8-1-2021

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Journal of Earth Science and Engineering 9 (2021) 13-19
doi: 10.17265/2159-581X/2021.01.003

Cradle to Gate Life Cycle Assessment (LCA) of 3D Printing Houses

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Abstract: This paper presents a comparative "cradle to gate" life cycle assessment (LCA) of 3D printing houses and conventional buildings using SimaPro software, as a tool to model and compare the two alternatives. The study considered a terraced type of buildings with a floor area of 60 m^2 (functional unit), which could occupy 2-3 households. The results indicated that 3D printing houses have a smaller environmental impact than conventional buildings in all impact categories except in terrestrial ecotoxicity, in which both alternatives resulted in 172 kg 1,4-DB eq. 3D printing houses exhibit a higher climate impact from Timber floorboards, window frames, and Portland cement which are responsible for 7.39 × 104 kg CO_2 eq, 9.34 × 104 kg CO_2 eq, and 3.82 × 104 kg CO_2 eq respectively.

Key words: 3D printing, LCA, environmental impact, impact categories.

1. Introduction

3D printing, also called additive manufacturing (AM) is a process by which physical objects are created by depositing the materials in a layer-by-layer fashion based on a digital model. It was initially utilized to quickly and accurately creating prototype parts and for more than a decade, 3D printing has been used in several ambitious initiatives and projects in construction. For example, in 2004 a University of South Carolina professor attempted to 3D print a wall in what's widely accepted as the technology's first entry into construction [1]; a full canal house built using 3D printing was completed in 2014 in Amsterdam; in 2016 a 3D-printed mansion was completed in China; also in 2016, the Dubai Future Foundation built its Office of the Future via 3D printing, a major milestone for the technology in the commercial construction sector [2]. This technology is gaining popularity in construction because it offers a significant potential to increase efficiency in the building sector, including speed of construction which makes it ideal for emergency, less waste material compared to 1 billion waste materials from conventional concrete structures, accuracy, affordability, and design flexibility and freedom. Global value for the 3D printing activities reached $5.8 billion in 2016 and with the current rate concrete 3D printing marking is projected to be valued at $55.8 billion by the year 2027.

With all the explosive growth in 3D printing, there are only a few available web pages and articles trying to assess the LCA of 3D printing such as Sakin M. and Kiroglu Y. C. (2017); Nichols M. (2017); Flynt J. (2017); Barros K. S., Zwolinski P. and Mansur A. I. (2017); Liu Z., Jiang Q., Zhang Y., Li T. and Zhang H. C. (2016); and Cerdas F., Juraschek M., Thiede S. and Herrmann C. (2017) [2-7]. A new composite construction material manufactured using 3D printing (AM) for fire and blast loading resistant buildings and its energy efficiency was discussed and presented in Ali E. Y. and Bayleyegn Y. S. (2018, 2019) [8, 9]. Even though in all of these sources, 3D printing is presumed to be a viable solution that offers key benefits in cost savings and environmental friendliness for building's future, none of these available publications offers qualitative environmental

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implication assessment on 3D houses. Thus, the purpose of this paper is to address this gap by carrying out a Life cycle assessment (LCA) of 3D printed houses and assess their environmental impacts.

Fig. 1 Development in 3D printed buildings in the last decade.

2. The Goal and Scope of the Project

Since 3D printing technology in construction is still in its infancy, there is limited knowledge on its environmental implications. The goal of this project is thus to assess qualitatively the environmental impacts of 3D printed houses and compare the LCA with conventional buildings, which would ultimately shade light for future research. Furthermore, this project was a learning opportunity for the author on the processes of LCA, the use of SimaPro software, and to familiarize the environmental impacts of the two-building alternatives.

This project considered a comparative "cradle to gate" LCA, by using SimaPro software as a tool to model and compare the two building alternatives, 3D printing houses, and conventional brick houses. Both scenarios consider a terraced house type of 60 m^2 (functional unit), which was chosen based on the current capabilities of 3D concrete printers.

