Chapter 13

3D Printing Technology Within a Regenerative Construction Framework

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Abstract 3D printing (3DP) is considered as a promising technology in construction industry due to a number of advantages that among others include fast and accurate construction, as well as elimination of formworks and material waste. Although 3DP technology is at an early stage of adoption in construction industry, its positive contribution towards a more sustainable construction approach is well acknowledged. Nevertheless, various constraints prevent its further establishment that include among others lack of knowledge among construction actors, premature investigation regarding techniques and material properties, as well as limited work on design optimization, cost, and environmental impact performance analysis. This chapter aims to contribute towards this direction by analysing the 3DP cost and environmental impact of a number of brick units, forming walls with different geometrical complexity. Results show that while walls' complexity is increased, there are no significant changes in cost, global warming and primary energy consumption. In contrast, through the application of traditional construction processes, the result values would have been increased proportionally to the degree of complexity. This proves the potential of applying the 3DP technique to the construction of any structure at no extra cost and without increasing the environmental impact. Also, it provides an indication of its potential to be included within a regenerative construction framework.

Keywords Sustainable 3DP · Design optimization · Cost · Environmental impact · Material minimization · Design complexity

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13.1 Introduction

Nowadays, 3D printing (3DP) in large scale is recognized as an emerging technology that could potentially be applied in the construction industry, bringing about improvements, as well as offering opportunities, towards a more sustainable future. In particular, it can be implemented towards material waste minimization and reduction of time and effort during construction. More specifically, 3DP can positively contribute towards effective material waste management due to its ability to use only the required quantity of materials by avoiding the application of moulds or formwork (Buswell et al., 2007; Camacho et al., 2017; De Schutter et al., 2018). Also, it can contribute towards construction time reduction (Kontovourkis & Tryfonos, 2020), especially in cases of non-conventional and complex designs, where the use of standard construction techniques would be less economically advantageous (Buswell et al., 2005; De Schutter et al., 2018).

The inevitable need for automation in the construction industry through the application of 3DP technology brings a number of additional advantages such as its integration into a seamless workflow, incorporating design optimization techniques, for instance topology optimization. This can be applied during the design stage in order to achieve material and cost reduction, ensuring at the same time the structural efficiency of the systems. Geometrical correlations can be found in the anatomy of natural organisms such as bones, where material is distributed only in areas that is needed, similar to the principles discussed in biomimetics (Vincent, 2014). Recently, direct links with 3DP can be found that offer comprehensive design to fabrication solutions. Apart from environmental impact reduction benefits, these can achieve improvements in regard to architectural design and construction approaches (Camacho et al., 2018).

This chapter discusses the capability of 3DP technology to contribute towards a comprehensive regenerative construction framework, in which design optimization and sustainable 3DP are integrated and have a key role. In particular, this study emphasizes the need of using the specific technology in cases of increased geometrical complexity, where cost and environmental impact reduction is important to be considered. This might provide more affordable solutions in comparison to traditional construction approaches. A number of brick units are used as examples, which are derived from selected masonry walls with gradually increasing complexity. These are examined in terms of 3DP cost, carbon dioxide emissions and primary energy consumption. The purpose is to compare the results based on an incremental degree of complexity and discuss the possibility of using this technology in irregular shapes construction. At the same time, advantages that can bring to construction industry are discussed.

Following part of the chapter provides a literature review in this area of research. Then, the research method is presented, which outlines the regenerative construction framework in general and the sustainable 3DP procedure in particular. This is followed by experimental results and discussion. In the last part of the chapter conclusions are drawn.

13.2 Literature Review

In the last few decades, the potential application of 3DP technology in construction industry (Wu et al., 2016) has been interrelated with other investigations like environmental impact, productivity and cost analysis, as well as topology optimization. Also, the technology has been discussed and explored, emphasizing in parallel its application importance. Several research works related to technology readiness and material properties used for 3DP were conducted, focusing either on the application of 3DP techniques (Ngo et al., 2018) or on the material properties related to their workability and buildability (Long et al., 2019). Moreover, other examples were focused on the application of environmentally friendly and recyclable materials like clay and earth-based in comparison with cement-based ones, emphasizing investigation into their mechanical properties (Perrot et al., 2018). In addition, 3DP works were discussed in terms of their environmental impact and cost analysis, particularly related to the application of scale, process cost, construction time and material type (Wu et al., 2016). Also, works were conducted by following economic analysis, in conjunction with environmental analysis of composite-type 3DP materials (De Schutter et al., 2018).

