Chapter 42
Life Cycle Assessment at the Early Stage of Building Design

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Abstract In view of the urgent need to construct informed and advanced vision of the built environment in terms of environmental impacts, Life Cycle Assessment (LCA) is even more emerging as the most recognized supporting tool for Architectural, Engineering and Construction (AEC) practices. This is proved by Level(s), a voluntary framework established in Europe that is fully life cycle-based, looking buildings beyond energy performance to the whole life cycle, while fostering the implementation of circular economy strategies. To face buildings complexity, it recommends applying life cycle approach with an increasing level of detail and accuracy, shifting from the assessment of carbon emissions to complete cradle to grave LCA. In this context, many calls for competitions at the reach of environmentally sustainability include Level(s) measures as reference frame to deal with. The paper provides insights of building LCA application performed during the preliminary design phases, since crucial for the decision-making process especially if operating into competition aimed at minimizing environmental impacts. In particular, a sample of building projects developed to address an international architecture competition specifically committed to decarbonization issues in compliance with Level(s) is discussed. Starting from a concrete in situ scenario, the attention is on integrating dry assembled solutions composed of environmental-friendly materials. Results show range of carbon footprint of low-carbon buildings in relation to building shape and volume, outlining building parts that generally contribute to highest release of CO_2 and providing effective technological solutions. The aim is to support AEC practitioners in the design and implementation of buildings embracing a life cycle approach starting from the early design process.

Keywords Life cycle assessment · Preliminary design · Low-carbon building · Decision-making

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42.1 Introduction

Technological innovation is commonly defined as a purposeful activity aimed at developing new products/services as well as new methods to produce, distribute and use them. However, if it intends to have a positive impact on human life, the associated impacts on the environment has too long been neglected, now turning out to be at the forefront of the debate. An evidence is the stressing of advanced technologies to ensure energy efficiency but producing some kind of rebound effects on the environment in terms of resource consumption and waste generation (Huang et al. 2018). Hence the pressing need to develop and apply technological innovations looking at the whole life cycle to take a holistic and systemic approach.

In the field of construction, due to the high environmental, economic and social impacts, this vision is even more shared, promoting the adoption of life cycle criteria, methods and metrics (Röck et al. 2021). At European level such effort is sustained in practice by Level(s), a common EU framework of core indicators for assessing the sustainability of buildings over their full life cycle (European Commission 2021). It offers an extensively tested system for supporting stakeholders across the construction and real estate value chain in measuring and achieving improvements from design to end-of-life, by identifying sustainability hotspots to develop future-proofing buildings, contributing to key EU policy goals (e.g., European Green Deal, Circular Economy Action Plan, Renovation Wave and green transition toward carbon neutrality). In particular, the core sustainability indicators concern carbon, materials, water, health, comfort and climate change impacts throughout the entire building life cycle, acknowledging Life Cycle Assessment (LCA) to estimate effects and define effective ecological transition actions (Sala et al. 2021).

42.2 Call for Competition as Driver Toward Life Cycle Design

In this context, building design becomes a favorable testing ground for experimentation, because here technological innovations are still malleable unlike once completed.

Besides creativity that clearly play a crucial role, design is seen as a form of structured decisions driven by rationality and a set of criteria. Accordingly building project is meant as multi-criteria decision problem to be solved by choosing the design option that maximally meets all requirements. This is why it is pivotal the integration of life cycle criteria into the design decision-making process (Trigaux et al. 2021).

As a result, many design competitions start calling for the application of LCA to verify the implementation along the whole life cycle of solutions aimed at the environmental sustainability. In compliance with Level(s), the claim is for a progressive integration of LCA into design process, starting from simplified assessments based on a single environmental indicator up to complete assessments based on the whole set of indicators (Hollberg et al. 2020). Aim of the paper is thus to check up on the life cycle design pursued to meet competition requirements at the forefront of environmentally sustainability. In particular, the focus is on the early stage decision-making, where leading strategical ideas are arguably placed (Bueno et al. 2018; Najjar et al. 2019) to later affect the entire building process (Rezaei et al. 2019). To this end, a sample of competing projects is discussed in detail, providing insights on LCA application within Architectural, Engineering and Construction (AEC) practices to foster the development of low-carbon buildings proposal.