3. System Boundaries, Assumptions, and Limitations

The life cycle process of the buildings considered in this project is "cradle to gate" as shown in Fig. 2, which includes raw material extraction, material manufacturing, transport, and construction. Operational and demolition stages are neglected due to a lack of data in 3D printed houses after occupancy. It was just in April 2021 that the Dutch couples became the first residents of 3D printed houses and the complexity of the 3D process needed to include in the LCA. Moreover, previous researches show that a building demolition stage has a smaller impact on the environment than the construction and operation phases [10]. For this project, the design process of the blueprint of the buildings is not considered, since there is no available information about the design stage; the 3D printer is transported in parts to the construction site; utilities (piping, wiring, ventilation, etc.) for the dwelling functional were not considered; for conventional buildings 10% off raw material was added during the modeling, to compensate wastage during manufacturing, transportation, and construction. The lifetime of both building alternatives is set to be 50 years, an average expected lifetime of buildings considered in many LCA literature.

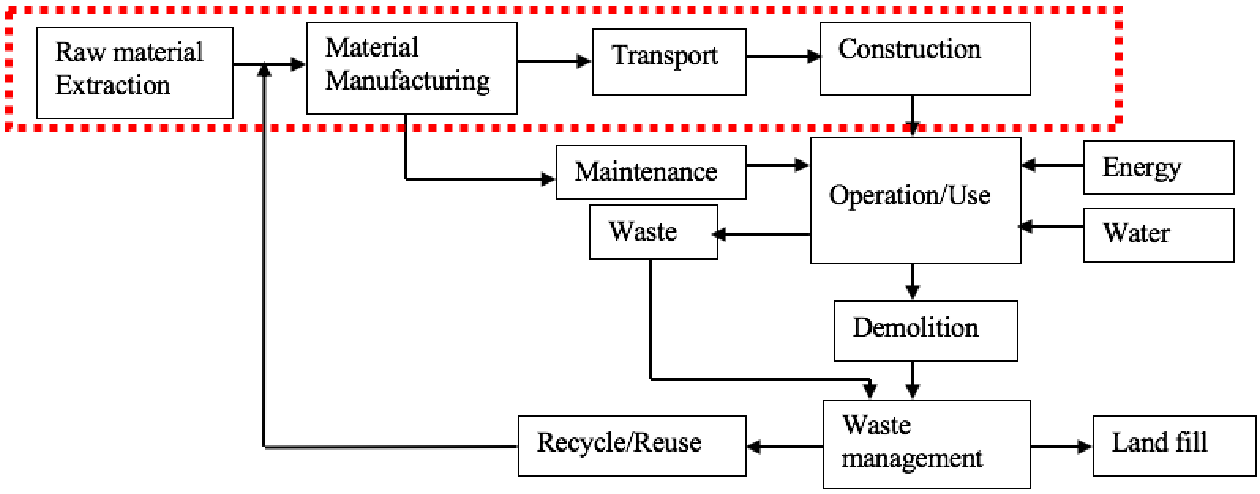

Fig. 2 System boundary and life cycle stages in buildings.

4. Life Cycle Inventory

All the information and data collected to perform the LCA were found for conventional buildings from Ref. [10] and for 3D printed buildings from Ref. [11], in which all values are approximated for the terraced type of houses, 60 m^2 (functional unit). The data collected are presented in Tables 1 and 2 below.

Table 1 Materials and process in 3D printed buildings.

Materials	SimaPro Reference	unit	Building (kg)	Foundation (kg)	Roof (kg)
Cement+flyash	Portland cement, strength class Z 42.5, at plant/CH S	kg	25699.8	11160	9674.05
Silica fume	Silica sand, at plant/DE S	kg	2867.05	1245	1079.23
Sand	Sand, at mine/CH S	kg	42867.6	18615	16136.5
Water	Tap water, at user/CH S	kg	8014	3480	3016.6
Fibers	Glass fiber, at plant/RER S	kg	48	21	18
Transport	Lorry transport, Euro 0-4 mix, max payload RER S	kg	8394.93		
Transport of printer	Transport, lorry 16-32t, EURO5/RER S	tkm	500		
Transport of materials	Transport, lorry 16-32t, EURO5/RER S	tkm	50		
Ceramic floor tiles	Ceramic tiles, at regional storage/CH S	kg	170.2		
Timber floorboards	Glued laminated timber, outdoor use, at plant/RER S	m^3	331		
U-PVC frame	Window frame, aluminum, U+1.6 W/m2K, at plant/RER S	m^2	192		
Hardwood timber	Door, inner, wood, at plant/RER S	m^2	331		
Electricity (1440 kWh)	Electricity, medium voltage, at grid/CH S	kWh	795.28	345.35	300

Table 2 Materials and processes in conventional buildings.

Materials	SimaPro Reference	unit	Building (kg)	Foundation (kg)	Roof (kg)
Brick (Imperial 9'')	Light clay brick, at plant/DE S	kg	30002	10956	
Cement mortar	Cement mortar, at plant/CH S	kg	7983	726	1079.23
Concrete block (aerated)	Aerated concrete block, type P4 05 reinforced	kg	6716	12906.85	
Concrete slab	Concrete, sole plate, and foundation, at plant/CH S	kg	7097.14		
Sand and gravel	_16 sand, gravel, and stone from a quarry	kg	3312		
Concrete tiles	Ceramic tiles, at regional storage/CH S	kg			1991
Plasterboard	Gypsum plaster board, at plant/CH S	kg	3088		
Softwood timber	Sawn timber, softwood, planed, air dried, at plant/RER S	m^3	1362		
Timber floorboards	Glued laminated timber, outdoor use, at plant/RER S	m^3	331		
U-PVC frame	Window frame, aluminum, U+1.6 W/m2K, at plant/RER S	m^2	192		
Laminated floor	Three-layered laminated board, at plant/RER S	m^3	331		
Transport of materials	Transport of materials	tkm	3611.82	1487.61	67.91
Energy consumption	Electricity, medium voltage, at grid/CH S	kWh	3102.39	1285.06	61.26

5. Life Cycle Interpretation

Characterization results of 3D printing and conventional buildings using the ReCipe midpoint method were performed and the results are presented in Table 3 and Fig. 3. It was found that the conventional building showed a higher impact in almost all categories except in Terrestrial ecotoxicity, in which both alternatives resulted in 172 kg 1.4-DB eq. Considering the climate change impact category, 3D printing resulted in 2.21×10^5 kg CO_2 eq and conventional building resulted in 1.14×10^6 kg CO_2 eq, which is 80% higher. In terms of each material inputs, 3D printing houses exhibit a higher climate impact from Timber floorboards, window frames, and Portland cement which are responsible for 7.39×10^4 kg CO_2 eq, 9.34×10^4 kg CO_2 eq, and 3.82×10^4 kg CO_2 eq respectively. Whereas in conventional buildings, higher climate change impacts are observed from concrete (1.13×10^6 kg CO_2 eq), laminated floor (9.12×10^4 kg CO_2 eq), window frames (4.7×10^4 kg CO_2 eq), and bricks (6.58×10^3 kg CO_2 eq). Detailed contributions from each material inputs and flow charts of impact assessment are presented in Fig. 3 &4 for both building alternatives.

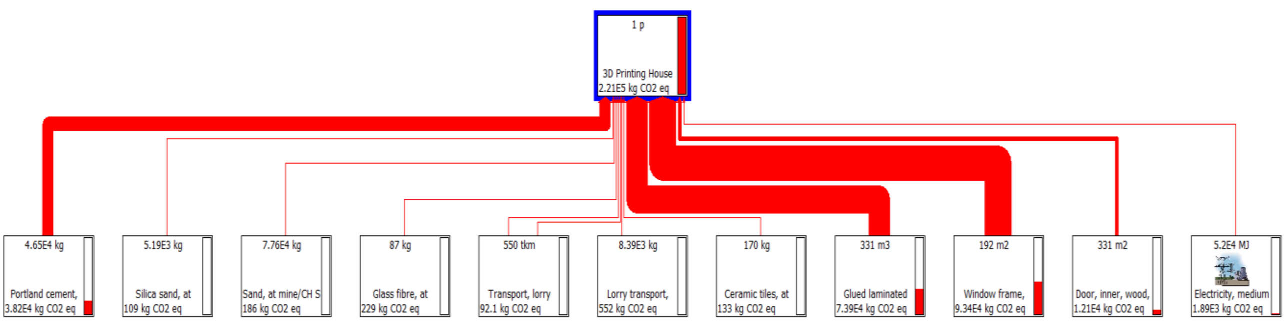

Fig. 3 Detail flow chart of impact assessment in 3D printed houses using SimaPro.

Table 3 Characterization results of the two alternatives using ReCipe midpoint.

Impact Category	unit	3D printed building	Conventional building
Climate change	kg CO_2 eq	2.21E5	1.41E6
Ozone depletion	kg CFC-11 eq	0.017	0.0729
Human toxicity	kg 1,4-DB eq	9.95E4	2.57E5
Photochemical oxidant formation	kg NMVOC	980	5.37E3
Particulate matter formation	kg PM 10 eq	422	1.63E3
Ionizing radiation	kg U235 eq	7.41E4	3.39E5
Terrestrial acidification	kg SO2 eq	914	3.84E3
Freshwater eutrophication	kg P eq	88.5	225
Marine eutrophication	kg N eq	275	1.51E3
Terrestrial ecotoxicity	kg 1,4-DB eq	172	172
Freshwater ecotoxicity	kg 1,4-DB eq	1.77E3	4.41E3
Marine ecotoxicity	kg 1,4-DB eq	1.84E3	4.6E3
Agricultural land occupation	m2a	1.09E6	5.45E6
Urban land occupation	m2a	1.36E4	7.34E4
Natural land transformation	m^2	144	759
Water depletion	m^3	1.41E3	2.67E4
Metal depletion	kg Fe eq	1.19E4	7.23E4
Fossil depletion	kg oil eq	6.16E4	2.33E5

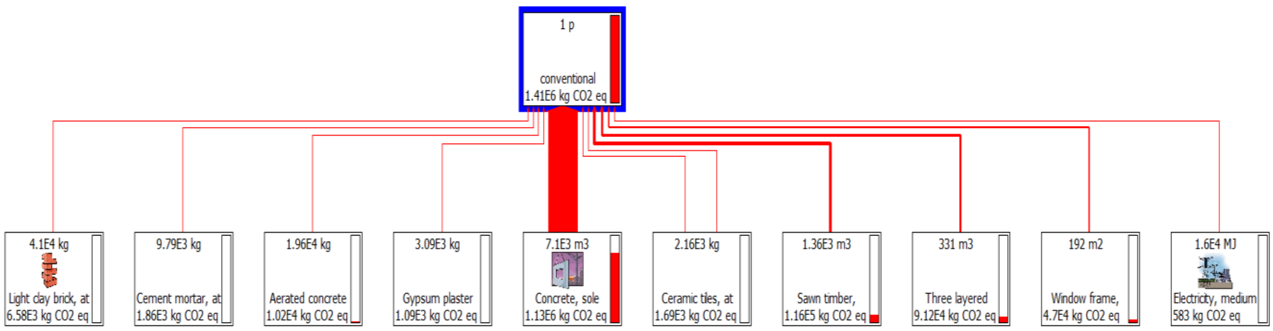

Fig. 4 Detail flow chart of impact assessment in conventional building using SimaPro.

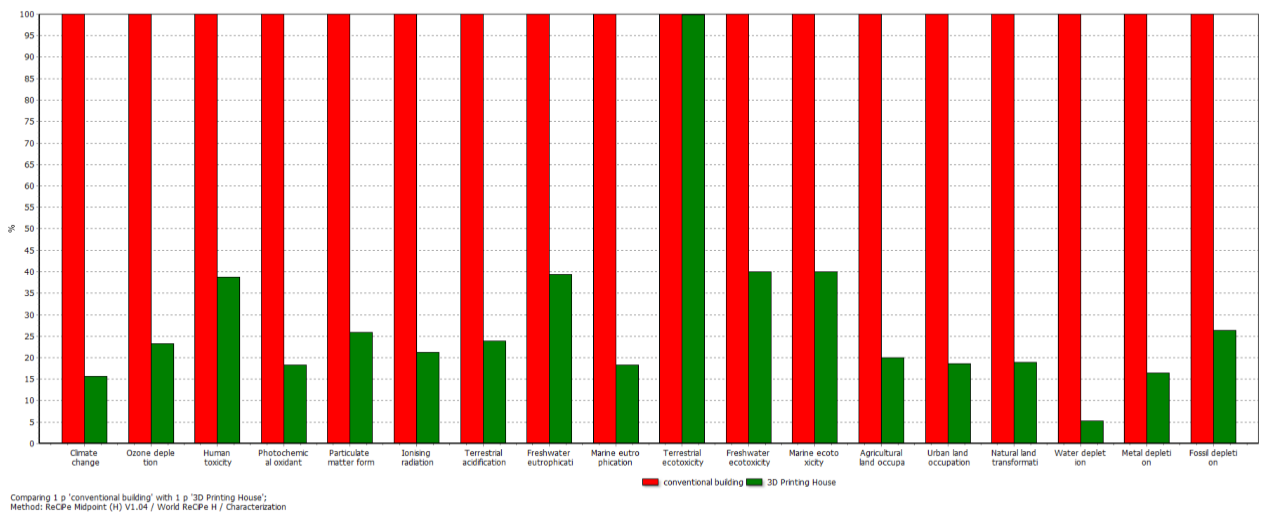

Fig. 5 Characterization results of the two alternatives using ReCipe midpoint.

The normalized comparison result from ReCipe midpoint is shown in Fig. 6 for each impact category. It can be observed that both 3D printing and conventional buildings have a significantly higher impact on marine ecotoxicity, human toxicity, and freshwater eutrophication compared to other categories.

Environmental impact damage assessment was also performed for the two-building alternatives using the IMPACT 2000+ method in SimaPro as shown in Figs. 7 and 8. In all impact damage assessment categories, conventional building alternatives resulted in higher damage than the 3D printing houses. It can also be observed that conventional buildings have 78%, 76%, 80%, and 75% more damage than3D printing houses in terms of human health, ecosystem quality, climate change, and resources respectively.

6. Conclusions and Recommendations

This project aimed to assess the environmental life cycle of 3D printing houses comparing the results with conventional buildings. It was found that in almost all impact categories, conventional building practice resulted in higher impact. These observations are because 3D printing uses significantly smaller

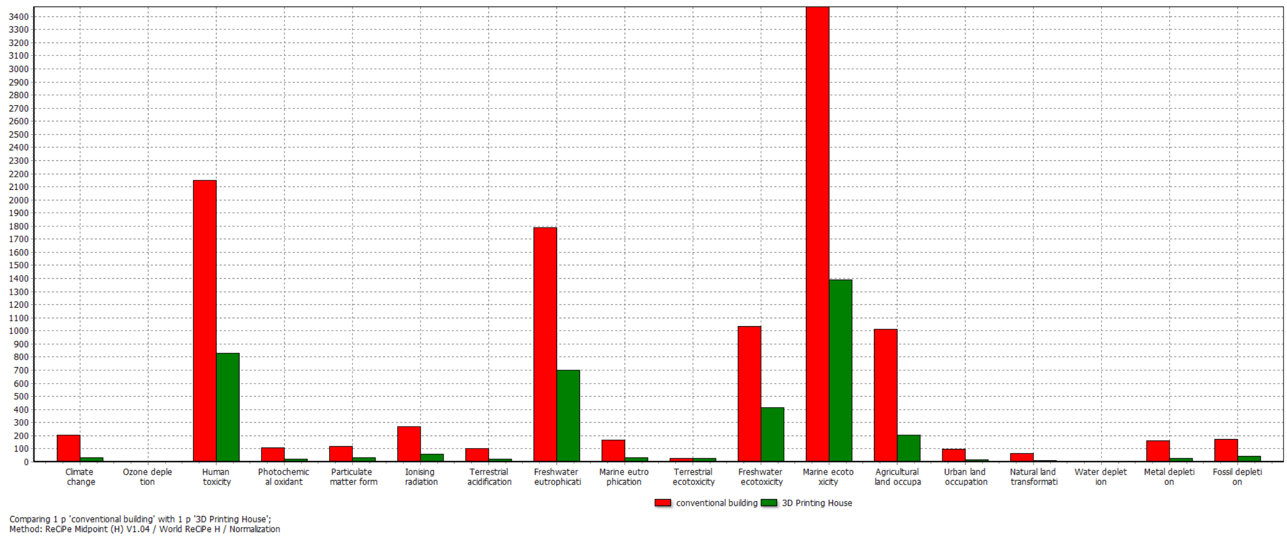

Fig. 6 Normalization results of the two alternatives using ReCipe midpoint.

