Design-static analysis and environmental assessment investigation based on a kinetic formwork-driven by digital fabrication principles

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This research focuses on design-static analysis and environmental assessment procedures that are based on the idea of a flexible kinetic formwork used as the automated mechanism for the production of bricks for porous wall structures. A key aspect of this investigation is the Life Cycle Assessment (LCA) analysis study that is applied in order to achieve, in parallel with the automated procedure, the sustainable potential of the products. For this purpose, the design and construction flexibility of the product is taken into account from the early design decision making stage by examining different sizes of bricks under fabrication including massive or porous ones in order to test their design and static performance, aiming to adapt their shape in multiple functional and environmental scenarios. In parallel, the LCA impact of the given design scenarios are taken into consideration, again from the early design phase, and include, among other objectives, material minimization, less environmental impact of building materials and less energy consumption based on the proposed digital fabrication technology. This is examined by comparing digital design and robotic automated results using three types of ecological materials.

Keywords: *Sustainable design, LCA analysis, custom-made end-effector tool, kinetic formwork, brick wall, robotic manufacturing*

INTRODUCTION

Currently, the rapid development of digital design and fabrication tools allow a more thorough and comprehensive control over design intentions and later on over the construction of any building part in actual scale. This prevents possible failures and misfits that are the result of direct design implementation of ideas by workers during the construction stage and after the design is completed (Kontovourkis and Konatzii, 2016). This is done on a case to case base depending on each construction scenario under implementation. For instance, in case of brickworks, a conventional design and construction procedure, this new paradigm shift and especially the dislocating aids as well as the robotic and automated processes are in a continues development (Bock, 2008). Moreover, the need for similar mechanisms is increased due to their accuracy, flexibility and fully programmable nature that make them to be superior to conventional construction approaches. In most of the cases, indicated tasks of robotic construction are executed by custom-made end-effector tools. Within this frame, apart from brick manufacturing, cases where kinetic formworks or customized formworks for casting free-form geometries are applied (Stavric and Kaftan, 2012), aiming to achieve minimum time of fabrication (Kristensen et al, 2013).

In an example of robotic implementation for wall construction, a custom-made end-effector tool fabricates the rebars and the formwork before concrete pouring occurred and this achieves to minimize wall thickness and to improve the environmental performance of a conventional wall (Hack et al, 2017). Moreover, in an attempt to mitigate material waste and to minimize environmental impact, researchers at ETH Zurich (Oesterle, 2012) have developed a flexible mould where hot wax is cast onto and then is solidified to serve as temporary concrete formwork. Later on, the wax is melted down and re-used based on the same procedure.

Nowadays, possibilities to incorporate environmental impact assessment criteria within digital design, fabrication and construction procedures have an increased trend. This becomes more significant due to the fact that the manufacturing of building materials represents 5-10% of the global CO2 emissions (Habert et al, 2012). In order to overcome this, digital design and fabrication are introduced, aiming at material usage minimization (Agustí-Juan and Habert, 2017; Agustí -Juan et al, 2017) and selection of construction materials with low carbon emissions. An example of such material is the adobe that is used for the production of bricks. Adobe is widely considered, both in Cyprus (Illampas et al, 2011) and world-

