Life cycle assessment (LCA) based concept design method for potential zero emission residential building

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Abstract. Regardless a large number of published researches on environmentally friendly building design, realized buildings with a low or zero-emission balance throughout the whole life cycle are rare. Life cycle assessment during building design is not considered a creative but merely calculating task with no direct relation to architecture itself. This research offers an iterative design method, based on life-cycle assessment for buildings, allowing during concept phase to set path for achieving low or zero environmental impact levels. The paper analyses the interrelation of main aspect fields of life-cycle assessment, such as: emission reduction, energy and cost saving as well as implementation of renewable resources during concept design phase for residential buildings. The applicability of the developed LCA based concept design method, its effectiveness for the environmental quality of buildings and influence on architectural factors is examined in a case study project for the hot and dry climate of Cairo. The authors consider, that a combined application of digital environmental assessment tools in initial project phases creates synergies for architectural quality and environmental performance. A combined use of digital tools for the three main aspects; emissions, renewable energy and economic factors allows architects with reasonable effort to design low emission buildings with strong incentives for the creative architectural design process.

1. Introduction
Since the discussion on climate change is intensifying, more and more research on comprehensive methods to eliminate negative impacts of buildings on the environment and global climate is carried out. Nevertheless, most countries in the developing world have no proven or scientifically documented building of a high environmentally friendly standard, which would allow stakeholders in the construction sector to understand the state-of-the-art possibilities for climate neutral building design. Reasons for the low interest to consider zero global warming gas (GWG) or reduce other environmental hazardous emissions are: the manifold of design, construction and the lack of knowledge among architects and planners. As a result, this leads to a reluctant practical application of life-cycle methods in architectural design, one of the comprehensive methods to analyse large amounts of environmental building data to identify systematically the impact on the local and global climate of built environments.

This research presents a digital design method for early planning stages to optimize the ecological footprint and minimize the global climate impact of residential buildings throughout their whole life span. Different assessment tools with their specific environmental, energetic and economic parameters are integrated in an iterative design method, based on a sequential and complementing use. Subsequently, the effect of applying the method to the architecture and design process along its main life cycle parameters was examined and presented in this research report.
2. Life cycle optimized design: a switch to renewable resources
A relevant approach in optimizing the buildings life cycle is to consider the usage of renewable building materials and renewable energy resources, which helps to keep harmful greenhouse gas emission as low as possible or even avoid them completely. Nearly zero-energy buildings (NZEBs) also have a very high energy performance. These buildings depend mostly on renewable sources. The EU Energy Performance of Buildings Directive requires all new buildings to be nearly zero-energy by the end of 2020 and all new public buildings being nearly zero-energy by 2018 [1]. Under the usage of life cycle assessment to optimize building design we understand buildings depending on; active or passive sun, biomass, wind and geothermal energy technologies as well as renewable materials with a minimum of harmful emission for the structural and non-structural building components. Life cycle assessment is considered a method that evaluates every main, sub and sub-sub field of the building in addition to its construction industry in general. By dealing with materials, delivery to the site, construction, operation, use and demolition of the building at the end, life cycle assessment adapts the term “cradle to grave” to be “cradle to cradle” [2]. The main task of Life Cycle Assessment is to optimize the architectural design by repeating, weighting and comparing planning, design and material solutions.

The widespread focus on energy-efficiency in building design can be considered too reluctant in terms of climate saving requirements. Energy-efficient buildings like the Passive House standard or the German KFW 45 standard reduce significantly greenhouse gas emissions through low primary energy consumption but do not avoid CO2 emissions completely, which means that even the most innovative up-to-date building standards still have a negative impact on the local and global climate. Harmful emissions, resulting from building material manufacturing processes, installation, demolition and recycling are not actually considered although they are of high significance. A combined life-cycle assessment, energy benchmarking and passive solar optimization method during architectural concept design phase, supported by several planning tools could lead to a significantly enhanced environmental performance. Evaluating the interplay between different and contradictory physical, architectural, spatial and energetic solutions becomes here of particular importance. Addressing this, the German government now proceeds with the life cycle assessment, highlighting sustainability by introducing the free eLCA online tool, focusing and intensifying the assessment of buildings resources and energy consumption throughout the whole life cycle, particularly in the early stages of the design process [3].

