The role of Life Cycle Assessment (LCA) and energy efficiency optimization during the early stage of building design

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Abstract

The environmental impact of buildings could not be minimized only by optimizing the operational energy since the reduction of operational energy frequently consumes more embodied energy due to the increase of materials and systems used for energy efficiency. Meanwhile, although LCA has been widely used to evaluate the environmental footprint, few studies explored its role in the early building design stage during which majority of the prominent decisions actually already have been made. This paper tries to offer a roadmap by incorporating LCA with energy optimization during the early design phase, to make LCA a more useful guidance tool for improving the design sustainability rather than a method only for the final verification. The workflow of integrating these two approaches is proposed. Several mainstream LCA software are compared and simplified LCA approaches are introduced for the implementation. In the same time, limitations related to this integrative work are also pointed out. For instance, the nature of design is a sequential processing work which fights against the demand of simulation software.

1. Introduction

The building sector has a dominant impact on our environment. In the European Union, buildings are responsible for 40% of energy consumption and 36% of CO_2 emissions (European Commission, 2016). In the United States, 41% of primary energy was consumed by the buildings sector during the year 2010, compared to 30% by the industrial sector and 29% by the transportation sector (U.S. Department of Energy, 2012). Operational energy consumption of buildings is the main focus of this aim and many countries have achieved progress in that regard. But the reduction of the operational energy consumption is not a complete criterion to assess environmental performance because a life cycle evaluation is necessary and many environmental impacts associated with material production are not energy-related (Wang et al., 2005). Previous studies also have identified that the materials used to construct green buildings have higher environmental impacts than those of traditional buildings (Thiel et al., 2013). Comparing with the operational energy optimization, Life cycle assessment (LCA) is a more completed method to minimize the human impact on nature, which addresses the environmental aspects and potential environmental impacts throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e. cradle-to-grave)(ISO 14040, 2006). LCA has been used as a technical tool in construction industry since 1990 (Fava, 2006) and many academic institutions have theoretically worked on building LCA ever since 30 years ago.

Although there is a great number of LCA studies, the research incorporating LCA with other building design approaches, which is the real need of practical projects, is still in a shortage. The design phase of a building exerts great influence on the production, construction and operation stages which are significantly crucial for environmental sustainability. Commonly, four aspects need to be examined for a sustainable building design: energy efficiency, environmental impact, occupant comfort and the cost. These goals are not mutually independent but closely related and interplaying with each other and some of them are even in a trade-off condition. As a result, it should be a multidisciplinary design optimization (MDO) method to design sustainable buildings (Welle, 2007), which is a complicated algorithm rather than simple decision making only for one singular objective. It means that different design approaches have to cooperate with each other for achieving the synthesized goal. Only incorporating LCA with design or correlating energy efficiency with design is unable to design sustainable building. For specific projects in specific conditions, which objectives need to be emphasized and how to integrate those design approaches together should be studied. There are several studies coupling LCA with life-cycle cost assessment methods that consider economic impacts (Norris, 2001), the most related design approach with LCA. Nevertheless, it is not easy to make cost-effective decisions without knowing the trade-off relationship between economical and environmental performance (W. Wang et al., 2005). For most of the construction projects, comparing with the optimization of life cycle cost, actually the energy efficiency is more like a prerequisite. The European Union (2010/31/EU) requires all new buildings inside EU to be nearly zero-energy by the end of 2020. China, United States and other countries all have such kind of guidelines and planning. Thence, energy efficiency and environmental impact can be two basic aims of four objectives which is mentioned above.

The main aim of this paper was to conduct an understanding of the role of LCA and energy optimization in the early design stage. In detail, the purposes of this study were: a) Outline the working process integrating LCA with operational energy optimization; b) