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Circular building design: a case study in Pakistan

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Circular building design: a case study in Pakistan

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Abstract:
A major transformation from the current, linear practice to a closed-loop system, linked with a circular economy, is required to transform the negative effects of buildings on the environment. Pakistan has one of the fastest growing populations, and conventional building construction is increasing in urban areas due to urban sprawl. This research aims to demonstrate the possible shift to a circular construction industry in Pakistan by comparing the linear design components with the circular design components of exterior walls of a case study taking advantage of life cycle assessment. The results of life cycle assessment applied to the external walls of a house in Karachi show that finding the solution with the lowest impacts is not obvious and that use of apparently "green" solutions may turn out to have higher impacts. Study suggests that building components can be gradually replaced with more circular ones to create a circular built environment.

1. Introduction

The building sector has a substantial negative influence on the environment, as it consumes resources, and produces waste, all of which contribute to the quick depletion and wasteful use of natural resources [1]–[4]. If current industrial methods continue to be used, these problems will get worse due to increased resource demands from a growing global population and urbanization.

The circular economy paradigm (CE) was proposed to maintain the value of materials and products while attempting to extend the efficiency of resources through practices which include reducing, reusing, and recycling (Ellen MacArthur Foundation, 2015). Understanding the complex life cycle material metabolism and relevant environmental impacts of buildings is increasingly crucial as political and industrial CE initiatives start to take shape on a larger scale [5][6][7]. This will help to identify CE potentials (such as alternative recycling and reuse scenarios) within the building stock and make sure that waste and resource management initiatives are effective. Performing life cycle assessment (LCA) is one of the ways of gaining this vision [8]. Many LCA tools, methods, and standards are now available, and the approach is now being used in the construction sector and in several newly published studies, attempting to highlight the advantages of CE [9]–[11]. However, the practical use of LCA for supporting decisions is limited because the decision makers often lack the skills necessary to analyze and interpret environmental data. Since LCA solely examines the environmental effects of primary functions or product systems, it may not be entirely appropriate for meaningfully interpreting results in a CE context [8]. Consequently, for the purpose of CE, a "rethinking" of how LCAs are conducted and interpreted is needed, because the available tools to help in evaluating the environmental consequences and advantages of CE (like the controversial "Module D"), supporting decision-making, and inspiring industrial stakeholders, are often difficult to use [12]. In addition, for the socioeconomic system to support circularity approaches, new business models must be developed in addition to enhanced construction methods and building materials [13].

The current work offers a methodological approach for explaining life cycle impacts on the environment, as well as how they are modelled in LCA, in order to address this knowledge gap between research and industry in Pakistan. A LCA is performed on linear design component (LDC) of common construction materials used in building component (the concrete exterior walls) of house in Karachi, Pakistan, based on existing market products: with a long- service life respectively. Then LCA is used to evaluate alternative circular design components (CDC) in order to identify the one with the lowest impacts. The LCA results are then reported and interpreted highlighting the environmental impacts generated in the process of linear building materials versus prospective circular building materials. The results are also analyzed and compared with reference to two variants of circular materials. This helped showing the potential of circular materials as building components, and at which point in time they start contributing to maintain the circularity loop in the construction. A discussion of the identified challenges in the construction sector of Pakistan concludes the paper.

2. Methodology

2.1 Case study

A representative house has been selected with reference to the city of Karachi (Pakistan). The house falls in the category of detached house with covered area of 92 square meters. The selected house is considered as a typical house in Pakistan for a family of six residents. The house is consisting of ground floor with one upper floor. The construction of house is based on contemporary architecture. In this study, in order to provide a first example of the methodology, only the exterior walls of the building were selected to assess their environmental impacts. The effects from cradle to grave were considered. All life cycle stages under Modules A-C are included in a cradle-to-grave evaluation using OpenLCA tool. Composition of walls is shown in figure 1. The materials used in the selected LDC and prospective CDC, with relevant quantities and life cycles are shown in the table 1. The LDC included mostly concrete blocks and mortar and were designed to be disposed and demolished at the completion of their service life, while the CDC (circular1 and circular2) included light clay bricks, cellulose fiber or wood wool and bamboo, and were designed to be reused or upcycled and disassembled. Both CDC combinations were designed by selecting sustainable bio-based materials with eco-efficient properties in their production and/or service life. In circular2 combination, cellulose fiber was replaced by wood wool. Both are eco-friendly materials as they are renewable and biodegradable, having low embodied energy. In addition, wood wool and cellulose fiber panels reduce heating and cooling loads in buildings, which helps energy efficiency and decrease carbon emissions also during the life span of the building (although this step was not considered in the analysis at this stage). As the exterior of the building was considered as a long-service building component, the life span of materials used in the walls was considered 75 years for the baseline case except for the exterior walls paint finish. The exterior wall requires repainting every 5-10 years due to multiple factors affecting the exterior of walls. Similarly, lifespan of bamboo cladding was assumed to be 30 years and 20 years for cellulose fiber.