3. LCA integrated architectural design
LCA-optimized concept design represents a great potential, as it offers architects clear solution-making rules for a coordinated environmentally friendly building design, as well as identifying hotspots of excessive negative environmental impacts. Benchmarking of energy consumption and material use based on objective criteria allows to control harmful building emissions and improve environmental quality in addition to identifying synergies between the environmental performance and architectural appearance in the initial design stages. Architectural design taking into account LCA optimization and renewable resources to achieve a climate neutral performance, should consider and balance the following minimum requirements:

- Availability and characteristics of renewable construction materials according a scientific database;
- Climate and environmental conditions for renewable technology implementation into the building;
- Level of energy-efficiency of the building skin and building technology, achievable with a reasonable effort in the cultural and climatic context of the building.

The application of life cycle assessment in the preliminary design stage, supports decision making during design and construction phase, includes the material selection, and has a great impact on the environment [2]. All design solutions, building orientation, considerations of materials and building technologies and energy efficiency are primarily assessed within LCA to reduce emissions concerning average values. The following figure compares a late Life Cycle Assessment (traditional method), where assessment is not done from the beginning with an initial method (optimized LCA), using the method integrated into the initial design process from the beginning.
4. Balancing life-cycle factors and environmental conditions

To reach high quality architectural building design, it is necessary to consider local environment, and specific climate conditions. Different countries develop LCA techniques according to their distinctive situations in addition to applying LCA outcome to the green building certification systems, but some certification systems lack the interpretation for ecologic materials and buildings environmental performance, which need to be urgently considered in these systems [4]. Ideally, buildings are part of the local environment, they make use of the solar conditions and prevailing winds and hence they can be optimized in terms of orientation and self-shading. These complex considerations should be balanced in the beginning of every concept design phase and have a great influence on the life cycle performance.

In a conventional design process for residential buildings, the mentioned factors are usually superficially considered but not optimized with a scientifically comprehensible method or by using specific simulation tools, as this is commonly seen by architects as the task of engineers. It is concluded, that key design decisions are to be made to prevent further use of the nonrenewable energy consumption, reduce harmful emissions to the environment and maximize energy efficiency.

5. Building components relevance for LCA optimization in concept phases

Holistic life cycle assessment based on complex requirements of 2nd generation sustainable certification systems is commonly practiced on large scale projects with interdisciplinary planning teams. On the other hand, the majority of small and medium scale buildings worldwide, are designed commonly by smaller architectural practitioners, planned without environmental impact calculation. Missing governmental requirements for lifecycle and environmental impact assessment in the building sector as well as absence of relevant building codes for nearly all building typologies, make it a neglected discipline, despite the deep awareness of the severe impact of the buildings on the global climate through CO2 emissions. The systematic choice of building components with low or no environmental impact, starting from the concept phase, needs to be considered from the beginning of the design stage. The case study for residential buildings in central Cairo, prepared by the authors during this research shows, which building components are of particular high relevance for the environmental impact and how these components affect the early concept phases. The following table represents the outcome of case study design project of high-rise residential buildings in hot and dry climate of Cairo, in which LCA relevance as well as influenceability are studied and described.
Table 1. LCA relevant building component during concept design phase (source: the Authors)