In the category of structural optimization associated with 3DP techniques, main emphasis was given to small- to medium-scale examples. In this case, topology optimization was used as form-finding technique, and then 3DP technique was implemented for the physical production of shapes. Among others, examples include the work on the production of steel nodes used in the construction of tensegrity structures (Ren & Galjaard, 2015) and the work on the design and fabrication of topologically optimized pedestrian bridges using large-scale 3DP (Yuan et al., 2018); also, the 3DP example of a spatial structure that was examined in terms of its structural performance using topology optimization principles (Chen et al., 2019); finally, the work on the optimization and 3DP building elements based on infill patterns using clay and earth-based materials (Kontovourkis et al., 2019a).

Despite the already existing work, the adoption of 3DP in the wider construction industry is still at an early stage due to a number of reasons. These include, apart from the necessity for improving technology and materials, the lack of knowledge regarding its potential benefits that it can bring to the construction industry towards a more sustainable future (Villoria Sáez et al., 2019).

In order to provide an overview on this direction, this chapter attempts to analyse the 3DP cost and environmental impact of selected masonry walls with different level of geometrical complexity. The aim is to examine the sustainable potential of 3DP used in complex shape production through the comparison of results. Also, to identify future benefits in contrast to traditional construction techniques. Finally, to discuss possible contribution towards the development of a regenerative construction framework, where design optimization and sustainable 3DP will mutually interact with each other, providing more sustainable construction solutions. This approach is based on design optimization, aiming at reducing material, and on sustainable 3D printing of solutions, aiming at reducing cost, global warming potential

and primary energy consumption. At the same time, 3DP and accompanied results aspire to positively affect the environment and to contribute and maintain a healthier state and evolvement of social and ecological systems (Brown & Haselsteiner, 2018).

13.3 Research Method

The suggested regenerative construction framework consists of two equally significant parts, the design optimization and the sustainable 3DP of an initial geometry. The design optimization incorporates topology optimization and structural analysis, aiming at redesigning a solid geometry in order to achieve material reduction through an infill pattern for 3DP execution. The sustainable 3DP involves 3DP pre-processing, where the cost, the global warming and the primary energy are calculated. Then, 3DP execution, where the infill geometry is physically produced (see Fig. 13.1).

Analytically, in design optimization part, the topology optimization of an initial solid geometry is applied, aiming at material reduction but also at maximization of its stiffness. Towards this direction, an in-house approach based on infill design and optimization is proposed in order to achieve the 3DP of irregular and complex shapes with surface overhang limitations, controlling at the same time the 3DP tool-path. In particular, two main steps are incorporated in this approach. First, material minimization based on topology optimization (TO) principles using bio-directional evolutionary structural optimization (BESO) (Li et al., 2018) in the parametric design environment of Grasshopper (2020) (Kontovourkis et al., 2019a, b). This is done in order to gradually reduce material from a solid to perforated geometry with variety of infill patterns thickness according to structural efficiency constraints. Second, further structural analysis of results using the Finite Elements Analysis (FEA) software ABAQUS CAE (2020) in order to evaluate compressive strength with the aim of being within the allowable limits.

Fig. 13.1 Diagrammatic representation of the suggested regenerative construction framework that involves design optimization and sustainable 3DP

In sustainable 3DP part, the performance analysis of a derived infill geometry is suggested, aiming at identifying indicators that contribute towards a comprehensive sustainable 3DP approach. Among others, these include 3DP cost and environmental impact analysis. The cost analysis incorporates the cost values for the 3DP extruder tool manufacturing and for the overall 3DP construction procedure. The latter is the sum of the cost of the energy consumed during 3DP construction, the labour cost and the cost of material applied. The environmental impact analysis examines the carbon dioxide emissions and the primary energy consumption performance of selected designs. In this part, life cycle analysis (LCA) is conducted, which considers construction materials (A1-A3), transportation to site (A4), construction/installation process (A5) and deconstruction (C1-C4). The global warming (kg CO₂e) and primary energy consumption (MJ) values are obtained through the use of OneClick LCA software (2020).