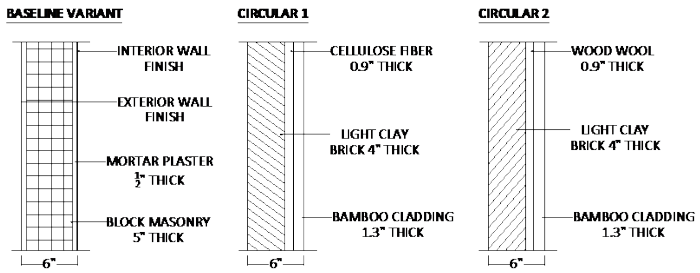

Figure 1. Selected case study: showing exterior wall composition of a detached house with variants

2.2. Life cycle assessment

Building component's environmental profile was calculated using the LCA approach outlined in the standard EN 15978 using the openLCA v1.10.3 software and characterization factors from the Centre for Environmental Studies (CML) baseline. Based on the different characteristics of the walls that were investigated, the most obvious choice in terms of functional unit was to assume the covered area as a reference and, hence, one square meter (m^2). At this stage no comparison of the thermal performance was made as this is not currently considered in the study. The background life cycle inventory (LCI) was created using the Ecoinvent 3.8 database and system processes to provide consolidated results. The manufacturing of building materials was included within the product system modeled in OpenLCA.

Table 1. Quantities of materials used in building components for three variants.

Building component Exterior walls	**Material used in the layers of walls**		**Mass (kg/m^2)**	**Use (Two use cycles)**	**Repair/ Replace/ refurbish**	**End of Life 1st use and 2nd use 0-75 years – 75-150 years**
Baseline	concrete blocks	Cement	39.25	75 years	one time	99% reuse as pit filler 1% landfill
		Cand	117.75			
		gravel	78.5			
	mortar plaster	cement	13.25	75 years	One time	99% reuse as pit filler 1% landfill
		sand	52.98			
	paint	Double coat	0.79	5 years	15 times	100% landfill
Circular1	light clay brick		68.33	75 years	one time	99% reuse as pit filler, 1% landfill
	cellulose fiber		28.44	50 years	2 times	95% biodegraded/ energy recovery, 5% landfill
	flattened bamboo		5.48	30 years	3 times	50% upcycled, 50% energy recovery
Circular2	light clay bricks		68.33			
	wood wool		12.86	70 years	one time	95% reused/ energy recovery, 5% landfill
	flattened bamboo		5.48			

The environmental profile of different materials used in the building component was assessed. Based on the three combinations described before, three LCA inventories were generated in the OpenLCA, one for the baseline (LDC) and two for the circular alternatives.

Building components can be thought of as a composite of pieces and materials with varying lifespans. Parts or materials might have longer, or shorter lifespan as compared to building component. Different life spans of the materials have been selected for this analysis because different materials used might have different or multiple use cycles. CE emphasizes on the retention of value of the supply chain of materials (for example panels used can be refurbished and re-fitted or they can be re-used somewhere else). Therefore, a total of 150 (75+75) years of life span of building components was considered, in which two use cycles were included (0-75 years and 75-150 years). Lifespan of parts of components is complex to evaluate as they can be variable. For the present analysis, service lifespans of materials as well as the different waste scenarios (i.e the amount of materials that can be recycled at the end of each cycle) were taken from the reference list of Stichting Bouwkwaliteit (2019). In the “after-life” cycles, the system boundary needs to be expanded to incorporate the possibilities for reuse, recycling, and recovery of building products and materials as prescribed by Module D, but finding the required information was difficult at this stage. The first LCA inventory modelled in system processes included all the linear materials used in the construction of LDC. For second and third inventories, circular1 and circular2 combinations were considered as CDC (table 1 and figure 1). The two different combinations were assessed to analyze their environmental impacts and show how LCA can help identifying the most eco-efficient components for the building design. As there is lack of standards for Pakistan, EU standards are considered in the analysis. Wood wool and cellulose panels were considered as organic insulations, the re-use of such panels in Pakistan is possible for different purposes in local markets, therefore, 95% of material is reused or used for energy recovery. In the case of bamboo cladding the percentage of upcycling is 50% at local level, while 50% of the material is combusted for the energy recovery at the end of life. The metal fittings and fixing are not considered in the LCA but according to the waste scenarios 90% of the metal fixing material is recycled, 5% is incinerated and 5% is left in the landfill.