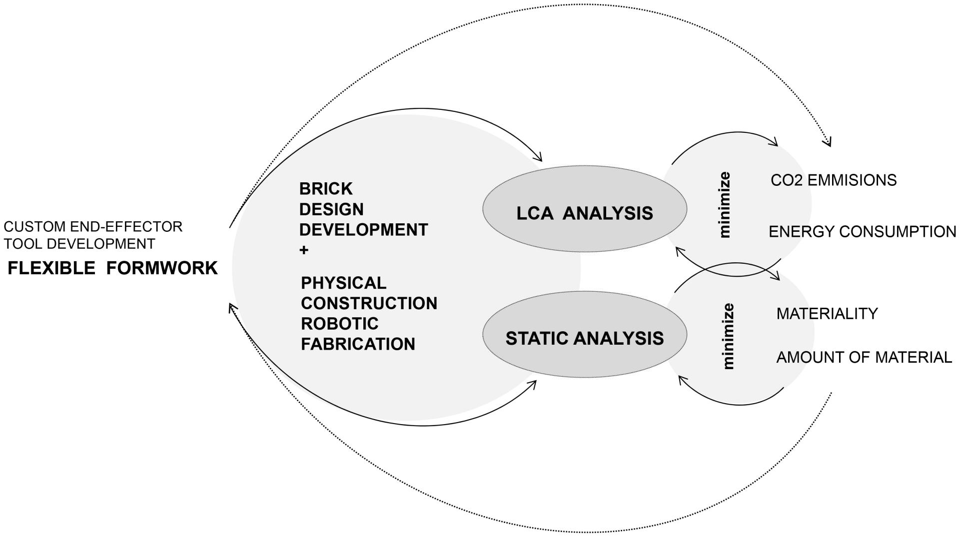


Figure 1
Diagram of suggested methodology

wide, as an eco-friendly, reusable, energy and cost-efficient construction material (Pacheco-Torgal and Jalali, 2012).

This research examines further the environmental impact of customized bricks design and production using a robotic construction procedure. More specifically, a flexible custom-made end-effector tool is applied to fabricate the custom bricks according to predefined parameters that lay within two equality important pillars, on the one hand design-static analysis aiming at the minimization of material, which is connected with material waste, and on the other hand LCA analysis that include materiality, CO2 emission and energy consumption during the fabrication procedure (Figure 1).

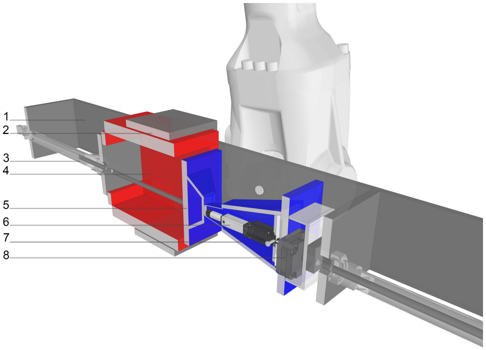


Figure 2
Section of the end-effector model

CUSTOM-MADE END-EFFECTOR TOOL DESIGN AND DEVELOPMENT

In this part of the paper, a thorough explanation in regard to the design and production of the custom-made end-effector tool is demonstrated. This is done in accordance with the design and static analysis results of customized brick elements that are compared with each other. Also, is done in accordance with the process of LCA assessment, which depends on the building material, the brick size and the fabrication method.

The custom-made end-effector tool is developed in order to allow automated production of custom bricks using pressed mechanism. A formwork consisting of two parts is developed, which press and formulates the material towards brick production. According to the scenario, for the automatic production of bricks, a flexible mechanism is developed, which is mounted on an aluminium base (1,2) at the edge of the robotic arm. The end-effector tool consists of a pressure system and a formwork that is capable of adapting to multiple brick shapes, producing bricks based on different desired morphologies. The final result is the production of a porous or non-porous masonry system based on the design scenario.

Specifically, the investigated procedure includes three steps: pressure, demolding, and positioning. At this point it should be noted that the process is carried out in the workshop whereas bricks and parts of masonry system are produced, and then are transferred to the site for assembling. During the production scenario, bricks are laid on a flat surface to complete the maturing stage of the building material. In the production scenario of masonry parts, the bricks could be demolded and stacked simultaneously on top of each other, in a way that bricks and parts of masonry can be produced in parallel.

The kinetic formwork system consists of two automated mechanisms. The first mechanism is responsible for the compression of the material using two pneumatic pistons (3). At the ends of the pistons, the two members consisting the formwork are adjusted on each side as shown in (Figure 2). One part of the formwork is static (5) and one is flexible. Both shapes are determined and adapted according to different hole sizes and thickness of the bricks under production. The flexible part (7) of the formwork consists of three extruded pieces that can be expanded and rotated to produce different results. The shape of each brick is defined in the design exploration stage, where number of criteria like shading area, orientation of masonry system and minimum use of construction material in each scenario are taken into account.