| Building component | Indicator | LCA relevance (during concept design) | Influenceability (during concept design) |
|--------------------|-----------|---------------------------------------|------------------------------------------|
| Foundation         | CO2 equiv/ sqm NF | High                                 | Medium                                   |
| Floor slab         | CO2 equiv/ sqm NF | High                                 | High                                     |
| Exterior walls     | CO2 equiv/ sqm NF | High                                 | High                                     |
| Exterior doors & windows | CO2 equiv/ sqm NF | Medium                               | Medium                                   |
| Sunscreen          | CO2 equiv/ sqm NF | Low                                  | Medium                                   |
| Interior walls     | CO2 equiv/ sqm NF | Medium                               | High                                     |
| Interior doors & windows | CO2 equiv/ sqm NF | Medium                               | Medium                                   |
| Roof               | CO2 equiv/ sqm NF | Medium                               | Medium                                   |
| RE. Techniques     | kWh / m²a | High                                 | Low                                      |
| Building orientation | Degrees | High                                 | High                                     |
| Walls              | Percentage | High                                 | High                                     |
| Windows            | Glazing type | High                                 | Medium                                   |
| Sun shading         | Perforation | Medium                               | High                                     |
| Wall construction  | Materials | Medium                               | High                                     |
| Roof construction  | Roof type | High                                 | High                                     |
| Facade tightness   | Air tightness | Medium                               | Low                                      |
| Light efficiency   | Watt/ sqm | Medium                               | Low                                      |
| Daylight & occupancy control | Daylight & occupancy control | Medium | Low |
| Plug load efficiency | Watt/ sqm | Low                                  | Low                                      |
| HVAC               | HVAC types | Medium                               | Medium                                   |
| Operating schedule | Hour / day | Medium                               | Medium                                   |
| PV panel efficiency | Percentage | Medium                               | Medium                                   |
| PV payback limit   | Year       | Low                                  | Low                                      |
| PV surface coverage | Percentage | High                                 | High                                     |
| Building model     | Solar analysis | High                               | High                                      |
| Location           | Solar analysis | High                               | High                                      |

6. Integrated method using digital assessment tools

During concept phases, necessary data for a detailed life cycle assessment and energy simulation are usually incomplete or to a big extend missing. On the other side, main design decisions made by architects in the initial phases, define building components, which highly influence the CO2 footprint. In table 1, building components and building properties; contributing significantly to CO2 balance; are evaluated according to the three used digital applications. During the case study project, a quantitative analysis described the indicators in terms of their "Life Cycle Relevance" and "Influenceability"; and their significance was determined by high, medium and low categories. The relevance for life cycle assessment was evaluated when working with each tool in terms of the influence on the architectural design development. The results of the comparison show the importance of specific design measures in the early design stage and the potential of these measures in achieving NZEB. Nearly all main LCA influencing aspects can be sufficiently determined and considered in the early design stage. Simple and scientifically correct evaluation tools can significantly support the architectural design process. There are many LCA evaluation programs now available, such as (LEGP, GaBi, Sima Pro), BIM (Building Information Modelling) or even guidelines (e.g., SNARC) [3].

The authors investigate the applicability of digital tools in early planning stages in several case study projects, aiming to optimize the ecologic footprint for residential buildings throughout their whole life span and explore the implication on the architectural quality. Different assessment tools and their specific environmental, energetic and economical parameters were examined on their environmental and architectural significance to develop an easy design method based on interactions of different digital assessment tools. This was followed by examining the effects and potentials on the traditional architectural design process. The three chosen tools that are used and tested in the case study are FormIt, Insight and eLCA. They integrate with each other to guide the design from its conceptual phase till the end.
The initially used application was the FormIt software, which can be used as an online or computer-based tool operated by Autodesk Corporation. FormIt explicates passive solar use and shading strategy, depending on location, form shape, orientation and solid &void of the building. The created 3D model can be subsequently enhanced within the digital Insight model to evaluate the forecasted energy consumption, life cycle costs and energy-efficiency level of the building by adjusting relevant building component parameters. The Insight application, also operated by Autodesk, is compatible to the 3D models created by Revit and FormIt software. Insight can be used as a plug-in in Revit software or accessed as a standalone online tool. Hence, this software analyzes the abstract 3D model of the case study and the chosen building materials. The eLCA online tool identifies and evaluates low emission materials, then calculates and represents the buildings’ environmental impact benchmarking [5].

Figure 2. Programs usage cycle (source: the Authors)

The scheme shown above represents the sequential process for optimizing building properties and building tectonic with respect to environmental parameters.

The represented steps are necessary to reduce ecological footprint, decrease carbon emissions and get successful compositional results for the building from life cycle assessment perspective ‘figure 3’.