3. Results and discussion

The life cycle impacts (LCI) were determined according to the criteria defined by the CML baseline which has eleven environmental, resource-depletion, and toxicology midpoint impact categories. The life cycle environmental impact resulting from the LCA study of the LDC, and CDCs of the exterior walls are shown in table 2. The results are for the baseline case study and the proposed circular1 and circular2 cases and show how materials will perform during their use cycles. All the environmental impact categories are indicated with their potential share in the impact generation. In the variants, additional results are shown for the materials used multiple times during the selected reference lifespan. The effects were examined based on a "what if" question: what if the LDC used in the construction of walls as baseline case were replaced with one of the two variants provided for the CDCs? Following this question, we analyzed the environmental share of the variants and also the materials used in the building components. A comparison of all the results showed that the baseline had the highest values of the negative impacts in the maximum impact categories due to new production of building component at the end of each use cycle. During lifespan of building component, the impacts further increased by multiple times repair and replacement of wall paints. Quite surprisingly, when compared with the share of circular1 variant, the baseline variant showed reduced share in four of the eleven impact categories, but major difference appeared in terms of global warming potential (GWP). There was a significant reduction in the GWP if the circular1 variant replaced the baseline. In circular1 variant cellulose fiber was used twice for single use cycle and bamboo cladding was replaced three times. The results showed that after replacing the cellulose fiber at the age of 50 years and bamboo cladding every 30 years the environmental impacts generated were higher than those produced by the baseline materials. Therefore, according to some criteria the baseline proved to be beneficial instead of circular1 variant.

Based on the above findings, circular2 variant was also added to find a hopefully better solution. In fact, circular2 showed decreased share in the impacts for all impact categories except for terrestrial ecotoxicity potential (TEP), but difference compared to baseline was quite negligible even after replacing bamboo cladding three times. After analyzing all the impact generation due to material replacement, the baseline variant still showed the highest values in maximum impact categories.

From results it was observed that the highest material-related impact derived from production of concrete blocks used in the construction of exterior walls. The process of making the product from raw materials was responsible of generating negative impacts on the environment. Conventional use of energy and resources resulted in an increased use of fossil fuels for energy production and utilization, as concrete consumes a large amount of virgin materials.

Furthermore, all the variants were analyzed for the 2nd use cycle. In this case, materials used in the baseline variant were considered 100% same with same quantities (table1) because of new construction of wall from raw materials. For circular1 variant, the materials used in the building component were the same and newly fabricated but, due to combustion, the amount of energy recovered from the materials used in 1st cycle was deducted from the 2nd use cycle LCA process (table1). Therefore, a noteworthy change in the environmental impact generation in the 2nd use cycle was observed and, again, the use of circular2 variant provided even better results.

From the results of the exterior walls variants, we found that, the conventional and linear components used in the construction of walls are likely to generate maximum impacts as shown in baseline variant. Circular1 variant was first proposed based on the use of materials that are generally acknowledged as being more eco-efficient, consume less embodied energy and reusable. But the combination proved to be not so much eco-efficient when LCA was carried out. Therefore, other alternatives were found using materials already available in the market and having an eco-efficiency label. The LCA result showed the efficiency of the materials selected in the circular2 variant when compared with the baseline variant. Clearly, replacing clay bricks with solutions with a lower overall impact might further improve the results, but, at the moment, it was difficult to find alternatives in Pakistan.

Table 2. LCIA results for the exterior wall building components with different variants.