The typologies of structural elements are defined

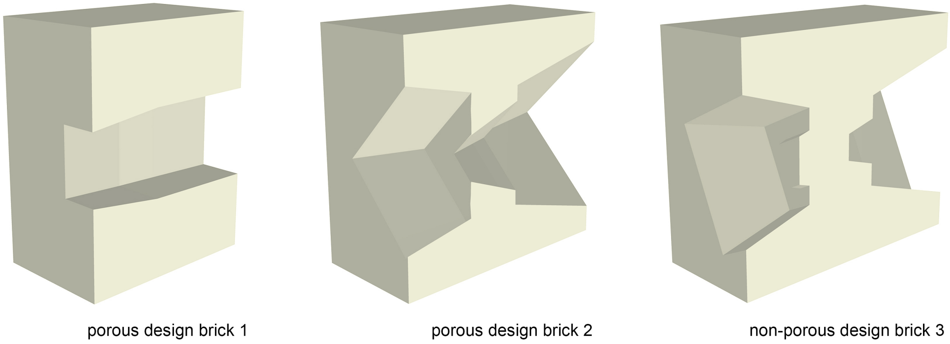


Figure 3
Sections of three representative brick geometries

as porous and non-porous. The final results of porous structural elements vary in their thickness, the morphology and the rotation angle of their openings. In terms of non-porous structural elements, these vary only in their thickness dimension (Figure 3).

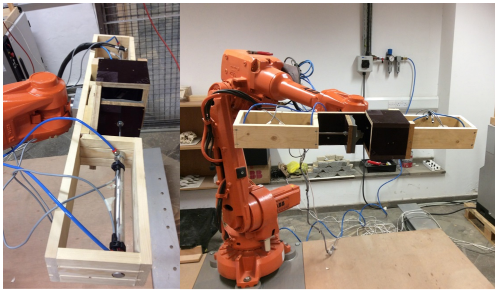


Figure 4
Physical model of the custom-made end-effector tool mounted on the robotic arm

An individual brick is produced each time and placed on working-site according to a motion planning process that is executed by the robotic arm. The robotic procedure is simulated on HAL [1] (plug-in for Grasshopper) [2] and the robotic motion is executed through Robot Studio 6.0 [3]. The task programming consists of the robotic motion control, defining the target points for bricks positioning, the actuation of the formwork mechanism and the calculated time duration for pressure. The whole procedure is repeated according to the necessary number of bricks under production. A physical model is developed in order to execute the whole procedure in real time (Figure 4).

The automated control of the kinetic formwork tool is determined by an algorithm responsible for activating the pneumatic pistons, the linear actuator (6) and the rotary motor (8). Through a series of algorithmic rules, the function of tool is determined as follows: after the robot reaches a specific position, and after the construction material is poured into the square tube, the linear actuator reaches its desired length and then the pneumatic piston is activated to move the flexible part of the kinetic formwork. If a rotated opening is required as end result, after the linear actuator is activated, the appropriate rotation is performed by the rotary motor.

In the next step, by moving the static part of the formwork, the pneumatic piston is activated to compress the material, accelerating in parallel specific formatting task. The two pistons are pressed for 30 seconds. Then, the piston 1 is deactivated at a smooth speed to transfer the produced component out of the square tube. Finally, for demolding, the piston 2 is also deactivated. Finally, each brick is placed at the desired target point by the robotic arm (Figure 5).

The pneumatic pistons, the linear actuator and the rotary motor are controlled by an algorithm developed in Robot Studio 6.0 [3] software in conjunction with the Arduino digital platform [4] for analogue control. The pneumatic pistons are activated and deactivated by sensors. In each piston, two electronic sensors at both edges, provide information to the code in order to advance the procedure as this is pre-defined. The sensor operates binary, where at its right part, informs whether the piston is actuated and hence the formwork. Respectively, at its left part indicates any deactivation of the piston-formwork.