Some limitations have been encountered in the investigation and application of the developed method during case study. These limitations were relevant to the sequential usage of the chosen tools, laying firsthand is the incomplete environmental data of building materials, libraries components and energy efficiency related parameters and secondly is the lack of integration among the applications. The proposed method requires inputs to be inserted manually for every sequential evaluation cycle.

Data used in the case study referred to both ASHRAE & ÖKOBAUDAT databases, sufficient in scope and accuracy to apply the available method in different climatic zones. In addition, The German Ministry for Interior, Building and Community; responsible for the ÖKOBAUDAT development; is recently harmonizing its material data through research and ISO standardization for a worldwide use [6].

Figure 3. Tools usage sequence (source: the Authors)
7. **Practical method application and case study design project**

The developed LCA based design method was applied in an academic case study project for a building located in the center of Cairo. The chosen district is located on the Nile with a project parcel exposed from three sides to the direct sunlight and surrounded by partly historical buildings of the 19th century. The building plot was chosen as an empty brownfield, which generally scores a positive point in sustainability general checklist, preventing to destroy existent buildings nor to build on a green land. With the Nile on the east side of the site, the building benefits from an unobstructed view of the Nile and an undisturbed natural ventilation from prevailing winds.

Applying the proposed method enabled the initial rectangular form of the building to reach its final tectonic form with stepped and extended floor slabs. The perforated building skin and the movable shading devices are optimized. Open floorplan with different apartment typologies, roof design with its active solar energy generators, photovoltaic cells equipped on pergolas & shading elements and green ventilation spaces in several floors were emerged gradually during the implementation of the design method. Each solution has enhanced and optimized the design. The recessed slabs and the shading elements; prevent sun rays, open the view of the Nile and enable the wind to buffer the building ‘figures 4 & 5’. The initial simple 3D model was analyzed with FormIt tool to inspect the solar effect on the building during different seasonal periods or even the whole year ‘figure 7’. As a primarily applied tool, it considers the building location, orientation, and the building mass in addition to solid & void of the building facades ‘figure 6’.

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**Figure 4.** Case study high-rise residential project in Cairo  
(source: the Authors)

**Figure 5.** Section façade of high-rise building in Cairo  
(source: the Authors)

**Figure 6.** Mass model shot, high-rise residential building in Cairo  
(source: the Authors)

**Figure 7.** Solar analysis, high-rise residential building in Cairo  
(source: the Authors)
Consequently, the building model was transferred to the second tool “Insight” to analyze the energy and cost efficiency of the building ‘figure 8’. Energy efficiency parameters were gradually adjusted and monitored through the benchmarking system ASHRAE to optimize energy consumption and energy costs of the building [7] ‘figure 9’. During insight analysis progress; the initial stages showed that the building consumed too much energy therefore, the parameters have been re-adjusted several times to get a better result. These results are translated into different scenarios, which were compared according to their impact on energy and cost consumption. The main parameters available in this tool are window to wall ratio, window glass and window shades (for: North, South, East & West facades), roof construction, PV panel efficiency, building orientation, infiltration, HVAC, operating schedule, plug load efficiency, wall construction, lighting efficiency, day lighting & occupancy controls, PV payback limit and PV Surface coverage.

Figure 8. Insight view, high-rise residential building in Cairo (source: the Authors)  
Figure 9. Insight energy consumption and life-cycle energy cost, (source: the Authors)

LCA optimized building design depends on materials and detailed solutions used in buildings [8]. This includes: reducing the amount of materials used, replacing non-renewable raw materials with renewable raw materials and last not least, replacing non-recyclable materials with recyclable ones [2]. Renewable materials play a great role in achieving a nearly zero emission building. eLCA tool depends on “ÖKOBaudat” database for a wide variety of materials [9]. The material database includes the emissions, u-value, material life cycle and cost of each material [10]. The benchmarking depends on five main environmental issues which are the focus of life cycle assessment evaluation in Germany, these points are: Global warming Potential (GWP), Ozone Depletion Potential (ODP), Acidification Potential (AP), Eutrophication Potential (EP) and Photochemical Ozone Creation Potential (POCP) [11]. (See figures 10 & 11)