Impact Categories	Unit	Baseline			Circular1			Bamboo cladding Every 30 years	Circular2	
		75 years	150 years	Paint Every 10 years	75 years	150 years	Cellulose fiber Every 50 years		75 years	150 years
GWP	kgCO2e	$9.79E^{3}$	$9.79E^{3}$	$1.06E^{3}$	$4.00E^{3}$	$4.09E^{3}$	$1.54E^{3}$	$3.80E^{2}$	$3.00E^{3}$	$2.82E^{3}$
OLD	kgCFC11e	$4.67E^{-4}$	$4.67E^{-4}$	$6.65E^{-5}$	$3.93E^{-4}$	$3.90E^{-4}$	$9.45E^{-5}$	$1.55E^{-5}$	$3.12E^{-4}$	$3.10E^{-4}$
PHOP	kg C2H4e	$1.42E^{0}$	$1.42E^{0}$	$0.58E^{0}$	$1.14E^{0}$	$1.18E^{0}$	$0.41E^{0}$	$0.61E^{0}$	$1.10E^{0}$	$0.80E^{0}$
AP	kg SO2e	$2.71E^{1}$	$2.71E^{1}$	$1.59E^{1}$	$1.72E^{1}$	$1.78E^{1}$	$1.00E^{1}$	$2.04E^{0}$	$1.06E^{1}$	$0.98E^{1}$
EP	kg PO4-e	$9.56E^{0}$	$9.56E^{0}$	$1.95E^{0}$	$8.07E^{0}$	$6.76E^{0}$	$3.70E^{0}$	$1.00E^{0}$	$4.05E^{0}$	$3.58E^{0}$
AD	kg Sb e	$7.42E^{-2}$	$7.42E^{-2}$	$1.58E^{-2}$	$8.00E^{-2}$	$7.06E^{-2}$	$3.63E^{-2}$	$2.29E^{-2}$	$4.75E^{-2}$	$0.04E^{0}$
AD (FF)	MJ	$6.37E^{4}$	$6.37E^{4}$	$1.00E^{4}$	$5.15E^{4}$	$5.15E^{4}$	$1.56E^{4}$	$3.81E^{3}$	$4.04E^{4}$	$3.90E^{4}$
FWAP	kg 1,4-DB e	$2.82E^{3}$	$2.82E^{3}$	$0.73E^{3}$	$3.87E^{3}$	$3.24E^{3}$	$2.01E^{3}$	$0.68E^{3}$	$1.75E^{3}$	$1.43E^{3}$
HTP	kg 1,4-DB e	$3.67E^{3}$	$3.67E^{3}$	$0.83E^{3}$	$4.61E^{3}$	$4.00E^{3}$	$2.00E^{3}$	$1.50E^{3}$	$2.92E^{3}$	$2.20E^{3}$
MAEP	kg 1,4-DB e	$5.17E^{6}$	$5.17E^{6}$	$1.40E^{6}$	$5.84E^{6}$	$5.67E^{6}$	$3.81E^{6}$	$1.05E^{6}$	$2.83E^{6}$	$2.33E^{6}$
TEP	kg 1,4-DB e	$1.56E^{1}$	$1.56E^{1}$	$2.60E^{1}$	$2.09E^{2}$	$1.74E^{1}$	$4.91E^{0}$	$5.32E^{0}$	$1.59E^{1}$	$1.33E^{1}$

Note: The colors show a gradient between the highest (dark) and lowest (light) value, the lowest value is the best value.
Grey: indicates difference of impacts in 3 variants during 1st use cycle.
Yellow: indicates difference of impacts in 3 variants during 2nd use cycle.
Orange. indicates difference of impacts generated by materials used multiples times.

This simple application showed that by combining circular design possibilities, environmental performance can be significantly improved. Selected materials such as wood wool, cellulose fiber, bamboo are organic products with low embodied energy. However, while using these materials it is important to analyze the materials flow and process. We can say that not all the circular options available are ready to be used in all possible combinations. It is important to carefully select the materials and analyze the whole loop cycle of the materials to identify the best environmental performing variant. LCA from cradle to cradle which also includes Module D was not possible to be considered in this paper, but research is under way to include all the phases in the LCA to identify the performance of different materials used in the construction of building components in future studies.