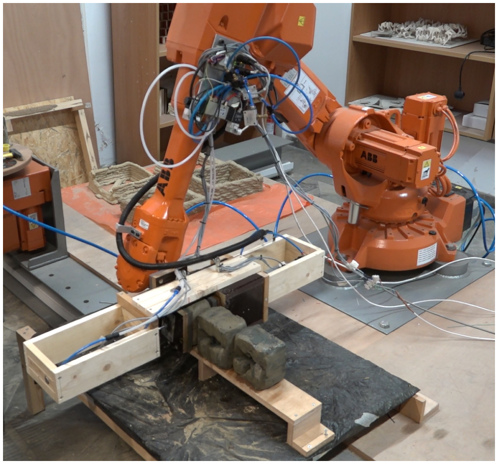


Figure 5
Produced bricks in series

DESIGN-STATIC ANALYSIS AND LCA ASSESSMENT OF BRICK ELEMENTS

As it has been stated, the brick design is based on a flexible custom-made extrusion mechanism that is digitally activated to produce the desired result. Based on a number of actuator, the activation scenarios produce several types of bricks with maximum or minimum size of openings from 2x2cm to 7x7cm, respectively. Also, there is a massive type of brick that is produced by the extrusion mechanism through a partial subtraction of material. In all cases, a rotation of subtracted volume can be activated in selected degrees. The size of formwork and the flexible morphology allow material minimization and further investigation of static behavior as well as response to environmental criteria.

For structural reasons and optimal static behaviour of the entire masonry system under production, a cross-sectional arrangement logic of the vertical joints of the bricks is followed. At the further stage of research, for the compressive strength of the entire masonry, the possible use of mortar for the connection of the bricks and their waterproofing will be taken into account.

The numerical static analysis of three different types of building materials: adobe, concrete and a hybrid mixture of clay and cement, are performed using ABAQUS CAE [5]. The selected materials have different static behaviour and this, in turn, influences their environmental characteristics.

Numerical static analysis

In the linear analysis stage of investigation, the load applied is calculated by the equation $P = F / A$, where P is the result of the total load (N) that exert force F on the structural elements on the mounting base of typical masonry with 3m height divided by surface area A of the loads being carried. The calculated pressure load for adobe brick masonry is 42,241.13 Pa, for concrete brick masonry 84,482.7 Pa and for clay with cement addition brick masonry 63,361.695 Pa. Based on the experiments made in the laboratory, the concrete is the heaviest of the three materials under investigation, and for this reason the pressure exerted is the highest.

Results of linear static analysis of brick typologies

The results of the linear static analysis focus on Von Mises, U22 and S22 maximum values. More specifically, the Von Mises criterion suggests that the performance of a ductile material starts when the force reaches a critical value. U22 is the displacement value that is caused on z-axis, perpendicular to the brick opening, after the uniformly distributed load is applied to the top surface area of the brick. It is measured in millimeters (mm) and it determines a maximum permissible value according to the brick strength. S22 is the compressive stress caused on the z-axis and perpendicularly to the opening of the brick, after the evenly distributed load is applied to the top surface area of the brick. It is measured in Pa and is differentiated on the basis of the materiality and the type as well as the maximum permissible value of the percentage of the brick's openings. The displacement and the stress on the z-axis are considered to be the most critical values because they act parallel to the load pressure and define the elastic-tension limits of the brick geometry.