The design call at issue is the Architecture Student Contest (Saint-Gobain 2022), a two-stage international competition, intended for collecting visions about the revitalization of the district around the East railway station of Warsaw (Poland). Participants are expected to design new housing and to transform the existing old factory into a community hub for meetings, cultural events and leisure activities. Beyond the standard technical parameters of previous editions (thermal/acoustic comfort, indoor air quality, fire safety, natural daylight, energy efficiency), the novelty is the request of building carbon emissions. Such calculations have to assess the whole building life cycle by means of OneClick LCA tool. Moreover, special attention is paid on the achievement of circular buildings and resource efficient solutions. Buildings have to be designed for longevity, resulting flexible in use and easily adaptable over time, with durable and reversible technological solutions, to become material banks for future generations. The embedded resources must rely on efficient products made with minimum use of non-renewable materials and maximum share of recycled content, valuable at their end-of-life for reuse (preferred option) or recycle scenarios. Note that the selection of a single environmental indicator (Global Warming Potential) is in line with the decarbonization goals of construction sector as well as with Level(s), drawing upon the suggested LCA methods and metrics toward circular economy.

The life cycle design promoted by the call is following deepened through the analysis of a sample of 12 architectural projects submitted to the first stage at Italian level. Specifically, with respect to the whole proposed district, one building is in the spotlight for each project for understanding how LCA affects the decision-making starting from early design phases. The goal is to outline the way of practice to reduce/optimize the embodied carbon of buildings for supporting AEC practitioners in the development of low-carbon buildings.

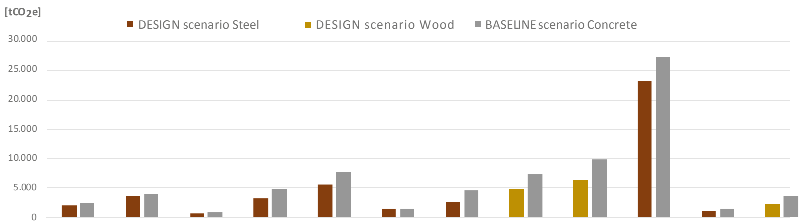
42.3 Building LCA Application for Low-Carbon-Oriented Decision-Making

The major challenge of the competition is to reach the greatest improvement to building performance (meeting all design requirements) while reducing the project carbon footprint. To succeed the call, the effort is to strike out against the conventional notion in which best performance imply the use of more resources: buildings need to be high-performing and resource efficient, carefully assessing design solutions for limiting the environmental impacts along the whole life cycle. For this purpose, all design teams carried out LCA analysis starting from the concept phase to orient the decision-making process and select the most suitable technological solutions. Building LCA have been developed in compliance with EN standards (EN15978) by experiencing the recommended LCA tool and focusing on carbon footprint (CO_2eq). As required, the evaluation considers the entire life cycle from cradle to grave (production, transport, replacement, end-of-life), including all building material flows (operational energy is out of scope) and assuming 60 years of service life.

For defining emission reduction, the designed buildings are compared with "Business As Usual" (BAU), modeled by accounting the same shape, function and location but with standard performance and technological solutions. In this way, the baseline models vary in terms of mass consistent with the investigated projects but keep equal constructive solutions, appropriately sized with the minimum performance demanded. BAU models are based on concrete in situ scenario and consists of: concrete foundation; concrete frame structure; concrete ground slab assembly including insulation (ground floors U-value at 0.30 W/m^2 K); hollow clay bricks wall assembly with insulation and render finishing (external wall U-value at 0.20 W/m^2 K); triple glazed aluminum frame window (windows U-value at 0.90 W/m^2 K); concrete roof assembly with concrete tiles (roof U-value at 0.15 W/m^2 K); concrete slab assembly for intermediate floors and balcony; ceramic tiles and plasterboards for slab finishes; concrete wall assembly and hollow clay bricks assembly for internal wall (10% and 90% respectively); concrete assembly for stairs and elevator shafts. All designed and BAU buildings are intended for student housing.