4. Conclusion

To overcome environmental problems related to construction industry, it is important to explore the availability of circular materials in the country. The building process is associated with multiple factors, in which materials profile from raw material extraction to demolition should be investigated beginning from small to large scale projects. The study presented a partial (an inherently limited) example of how LCA applied to different variants to be used in the construction of exterior walls may help identifying the most sustainable option. Further studies are under way to extend the LCA to the whole building to help the stakeholders of building sector to identify the hot spot areas of investigation for replacement and modification. These analyses will necessarily include the end-of-life step and the subsequent steps to fully include the advantages of a circular thinking. The results of the present study suggested that the conventional materials used in the construction of linear building component are not only degrading the environment, but they are equally harmful for human health. In the context of Pakistan where, air pollution is increasing day by day specifically in big cities, construction plays a vital role in the process of generating air pollution.

The findings of these analyses can be interpreted in various ways depending on how priorities are set and how decisions are made. It was demonstrated that the majority of circular design solutions do not automatically result in greater environmental performance. It depends on how and where they are applied. Therefore, the primary recommendation for Pakistani industry is to think about comprehensive processes while designing and building structures, also there is a need for a uniform LCA allocation strategy for boosting CE in the building sector, to give stakeholders a solid foundation for decision-making. Stakeholders will benefit from a wise use of resources and keeping track of the quality and quantity of building components on the site as in return this will reduce waste production, disposal costs, and construction costs for later phases. Governments may be able to support the private sector with policies and regulations, but even if the private sector can take the initiative, they will be able to promote CE while established markets are still developing.

Documentation of the key findings will be needed to share with the stakeholders as education and upskilling are necessary to support and achieve the expected progress during the whole process. However, unrestricted collaboration and substantial information sharing are needed to support the implementation of circular building practices not just within one project, but also across the entire sector.

References

[1] L. Aye, T. Ngo, R. H. Crawford, R. Gammampila, and P. Mendis, "Life cycle greenhouse gas emissions and energy analysis of prefabricated reusable building modules," *Energy Build*, vol. 47, pp. 159–168, Apr. 2012.

[2] E. Meex, A. Hollberg, E. Knapen, L. Hildebrand, and G. Verbeeck, "Requirements for applying LCA-based environmental impact assessment tools in the early stages of building design," *Build Environ*, vol. 133, pp. 228–236, Apr. 2018.

[3] H. P. Thanu, C. Rajasekaran, and M. D. Deepak, "Developing a building performance score model for assessing the sustainability of buildings," *Smart and Sustainable Built Environment*, vol. 11, no. 1, pp. 143–161, Mar. 2022.

[4] S. A. Islam and S. A. Chowdhury, "Life Cycle Environmental Impact Assessment of a Residential Building in Bangladesh," in *International Conference on Planning, Architecture &Civil Engineering*, 2021, pp. 138–143. [Online]. Available: https://www.researchgate.net/publication/362173741

[5] "Circular Economy Action Plan," Brussels, 2020.

[6] "The Advisory Board for Circular Economy Recommendations for the Danish Government," 2017.

[7] "The Danish Government 2018 Strategy for Circular Economy; Circular economy strategy - More value and a better environment through design, consumption, and recycling," 2018.

[8] Michael Z. Hauschild, Ralph K. Rosenbaum, and Stig Irving Olsen, *Life cycle assessment : theory and practice*. 2018.

[9] M. H. A. Nasir, A. Genovese, A. A. Acquaye, S. C. L. Koh, and F. Yamoah, "Comparing linear and circular supply chains: A case study from the construction industry," *Int J Prod Econ*, vol. 183, pp. 443–457, Jan. 2017.

[10] T. Malmqvist *et al.*, "Design and construction strategies for reducing embodied impacts from buildings – Case study analysis," *Energy Build*, vol. 166, pp. 35–47, May 2018.

[11] M. Haupt and M. Zschokke, "How can LCA support the circular economy?—63rd discussion forum on life cycle assessment, Zurich, Switzerland, November 30, 2016," *International Journal of Life Cycle Assessment*, vol. 22, no. 5, pp. 832–837, May 2017.

[12] Wastiels, L.; Dessel, J. To Module D or not to Module D? The Relevance and Difficulties of Considering the RecyclingPotential in Building LCA; Belgian Building Research Institute: Bruxelles, Belgian, 2013.

[13] U. Iyer-Raniga, "Using the ReSOLVE framework for circularity in the building and construction industry in emerging markets," in *IOP Conference Series: Earth and Environmental Science*, Institute of Physics Publishing, Aug. 2019.