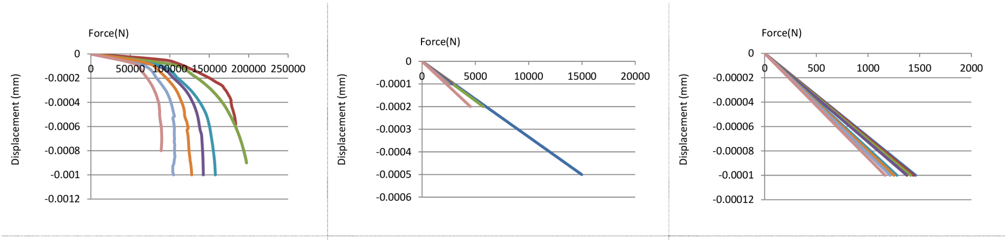
For adobe, concrete and clay materials a number of graphs have been developed based on the results extracted from the linear static behaviour analysis. The values for Von Mises, displacement and compressive stress are presented in relation to the bricks' opening size and its degree of rotation.

For the adobe material, through the graphical representation of Von Mises (Pa) in accordance with the typology of each scenario, it is observed that there is difference in values for bricks with small openings relative to the bricks with large openings. In scenario 1, the difference in values is almost double, in scenario 2 this difference is smaller and in scenario 2 is decreased further. For brick with small and large openings, while the rotation degree of the opening is increased, the Von Mises value is also increased.

According to the results of analysis, between adobe and concrete materials, higher values occur in the concrete due to its static behavior. In both cases, maximum values for compressive stress in z-axis and rotation angle 15 degrees are shown. In addition, geometries with minimum opening have lowest displacement values. The largest displacement is found in cases where highest values of rotation angle occurs. With regard to compressive stress, the maximum value in most of the cases for each scenario, is observed in 15 degrees of rotation angle of the opening.

The static behaviour of the mixture consists of soil and cement is between the behaviour of adobe and concrete materials. The values extracted from the linear static analysis of the clay approximate more to the concrete values. Also, the Von Mises, U22, and S22 maximum values in all scenarios are observed in same morphological typologies as the ones of adobe material. This concludes that they have the same static behaviour with adobe material but with more resistance.

Specifically, in the first phase, the static analysis of bricks shows that displacement and compressive stress values are below permissible. Between the cases of small and large openings, the pressure values are larger almost twice as well as the values in the z-axis. In all types of bricks that have been tested, Von Mises and displacement values are increased depending on the degree of rotation angle. Additionally, in scenario 1 and 2 for adobe bricks the compressive stress values in 15 degrees of rotation is increased, and then is decreased in 25 and 45 degrees of rotation. In scenario 3, the maximum compressive stress value is observed in the case of 25 degrees of



Material: Concrete
Porous design brick 1

Material: Adobe
Porous design brick 2

Material: Clay
Non-Porous design brick 3

Figure 6
Force – displacement graphs for the three materials

rotation. Finally, in the maximum openings with 25 degree of rotation, the compressive stress in z-axis is also strongly increased.

Results of non-linear static analysis of brick - force compression

In order to investigate the bricks' strength, a displacement force is uniformly distributed over the upper surface area of the brick. This allows measurement of the maximum value that can be applied to each brick until is cracked and crushed.

The force-displacement diagrams are derived as the sum of the reaction force that are uniformly applied to the nodes of the mesh geometry on the bottom surface area of the brick, divided by the displacement value occurs at a central node of the top surface. After the analysis of the models, these values are used to produce the graphs shown in Figure 6. Graphs show the force-displacement values for each scenario incorporating all cases, for large and small openings and for 0, 15, 25, 45 degrees of rotation angle of openings.

From each graph, the maximum force that can be applied to the computer model under compression is derived. By dividing this with the surface area where the force is exercised, the compressive strength is calculated. Practically, at the point where the maximum force is applied, it is considered that the brick is crushed and its plastic behavior ceases.

For the concrete material, a curve graph from the center of the axes is observed, while for adobe and clay the shape of graphs are straight lines from the center of the axes. It is concluded that materials have different static behaviour, where the concrete has larger compressive strength and therefore plastic behavior compared to the other two materials.