In this chapter, the suggested regenerative construction framework is tested through an experiment that deals with the sustainable 3DP performance analysis of selected prefabricated brick units derived from walls with different complexity level (WCL). Specifically, four (4) walls are selected for experimentation, starting with a regular one and moving on to irregular ones with different degrees of complexity. The aim is to compare the results and draw conclusions regarding the effects that the variability in design can bring to the 3DP performance of brick units.

Although the design optimization stage has not been conducted in this chapter, the potential of material reduction is discussed. The aim is to enhance the importance of the regenerative construction diagram as a whole, not only in terms of sustainable 3DP but also in relation to design optimization. Finally, a theoretical discussion on the possible correlation between similar results derived through the traditional construction approach is drawn, in order to stress the importance of using emerging technologies versus traditional ones.

13.4 Experimental Results

The geometrical parameters of the selected walls are described in Table 13.1. These examples shall be identified as WCL that is the acronym of wall complexity level. Their measurable information includes walls' base and top lines that control their shape, base and top width, height, overall volume and number of bricks. The selection of specific parameters achieves their gradual shape transformation from a regular wall to a complex one, increasing in this way their degree of complexity. Keeping the same overall volume, the WCL1 refers to a regular wall with linear base and top. The WCL2 is formulated on the basis of two identical and symmetrical curves, maintaining the same thickness throughout its height. The WCL 3 differs in terms of its base and top thickness, while the WCL4 is an asymmetric wall with thickness fluctuating from the base to the top (see Table 13.1).

In all selected walls, the same number of prefabricated brick units are identified, which are located on the same wall's position. Eight (8) brick units for each wall are

Table 13.1 Overall geometrical parameters of the selected walls in relation to their degree of complexity (WCL1–WCL4)

Wall complexity level (WCL)	Base – top line	Overall dimensions (m)			Volume (m ³)	Bricks (Num.)
		Length	Base – top width	Height		
WCL1	Linear – linear	6.00	0.25–0.25	3.0	4.5	210
WCL2	Curvilinear – curvilinear	5.15	0.25–0.25	3.0	4.5	210
WCL3	Curvilinear – Curvilinear	4.60	0.35–0.20	3.0	4.5	210
WCL4	Curvilinear – Curvilinear	4.72	0.35–0.20	3.0	4.5	210

Fig. 13.2 Top: The selected four (4) walls with different degrees of complexity, identifying walls from regular (WCL1) to irregular (WCL4). Bottom: The selected eight (8) brick units on each wall (WCL1–WCL4)

selected for further sustainable 3DP performance analysis, which have specific 3DP characteristics (see Fig. 13.2).

These include the overhang angle in front and in back surface of the brick units (degrees), the brick volume (cm³) and the robotic 3D printing time (min). The latter is influenced by a series of input parameters that control 3D printing performance. This experiment considers an infill thickness of 24 mm for all brick units, using an extruder with 24 mm nozzle diameter, 1x3 hex grid infill density and 8 mm layer height. Also, 11 m/sec extrusion velocity and 7 m/sec base layer velocity are selected (explanation on 3DP input parameters can be found in Kontovourkis and Tryfonos (2020)).

In the case of WCL1, the 3DP characteristics are the same for all brick units. More specifically, the overhang angle in front and in back surface is measured at 0°, the brick volume at 12,413.25 cm³ and the robotic 3D printing time at 97.95 min. In the case of WCL2, the same overhang angle in front and in back surface is measured

at 0°; however, five (5) different brick volumes and five (5) different 3D printing times are observed. Their brick volume ranges between 12,686.99 cm³ and 12,700.32 cm³ for brick unit no. 5 to brick units no.1 and 6. The 3D printing time for the same brick units ranges between 100.11 min and 100.22 min. In the case of WCL3, although the overhang angle in front and in back surface for all brick units remains the same, this is measured at 1.43°. Also, eight (8) different brick volumes that range between 11,000.20 cm³ for brick unit no. 7 and 13,816.73 cm³ for brick unit no. 1 are observed. In addition, the 3D printing time measurements are different, ranging between 86.80 min for brick unit no. 7 and 109.03 min for brick unit no. 1. Finally, in the case of WCL4, completely different overhang angles in front and in back surface for each brick unit, as well as differences in their volumes and 3D printing times are observed. The characteristics of WCL4 are demonstrated in Table 13.2.