To meet competition requirements, the preliminary phase is distinguished, besides the design of the architectural space and functional arrangement, by the evaluation of different technological solutions in order to minimize impacts compared to baseline buildings. As opposed to BAU wet solutions, all design teams opted first of all for dry construction technologies, off-site prefabricated elements, modular construction and lightweight systems in order to ensure circularity criteria. In particular, 75% of the investigated projects switch in favor of steel scenario, while the remaining 25% for wood scenario, later optimizing step-by-step the different construction technologies. Before getting into detail, it is important to emphasize that the life cycle-oriented decision-making process allowed an average reduction of carbon emission of −26% for the designed buildings compared to BAU. Figure 42.1 shows the carbon footprint reduction for each building project, ranging from −7% in less virtuous cases to −44% in the most virtuous cases. Normalizing the total building carbon emission per gross surface area, it is possible to identify the average BAU impacts at 534 kg CO_2e/m^2 (range 380–659 kg CO_2e/m^2), while the average design impacts at 391 kg CO_2e/m^2 (range 271–522 kg CO_2e/m^2).

Despite the correlation between building mass and carbon emissions is not evident (Fig. 42.2), shape and volume affect to some extent the impacts. This is proved by the fact that buildings with about the same surface-volume ratio (i.e., envelope surface and heated volume) present different values of kg CO_2e/m^2. For instance, with reference to 0.27 ratio, biggest is the volume, lower are the impacts. However, the



	B01	B02	B03	B04	B05	B06	B07	B08	B09	B10	B11	B12
Gross Floor Area [m^2]	3.988	7.300	1.402	8.593	19.952	3.500	8.525	13.596	16.662	52.540	2.304	6.837
Height [m]	25	22	15	24	26	25	21	23	25	17	25	25
Surface-Volume ratio	0,25	0,21	0,37	0,27	0,27	0,30	0,22	0,34	0,18	0,24	0,40	0,27
DESIGN [tCO_2e]	**2.082**	**3.438**	**697**	**3.176**	**5.417**	**1.346**	**2.548**	**4.607**	**6.284**	**22.628**	**951**	**2.186**
BASELINE [tCO_2e]	2.289	3.927	864	4.752	7.582	1.442	4.578	7.151	9.697	26.795	1.518	3.528
% emission reductions	*-9%*	*-12%*	*-19%*	*-33%*	*-29%*	*-7%*	*-44%*	*-36%*	*-35%*	*-16%*	*-37%*	*-38%*

Fig. 42.1 Reduction of carbon emissions (cradle to grave) between designed building and BAU model [tCO_2e]

display of scattered and oscillating values and thus the failure of trend evidence means that technological solutions grave deepest in the definition of impacts compared to surface-volume ratio. Hence the importance for the design teams of paying much attention to the decision-making selection process of the technological solutions to propose at building scale.

Concerning construction technologies, design efforts for carbon reduction were concentrated, depending on the projects, on specific parts or on the whole buildings, always assessing different alternatives by performing LCA from cradle to grave, to take a comprehensive view of impacts. The optimization process focused especially on building parts above ground, maintaining BAU solutions for foundations and ground slabs. Figure 42.3 (sx) displays the average contribute in terms of CO_2eq

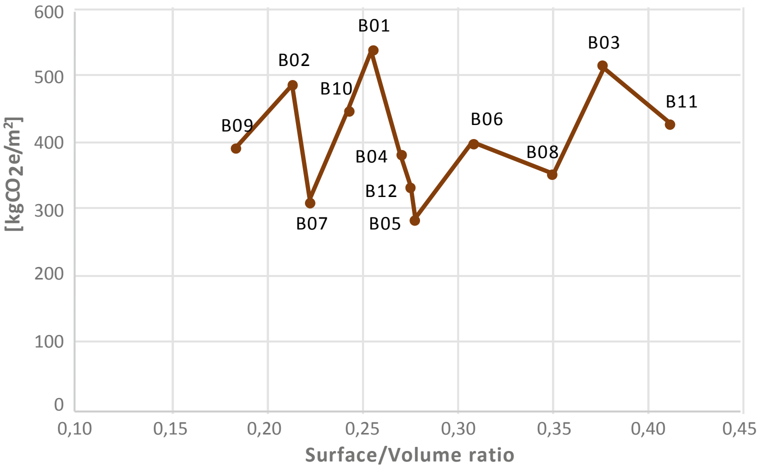


Fig. 42.2 Building carbon emissions (cradle to grave) by *S*/*V* ratio [kg CO_2e/m^2]

of the different building parts on the total carbon emissions, useful during preliminary design to steer decision-making process and optimize building parts with the greatest environmental impacts. Results reveal that the largest share is associated to intermediate floors (34.8%), including resistant slabs and both paving and ceiling finishes. They are followed in turns by: structures (15%), including frames and, if any, load-bearing walls; internal walls (12.1%); vertical envelope (11.1%), including external walls and cladding assembly; transparent envelope (10.7%); ground floors (8.1%); roof (4.5%), including resistant slabs and finishes; foundations (3.2%) and finally accessories as balconies (0.4%). Note that summing up vertical and transparent envelope the share rises at 21.8%, deserving thus close attention of designers, unlike balconies that appear negligible since not provided by many projects due to the climatic conditions of the application context. Anyway, it is worth mentioning that the percentage contribution to the total carbon footprint entails a variability of values among the different building projects because of the different technological solutions. Below an overview of the selected solutions, according to their importance within the decision-making process designed to reduce building carbon emissions along the entire life cycle.