For concrete bricks, the minimum characteristic crush strength is 10.241 MPa and the maximum is 34.537 MPa. Values up to 30 MPa are permissible, so those models above the threshold are under investigation, in terms of their morphology and the percentage of their opening relative to their total volume. The maximum value has been recorded in case of non-porous brick, combined with 15 degrees rotation of extruded volume).

For the adobe material case, the minimum value of compressive strength is 0.274 MPa and the maximum value is 1.7 MPa. Any case exceeding 1 MPa based on the Eurocode 6, do not fall within the permissible limits. The maximum value is observed in case of small opening without any rotation).

In case of clay with the addition of cement, the range of compressive strength values is from 0.15 MPa to 1.30 MPa. The rules of Eurocode 6 for adobe materials are applied in this case as well, where the permissible compressive strength value is up to 1

Table 1
Results of LCA analysis for CO2 emissions and energy consumption throughout the life-cycle of masonry for the three different construction materials

Sector on investigation		**Global warming (kg CO2e)**			**Primary energy (MJ)**		
		Adobe	**Concrete C20/25**	**Clay (soil, cement)**	**Adobe**	**Concrete C20/25**	**Clay (soil, cement)**
A1-A3	Construction Materials	3,71E1	4,89E1	3,23E1	3,83E2	2,72E2	9,86E1
A4	Transportation to site	1,34E0	2,41E0	1,46E0	1,97E1	3,55E1	2,23E1
A5	Construction/installation process	2,65E1	2,64E1	2,64E1	4,87E2	4,86E2	4,86E2
C1-C4	Deconstruction	7,86E-1	1,5E0	2,65E0	1,63E1	3,13E1	7,8E1
D	External impacts (not included in totals)	-3,15E-3	-6,31E-3	-3,25E-1	-5,29E-2	-3,23E-2	-4,29E0
	Total	**6,56E1**	**7,92E1**	**6,27E1**	**9,07E2**	**8,25E2**	**6,85E2**

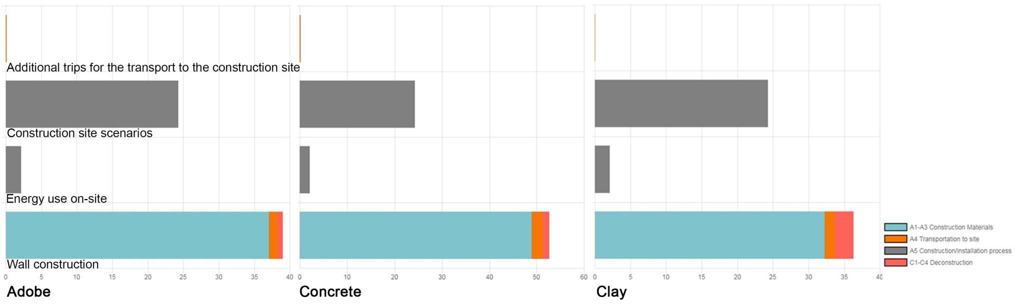


Figure 7
LCA charts for the three construction materials at the construction and life-cycle stages of the structure

MPa. The maximum value is observed in the case 2a0 (small opening, no opening) and the minimum value in the case of large opening and 15 degrees rotation of opening.

In a next step, the investigation focuses on the analysis of the design results according to the above mentioned materials, their environmental impact, as well as the energy consumption during the digital fabrication process. Within this frame, a comprehensive comparison of results derived from the selected construction materials is conducted in One click LCA [6] software for LCA analysis. Metrical results from LCA and LCI databases as well as several calculations show material cases with the best performance in accordance with CO2 emission percentage, the minimum amount of material waste and also the amount of energy that is used by the industrial robot, the custom-made end-effector mechanism and the assisted technology, in order to execute a wall section in actual scale. In the overall process, the flexible kinetic formwork and the type of material used, play a significant role for well performed results in terms of their design-static and environmental assessment performance.