Figure 13.3 demonstrates the bricks variety in relation to the complexity level for each wall. As it can be observed, while in the example of WCL1, all brick units are identical in relation to their overhang angle in front and back surfaces, their brick volume and their 3D printing time, in the example of WCL4 each brick contains different values. This comparison between the walls identifies the different level of complexity and provides a measurable benchmark for discussing their 3DP performance in each case.

13.4.1 Design Optimization

As it has been stated in the section ‘Research method’ of this chapter, in this experiment, the design optimization that deals with topology optimization and structural analysis has not been conducted, due to the concentration of the present research in the sustainable 3DP aspect of the method. However, some important initial information related to this part of the regenerative construction framework are presented herein. The aim is to emphasize the significance of the geometrical results obtained

Table 13.2 Measurable geometrical and 3DP characteristics for each brick unit in the case of WCL4

Brick unit no.	Overhang anglefront – back (degrees)	Brick volume (cm ³)	Robotic 3D printing time (min)
1	3.02° – (–4.8°)	13,974.24	110.27
2	10.32° – (–13.38°)	13,945.62	110.05
3	0.47° – (–4.11°)	13,899.51	109.68
4	5.04° – (–7.27°)	12,700.27	100.22
5	9.59° – (–12.55°)	12,296.79	97.03
6	3.65° – (–5.67°)	11,818.64	93.26
7	10.45° – (–13.20°)	11,135.85	87.87
8	1.49° – (–3.18°)	10,878.73	85.84

Fig. 13.3 Graph that demonstrates the variety of bricks in relation to complexity level for each selected wall

through design optimization in relation to the sustainable 3DP performance of brick units.

Specifically, it is observed that the selected brick units in their initial design as solid geometry are at their maximum volumes, which implies the greatest compressive strength. In this case and under certain conditions, the results of sustainable 3DP analysis, which are related to 3DP cost and environmental impact are expected to be maximum. In addition, constraints might occur regarding the 3DP capability of brick units as solid geometries. On the other hand, brick units with infills allow effective 3DP execution, while at the same time their overall volume and weight are reduced. Despite the parallel decrease in compressive strength, this may be within the permissible limits above an infill pattern thickness according to the applied material. Thus, brick units with large infill thickness and material volume are more statically adequate due to their larger compressive strength compared to results where the thickness of their infill pattern is smaller.

Figure 13.4 and Table 13.3 display information related to the solid and infill volume in the case of brick unit no. 1 for all walls (WCL1-WCL4). In the case of 1x3 hex grid infill density and 24 mm infill thickness, as it has been indicated in previous paragraphs, the volume reduction ranges between 42% for WCL1 to 51% for WCL4. The results of infill geometry for all brick units and for each wall are taken into consideration and used in the next steps, which deals with the 3DP cost and environmental impact analysis.

Fig. 13.4 Solid geometry (Top) and Infill geometry (Bottom) of brick unit no. 1 for all selected walls

Table 13.3 Information related to the solid and infill volume, as well as volume reduction of brick unit no.1 (WCL1–WCL4)

Wall complexity level (WCL)	WCL1	WCL2	WCL3	WCL4
Brick unit 1 – Solid volume (cm ³)	21,428.57	21,432.74	26,869.25	27,475.69
Brick unit 1 – Infill volume (cm ³)	12,413.25	12,700.32	13,816.73	13,974.24
Volume reduction (%)	42	41	49	51

13.4.2 3DP Cost Analysis

The 3DP cost analysis of the selected prefabricated brick units for all walls (WCL1–WCL4) is based on the 3DP time and infill volume. It is estimated as the sum of the cost for the 3DP extruder tool manufacturing and the overall 3DP procedure and is calculated as follows:

$$C_{\text{total}(3DP)} = C_{\text{total}(3DP-t)} + C_{\text{total}(3DP-p)}$$

Where $C_{\text{total}(3DP)}$ is the total cost for 3DP and includes the $C_{\text{total}(3DP-t)}$, the total cost of 3DP extruder tool manufacturing, and $C_{\text{total}(3DP-p)}$, the total cost for 3DP procedure.