Contrary to BAU, more than half of designed buildings chose metal-concrete intermediate floors, even if intending to provide a full dry constructive technology at present not available within the used LCA tool. The remaining opted for CLT slab assembly and, to a lesser extent, for wooden joist assembly or for traditional solutions in hollow-core or concrete slab assembly. Intermediate floors are finished on the top with parquet flooring and/or ceramic tiles, both including underlayment membrane, and on the bottom mainly with plasterboard or suspended ceiling and in only one case with wood cladding. As advanced, BAU concrete structures have been replaced, as appropriate, with steel or wood frame (in the latter switching also internal load-bearing wall in CLT panels) but maintaining concrete assembly for

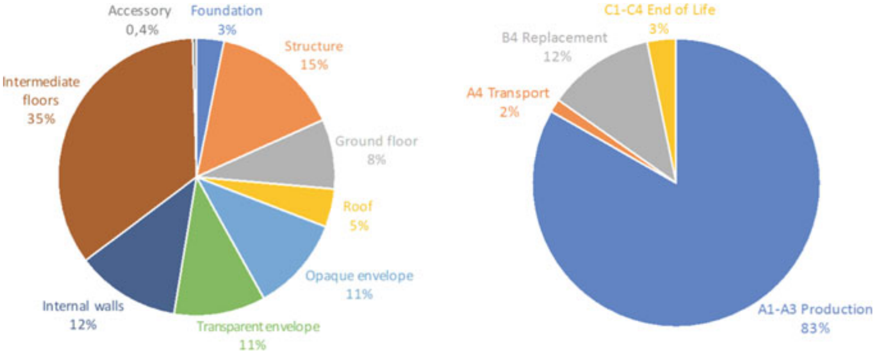


Fig. 42.3 Average carbon emissions (cradle to grave) per buildings parts (sx) and per life cycle phases (dx) [% of impacts]

stairs and elevator shafts due to missing dry solutions. In all building projects with underground spaces, basements are in concrete sandwich wall assembly including insulation.

Internal wall solutions rely for the majority of buildings on steel stud wall assembly and to a lesser degree on wooden stud wall assembly, both including insulation. Dry construction technologies are also selected for vertical envelope, in which timber frame external wall results the prevailing options, even if envisaged in most cases with metal frame (not present into the database). Alternatively, few projects choose insulated steel sandwich wall assembly. If technological solutions for external walls are mostly shared among design teams, they are miscellaneous for cladding system, ranging from the most common fiber cement sheet or natural stone cladding to wood cladding or curtain wall with aluminum frame. Concerning windows, the inclusion of triple glazed wood frame windows in lieu of aluminum frame allows to decrease carbon emissions. Nevertheless, more significant benefits are provided in buildings with double glazed windows both in aluminum and PVC, once ensured the availability on the market of products able to meet the required performance.

With regards to horizontal envelope, all projects modeled ground floors as equal to BAU, only changing the concrete roof solution into steel or wooden frame assembly and, to a lesser extent, into CLT compact roof. Regarding roof finishing, there are no predominant solutions among the investigated projects, composed of a wide range of alternative options: sheet roofing in steel, aluminum or fiber cement; OSB sheeting board and bitumen membrane; double layer of asphalt roofing membrane; slate roof tiles. Finally, for shifting from wet to dry technological solutions, balconies are mostly designed with wooden assembly, even when supported by steel structure (missing solution), to avoid excessive penalization of impacts by keeping the standard concrete balconies.