Results of LCA analysis

Quantitative results regarding the environmental impact on the life span of a section of 3m x 1m x 0.08m masonry wall are derived from the One click LCA software [6] that contains a large EPD database. The building life-cycle assessment is based on the European Standard EN 15978. The above mentioned LCA software covers life cycle stages from cradle to grave and can be separated into product stage, construction process, use stage, operational energy, and end of life. In the construction process, the calculated electrical energy required for the investigated masonry for one hour of work using the robotic arm can be introduced. Specifically, this is the sum of the electricity consumed by the robotic arm, the computer involved in the process and the energy consumed by the mechanisms incorporated in the end-effector tool, which are the pneumatic pistons, the linear actuators and the rotary motor. The total energy consumed in 2.39 kWh. In addition, apart from the data related to the electricity required as mentioned above, data related to the climate of the country where this is carried out are introduced, as well as data related to the energy consumed to transport the finished masonry to the construction site by truck.

The amount of carbon emitted into the atmosphere through the life-cycle of the masonry is a result of software analysis, taking into account the different values for each material due to their different material composition. The various stages in which the results of global warming effects (kg CO2) are reported, are the results of construction material selection, its transportation from the factory to the construction laboratory, its construction process and transportation to the site (See Table 1 of results).

The CO2 emission values for all processes in case of adobe material is 6.56e1 kg CO2, for concrete C20/25 is 7.82e1 kg CO2 and for clay composed by soil and cement is 6.27 e1 kg CO2 (Table 1).

The highest values are observed in the case of concrete, where the material used for its constitution have the most emissions, as well as for its demolition at the end of life of masonry (Figure 7). The values shown in the table for adobe and clay are smaller than the ones for concrete material and therefore, are more environmental friendly options. The reduced emissions of these two materials are mainly due to the way the structural components are maturing by the drying method and not by the use of thermal hob. The method of drying is a natural maturing approach of materials, and on top of this allows and facilitates the demolition process of masonry, as well as the reuse of the brick raw material. In addition, with the proposed method of masonry construction, the material waste is zero and the quantity of mixture required to produce the bricks is accurately calculated.

DISCUSSION

The proposed manufacturing process has the potential to produce individual bricks or brick masonry systems with different morphologies due to the ability of kinetic flexible formwork to adapt its shape according to the design under investigation. Time and material are saved during the production process of bricks with or without openings, and in parallel their static performance is taken into account. The aim is to use the minimum material for construction, according to the required final design results based on various parameters. This offers the opportunity for an ecological and environmental friendly construction approach in architecture. The exploration stage of CO2 emissions in the atmosphere and the selection stage of low-energy manufacturing are necessary parts towards such direction of architectural and construction studies.

In this investigation, the construction approach promotes the minimal use of construction material aiming at zero material waste during the process. The static exploration of the three materials aims to examine their strength limits, where the concrete C20/25 proves to be more durable than the adobe and clay material. On the contrary, adobe and clay are more environmental friendly, with lower CO2 emissions. Regarding the accuracy of the static analysis of different brick morphologies and materials, real stress tests of physical prototypes that are produced using the suggested end-effector tool can be performed in a further stage of experimentation in order to evaluate the results of computer analysis.

CONCLUSION

In conclusion, by examining the design and construction development procedure of custom adobe bricks in accordance with their static analysis and LCA assessment, an in depth knowledge in regard to the potential for introducing architectural strategies that take into account environmental criteria throughout the process will be acquired. More specifically, by using ecological materials, by minimizing material volume, material waste and energy consumption as well as by minimizing CO2 emissions, a low environmental impact and improvement of life-cycle of brick structures can be achieved. The results of suggested process can show the potential of innovative fabrication methods to be promoted in cases were actual scale construction objectives and complex design scenarios are examined. At the same time, this can improve industrial evolution towards more ecological friendly materials and processes.

Further work towards the refinement of the end-effector mechanisms and the physical production of bricks using the suggested materials will demonstrate the effectiveness of the suggested flexible kinetic formwork to achieve accurate results using data derived from static and LCA analysis investigation.

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