The total cost of the 3DP extruder tool manufacturing is calculated as follows:

$$C_{\text{total}(3DP-t)} = E_{\text{cost}(3DP-t)} + L_{\text{cost}(3DP-t)} + M_{\text{cost}(3DP-t)}$$

Where $E_{\text{cost}(3DP-t)}$ is the cost for energy consumed during manufacturing of the 3DP extruder tool, $L_{\text{cost}(3DP-t)}$ is the labour cost and $M_{\text{cost}(3DP-t)}$, the cost of materials and mechanical parts consisting the 3DP tool.

The total cost of the 3DP procedure is calculated as follows:

$$C_{\text{total}(3DP-p)} = E_{\text{cost}(3DP-p)} + L_{\text{cost}(3DP-p)} + M_{\text{cost}(3DP-p)}$$

Where, $E_{\text{cost}(3\text{DP-p})}$ is the energy consumed during 3DP, $L_{\text{cost}(3\text{DP-p})}$ is the labour cost and $M_{\text{cost}(3\text{DP-p})}$ is the cost of material applied in each case.

The energy consumed during 3DP procedure is calculated based on the electricity cost according to the time required for 3DP execution. This is the sum of energy required by the industrial robot, the 3DP extruder and the notebook and is calculated at the amount of 6kWh at maximum machine use. The cost of a kilowatt hour (kWh) is estimated at 0.25€. The total cost of 3DP extruder tool is estimated in the amount of 1197 € and is calculated only once in the total production cost of the eight (8) brick units in each wall (WCL1-WCL4). This is due to the ability of 3DP extruder mechanism to be applied repeatedly for the production of one or more prefabricated bricks without any extra cost.

The 3DP cost analysis shows obvious differences between the selected walls based on their complexity level. In the case of WCL1, the same 3DP cost is derived for each brick unit and is calculated in the amount of 18.68€. In the case of WCL2, the 3DP cost ranges between 19.104€ for brick units no. 2 and 7 and 19.118 € for brick unit no. 4. Greater differences are observed in the case of WCL3, where results show a cost range between 16.56 € for brick unit no. 7 and 20.812 € for brick unit no. 1. The greatest differentiation occurs in the case of WCL4, where 3DP cost values range between 16.382 € for brick unit no. 8 and 21.039 € for brick unit no. 1. Table 13.4 shows the cost inputs and Table 13.5 the total cost results of 3DP cost analysis for WCL4.

Figure 13.5 summarizes the 3DP cost per brick unit for all walls (WCL1–WCL4). The results show the same cost for every brick unit in WCL1, while cost gradations appear in the other three walls depending on the differences in 3DP time and infill volume. The differences become more pronounced in the case of WCL4 due to the increasing degree of complexity.

Also, it is observed that the average cost per unit for WCL1 is 18.68 €, for WCL2 is 19.11 €, for WCL3 is 18.93 € and for WCL4 is 18.94 €. In addition, the average 3D printing time for WCL1 is 97.95 min, for WCL2 is 100.16 min, for WCL3 is 97.93 min and for WCL4 is 99.27 min.

Table 13.4 Cost inputs of 3DP extruder tool manufacturing and 3DP procedure for the selected brick units in the case of WCL4

Brick unit no.	$E_{\text{cost}(3\text{DP-t})}$ (€)	$L_{\text{cost}(3\text{DP-t})}$ (€)	$M_{\text{cost}(3\text{DP-t})}$ (€)	$E_{\text{cost}(3\text{DP-p})}$ (€)	$L_{\text{cost}(3\text{DP-p})}$ (€) per unit	$M_{\text{cost}(3\text{DP-p})}$ (€) per unit
1	1197			2.75	16.193	2.096
2	N/A			2.75	16.161	2.091
3	N/A			2.74	16.106	2.084
4	N/A			2.505	14.717	1.905
5	N/A			2.42	14.249	1.844
6	N/A			2.33	13.695	1.772
7	N/A			2.19	12.904	1.67
8	N/A			2.146	12.605	1.631

Table 13.5 Total 3DP cost results for the selected brick units in the case of WCL4