The designed buildings result from the different combination of the presented technological solutions, reducing carbon emissions in a more or less distributed way between the various building parts. However, looking at the whole life cycle, it is important to emphasize not only the incidence of the different construction technologies, but also how they affect the different phases of life cycle. To this end, Fig. 42.3 (dx) provides an overview of the average percentage share allocable to each phase assessed within the preliminary LCA in relation to the overall carbon emissions. Since operational energy is outside the system boundary and the assessment focuses on material flows over the entire life cycle, the production phase (A1–A3) is as expected responsible for major impacts, counting about 83% of total building CO_2eq. It is followed by the replacement phase (B4) that accounts for approximately 12% and afterwards by the end-of-life phase (C1–C4) and the transportation phase (A4) which represent 3% and 2%, respectively. Of course, these percentage shares vary slightly among the different building projects depending on the selected technological solutions, which notably afflict production and replacement phases. Indeed, while carbon impacts of the transportation and the end-of-life phases are mostly constant, the production phase ranges from 74 to 89% and the replacement phase from 8 to 19% according to technological choices.

42.4 Conclusions

The results discussed above derives from the LCA application at early stage of building design, intended for orienting the decision-making process toward the decarbonization of construction sector and thus the creation of low-carbon buildings. In particular, they deal with a sample of building projects submitted to a design contest which targets carbon emission reduction along the whole life cycle as well as the implementation of circular strategies, in line with Level(s) goals and metrics. Findings are helpful for supporting AEC practitioners in the development of sustainable building and practice, by identifying hotspots over the entire life cycle and outlining effective technological solutions. Notwithstanding, for ensuring informed choices, it is necessary to bear in mind some key issues, related to both the modeling of the foreground system (quantitative data) and background system (environmental data).

Firstly, the constraints imposed by the use of the recommended LCA tool (Carbon Designer) in the definition of impacts (Meex et al. 2018), starting from the modeling of the building geometrical parameters. The tool setting is structured in a user-friendly way that allows automatic calculation of all building reference surfaces from very few parameters in input, such as gross floor area. This served well especially during the concept phases, while offering the possibility of manually adjusting parameters to better reflect the designed building mass. However, it is worth stressing that it is a simplified model, particularly when buildings have complex shapes both on floor (e.g., envelope efficiency factor variable between different sides) and in height (e.g., overlapping floors with difference shapes), but also merely in the presence of loggias instead of balconies. In fact, in the latter case, the loggia slab become the roof of the lower floor, inducing user to deduct the related surface from inter-floor slabs and to add it to the roof, in order to obtain a more representative evaluation (zeroing the balcony surface and considering insulation).

The second key aspect is the limited range of technological solutions to choose from.

If, on one hand, it is useful to orient the decision-making process especially in early design phase, on the other, it risks of restricting design freedom and thus the implementation of innovative solutions. A first attempt to solve the gap has been made by giving users the option to change the layer thickness and rarely also specific material. Nevertheless, in view of current construction sustainability goals and challenges, it is recommended to enrich the set of dry solutions (to date very limited), to enable the edit of external walls, including metal stud in lieu of wood stud, and to expand at least the range of insulation materials to make environmentally-informed decisions about. Moreover, concerning envelope solutions, it would be extremely valuable to display impacts of the chosen solutions in conjunction with transmittance values (pre-calculations to be refined over design process).

In addition, it is important to note that the LCA application at early stages of building design is based on a very few input data, relating in particular to the geometrical modeling of buildings (from which surfaces of different parts are derived) and the selection of technological solutions. This leads to the automatic calculation of material bill of quantities, associating them not only the environmental impacts during the production phase, but also those of the downstream phases by using default values. However, if this approach is effective in the preliminary phase, it is always necessary to check the representativeness of the pre-set quantitative data and gradually detail them as the design process advances (Dalla Valle 2021). For instance, transport distance, replacement cycles and assumptions underlying the end-of-life scenarios turn out to be of significant concern.

Also of note, the calculation of the carbon footprint does not consider the contribution of biogenic carbon of wood-based products, which is evaluated separately inside the LCA tool.

Whilst conducted at preliminary stage and thus with higher degree of uncertainty, it is possible to identify among the investigated projects more or less accurate assessments of building impacts in term of carbon emissions. Indeed, for each building part, the tool allows to select multiple technological solutions simultaneously, enabling users to assign to each one specific percentage of the total. This functionality has been exploited only by few design teams who, for example, specified the share of green roof, rather than of the glass partition wall including the aluminum framing. In this way, depending on the effort of designers, even at the preliminary phases, it is possible to define different levels of detail, that inevitably affect the obtained results and therefore the reduction in the rate of building carbon emissions.

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