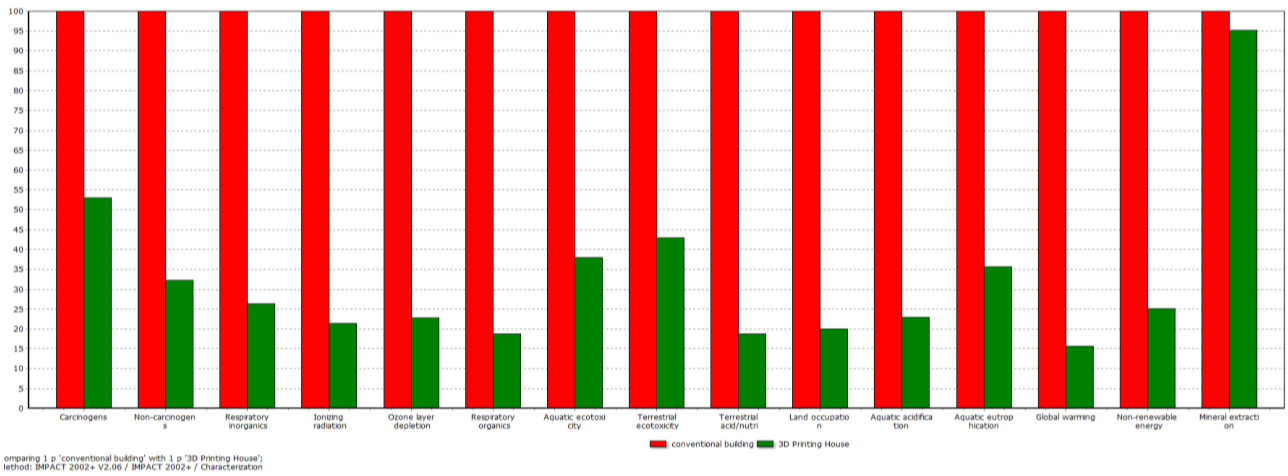

Fig. 7 Damage assessment characterization of the two alternatives using IMPACT2000+.

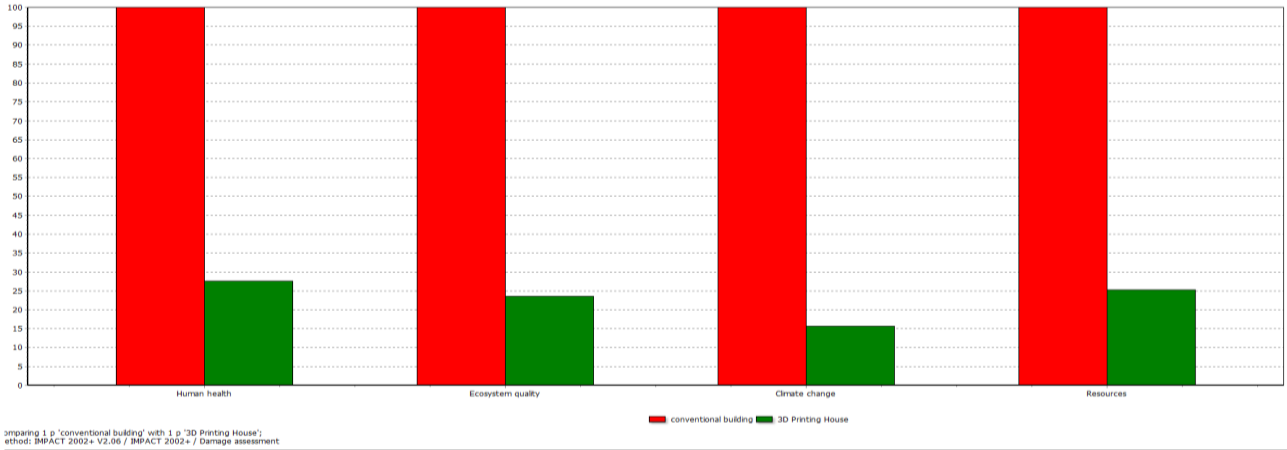

Fig. 8 Damage assessment of the two alternatives using IMPACT2000+.

construction materials compared with conventional buildings. However, the LCA performed here only considered "cradle to gate", which didn't fully capture the full life cycle and considered many assumptions due to lack of data. The results presented here were also prone to uncertainties as various assumptions were needed to fill the gap in data. Thus, it is recommended (in future research) to perfume uncertainty analysis. More or less, this project would hopefully provide a starting point in future research regarding 3D printing houses' environmental implications.

Acknowledgments

The authors received no financial support for the research, authorship, and/or publication of this article.

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