Brick unit no.	C _{total(3DP-t)} (€)	C _{total(3DP-p)} (€)	Average cost per unit (€)
1	1197	21.039	18.94
2	0	21.002	
3	0	20.93	
4	0	19.127	
5	0	18.513	
6	0	17.797	
7	0	16.764	
8	0	16.382

Fig. 13.5 Graph that shows the 3DP cost per brick unit for all walls (WCL1–WCL4)

13.4.3 Environmental Impact Analysis

The LCA analysis considers adobe as the material of implementation. Also, the results are affected by the energy consumed during 3DP process that is incorporated in the construction/installation process (A5) of the LCA analysis. This is calculated as the sum of the energy required for the 3DP extruder mechanism and the overall 3DP procedure. Also, the results are affected by the material volume of each brick unit, which is associated with the energy consumed during construction material (A1–A3), transportation to site (A4) and deconstruction (C1–C4) of LCA analysis.

The global warming results (kg CO₂e) show almost similar values in each case (WCL1–WCL4). In the case of WCL1, the global warming is calculated in the amount of 1.11E1 kg CO₂e. In the case of WCL2, the global warming results range between 1.12E1 kg CO₂e to 1.13E1 kg CO₂e. In the case of WCL3, the results range between 1.01E1 kg CO₂e and 1.21E1 kg CO₂e. Table 13.6 shows the results of global warming (kg CO₂e) for each brick unit in the selected wall WCL4.

Table 13.6 Inputs and results of global warming (kg CO₂e) for the 3DP of brick units of WCL4 using adobe as the material of implementation

Brick unit no.	A1–A3 Cons. materials	A4 Tran. to site	A5 Const./ Inst. process	C1–C4 De-cons.	Total per unit	Average per unit
1	5.1E–2	5.1E–2	1.19E1	1.4E–1	1.21E1	1.11E1
2	5.1E–2	5.1E–2	1.19E1	1.4E–1	1.21E1	
3	5.12E–2	5.1E–2	1.18E1	1.37E–1	1.21E1	
4	4.68E–2	4.8E–2	1.1E1	1.26E–1	1.13E1	
5	4.54E–2	4.7E–2	1.08E1	1.21E–1	1.1E1	
6	4.35E–2	4.58E–2	1.04E1	1.16E–1	1.06E1	
7	4.09E–2	4.4E–2	9.97E0	1.09E–1	1.02E1	
8	3.98E–2	4.33E–2	9.8E0	1.07E–1	9.99E0	

Table 13.7 Inputs and results of primary energy (MJ) for the 3DP of brick units of WCL4 using adobe as the material of implementation

Brick unit no.	A1–A3 Cons. materials	A4 Tran. to site	A5 Const./ Inst. process	C1–C4 De-cons.	Total per unit	Average per unit
1	1.19E0	7.39E–1	1.93E2	4.16E0	1.99E2	1.83E2
2	1.19E0	7.39E–1	1.93E2	4.16E0	1.99E2	
3	1.19E0	7.39E–1	1.92E2	4.09E0	1.98E2	
4	1.09E0	6.96E–1	1.79E2	3.74E0	1.85E2	
5	1.05E0	6.82E–1	1.75E2	3.6E0	1.81E2	
6	1.01E0	6.64E–1	1.7E2	3.46E0	1.75E2	
7	9.51E–1	6.39E–1	1.63E2	3.26E0	1.68E2	
8	9.26E–1	6.28E–1	1.6E2	3.19E0	1.65E2	

Similarly, the value of primary energy (MJ) is almost identical in each case (WCL1–WCL4). In the case of WCL1, the primary energy is calculated in the amount of 1.82E2 MJ for every brick unit. In the case of WCL2, the result of primary energy is 1.85E2 MJ for every brick unit. In the case of WCL3, the results range between 1.66E2 MJ to 1.98E2 MJ. Table 13.7 shows the results of primary energy (MJ) for each brick unit in the case of WCL4.

The results of 3DP environmental impact analysis show that the total global warming for the 3DP of a brick unit is calculated in the average amount of 1.11E1 kg CO₂e for WCL1, 1.12E1 kg CO₂e for WCL2, 1.1E1 kg CO₂e for WCL3 and 1.11E1 kg CO₂e for WCL4. Also, the total primary energy of a brick unit is calculated in the average amount of 1.82E2 MJ for WCL1, 1.85E2 MJ for WCL2, 1.81E2 MJ for WCL3 and 1.83E2 MJ for WCL4. Similar to the results obtained in 3DP cost analysis, the global warming and primary energy results show slight changes in values for each selected wall due to the differences in material volume and 3DP time of each brick units. This is more obvious while the complexity is increased from WCL1 to WCL4 (see Fig. 13.6).