Figure 10. eLCA benchmarking, high-rise residential building in Cairo, (source: the Authors)  
Figure 11. eLCA benchmarking table, high-rise residential building, (source: the Authors)

During working with both Formit and Insight: Areas, materials and uses were defined in advance to be used in the third tool. eLCA was used to find renewable low emission materials to match the building requirements and reduce the impact on the environment. Practically, eLCA tool supported the materials choice within a great database, which have the whole information related to the used materials. The benchmarking of this tool depends on Nawoh, which is the rating system for sustainable housing in Germany [12].
8. Architectural relevance

The developed concept design method, based on LCA and integration of renewable resources in the early design stages, proves to be applicable with reasonable effort for architects and at the same time it extends the architectural design possibilities. Moreover, the method allows multitude of additional parameters to be integrated into the design practice. The result is to enhance the core competence of the architect, who is the creator of the built environment, as well as responsible for the preservation of natural resources. Table 2 shows LCA aspects which have a great influence on the architectural design, affect building appearance and have significant potential on achieving a creative building form. Apparently, applying LCA, adds a new dimension in this architectural field.

Table 2. LCA and architectural design building component relevance (source: the Authors)

| Building component | Indicator                     | Architectural relevance |
|--------------------|-------------------------------|-------------------------|
| Foundation         | CO2 equiv/ sqm NF             | Low                     |
| Floor slab         | CO2 equiv/ sqm NF             | Medium                  |
| Exterior walls     | CO2 equiv/ sqm NF             | High                    |
| Exterior doors & windows | CO2 equiv/ sqm NF | Medium                  |
| Sunscreen          | CO2 equiv/ sqm NF             | High                    |
| Interior walls     | CO2 equiv/ sqm NF             | Medium                  |
| Interior doors & windows | CO2 equiv/ sqm NF | High                    |
| Roof               | CO2 equiv/ sqm NF             | Medium                  |
| RE. Techniques     | KWh / m²a                     | Medium                  |
| Building orientation | Degrees                     | Medium                  |
| Windows            | Glazing type                  | Low                     |
| Window shades      | Percentage from window height | High                    |
| Wall construction  | Materials                     | Medium                  |
| Roof construction  | Roof type                     | Medium                  |
| Infiltration       | ACH electronic payment        | Low                     |
| Light efficiency   | Watt/ sqm                     | Low                     |
| Daylight & occupancy control | Daylight factor | High                    |
| Plug load efficiency | Watt/ sf                   | Low                     |
| HVAC               | HVAC types                    | Low                     |
| Operating schedule | Hour / day                   | Low                     |
| PV panel efficiency | Percentage                 | Medium                  |
| PV payback limit   | Year                          | Low                     |
| PV surface coverage | Percentage                 | High                    |
| Building model     | Solar analysis                | High                    |
| Location           | Solar analysis                | High                    |

9. Conclusion

A combined and iterative use of common environmental assessment tools during concept design can played an important role in reaching low carbon levels for buildings. Architectural design based on LCA and a combined use of digital tools represent an easy applicable path to achieve environmentally friendly construction. In general, this path provides a distinct architectural expression adapted to the global climate and local urban context. The research shows that important environmental parameters have a major impact on the architectural design of the building appearance. Environmental parameters like the three main pillars of LCA, energy efficiency, renewable energy generation and renewable material are in direct relation to architectural issues like form, function and composition.

During case study design, it could be demonstrated, that the sequential and linked use of multiple digital evaluation programs, allows the architect to lead the design at a very early stage of the design according climate saving requirements. The explored digital tools enable the reduction of environmental emissions, while recognizing creative potentials for architectural expression. It is also proved that, the repetitive and iterative refinement of renewable materials, energy-saving, renewable energy-generating techniques as well as optimizing the building orientation can govern the design process in creative way. Furthermore, the research resulted in widening the historical architectural perspective to extend beyond “function, form and context” and add new dimensions, related to the physical and energetic environment. To sum up, integrating life cycle assessment within the initial design stage, proves to have a great effect on achieving remarkable architecture as well as controlling cost, energy consumption and the impact on the environment.
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