturer assists the robot in cases where very long beams are processed, by holding the remaining material after is cut (Figure 12). In parallel, the manufacturer is responsible to replace the leftover material in the right position for next execution.

Figure 15
Final prototype in 1:1 scale



Then, the robotic arm locates and assembles precisely the rod in the appropriate position, a last robotic action that follows inspection and gluing by the manufacturer using fast curing adhesive (Figure 13). Figure 14 demonstrates selected layers of sequential construction and figure 15 shows the final prototype in 1:1 scale.

CONCLUSIONS

Preliminary results of the robotic construction of the timber structure in actual scale show the feasibility of the process especially in cases where the complexity of design demands the use of advanced tools and mechanisms that move beyond conventional design and construction processes. Particularly, the integration of multi-objective design optimization with the robotic construction as well as the assessment of solutions and the selection of the best fitting ones, attempt to established an active and close collaboration between experimental and conventional design and construction processes. Moreover, results of optimization and then the selection of the best possible design that can be physically realized, attempts to give an understanding and promote awareness in regard to the way solutions can be evaluated and then materialized, aiming at sustainable construction. Within this frame, the minimization of cost and material waste is taken into consideration aiming at low environmental impact solutions. Furthermore, the transferring of information derived from the digital investigation to the physical execution and then the realization of product in actual scale might open the discussion in regard to the role of integrated computational design and robotic fabrication as mechanisms introduced in the wider area of AEC industry.

Further work will be concentrated on the physical construction of the entire structure as a pilot study that might open the ground for diversified and more complex implementations of advanced computational design and robotic fabrication tools in the construction industry. Nevertheless, the complexity of the tasks involved is integrally connected with the demand for more active collaboration between robots and manufacturers during the workflow procedure. This is also an area of investigation that requires further attention, especially towards a productive and close collaboration between those two agents that influence construction process.

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