Fig. 13.6 Graph that shows the global warming per brick unit for the selected walls (WCL1-WCL4)

13.5 Discussion

The results derived from this experiment show that the selection of adobe material has advantages in terms of environmental impact analysis due to its superior ecological and recyclable properties compared with other cement-based materials. This achieves to improve the environmental performance of results in terms of global warming and primary energy. Also, the process of material minimization through design optimization allows decreasing of material volume, preserving at the same time structural stability of the brick components. In turn, this influences positively the 3DP cost and environmental impact results due to their dependence with the material volume and 3DP time.

Based on the above outputs, a comparative graph is shown in Fig. 13.7, which demonstrates the average results derived from 3DP cost and environmental impact analysis in relation to the degree of complexity of the selected walls. It is observed that the resulting values do not show any significant changes, while the degree of complexity is rapidly increased from a regular (WCL1) to a fully irregular wall (WCL4). The latter demonstrates large variety of bricks with different geometrical characteristics.

The almost identical results obtained in relation to the increasing complexity of the walls indicate the importance of implementing 3DP in case of irregular designs. In parallel, the results stress the benefits that this technique could bring to the construction industry. This is due to the ability of the 3DP technology to be applied in any design without extra cost or increase in environmental impact. In contrast, the application of traditional techniques for the construction of the same walls with different complexity would provide results with large differences. This is based on the view that in the case of traditional techniques, a significant increment in the cost and environmental impact of results during gradual increasing of wall's complexity

Fig. 13.7 Graph that compares average cost and environmental impact results of the selected walls with different degree of complexity (WCL1–WCL4)

from WCL1 to the WCL4 could be observed. In this case, the construction technique might be one-off solution and the use of formworks might result in material waste, extra cost and time. The comparison between 3DP and traditional techniques has not been demonstrated herein because it is out of the scope of this experiment; however, further work will focus on this direction.

13.6 Conclusions

This chapter aims to review existing 3DP examples with emphasis on their sustainable performance, indicating in parallel their potential for a wider use in the construction industry. It was found that not much research work has been done towards the integration of construction time, cost and environmental impact performance that is driven by structural optimization principles. On the contrary, works in these directions are found to be fragmented and not thoroughly investigated, preventing the establishment of indicators and parameters that can positively influence their performance (Pan et al., 2018).

Towards this direction, the chapter presents a generative construction framework where 3DP technology can be applied in order to positively affect this industrial field. Within this framework, the design optimization and the sustainable 3DP of selected designs with different degrees of complexity play significant role towards the effective implementation of 3DP technology. This is exemplified through the demonstration of an experiment, where four (4) walls with different degrees of

complexity and in particular eight (8) brick units with specific geometrical characteristics are analysed in terms of their 3DP cost, global warming and primary energy performance.

The preliminary results indicate great potential for applying the 3DP technology to the construction industry, especially to automating customized production of geometries with increasing complexity level. This can be done at no extra 3DP cost, global warming and primary energy consumption. In addition, the selection of appropriate materials with superior performances in terms of ecological and recyclable properties and the opportunity for volume reduction through design optimization are important aspects towards environmental impact improvement. Nevertheless, research limits are also acknowledged, such as the initial high cost of purchasing the 3DP mechanisms that include the industrial robot and the 3DP extruders. Their cost depreciation can be achieved in case of increasing production of complex structures.

The results derived from this experiment, might provide an insight on the potential application of 3DP technique to the construction industry towards a more sustainable future. Also, might allow a first understanding on its role within a future regenerative construction framework. Factors that might prevent its widespread use such as lack of knowledge among the construction actors in regard to its sustainable benefits need to be addressed. This can be done through quantitative studies regarding cost and environmental impact performance.

Although, a comparison between 3DP and traditional construction technique has not been undertaken in this paper, future studies will focus on this aspect of investigation. This will allow a rounded and comprehensive examination of the possibilities the 3DP technology can offer to the construction industry.

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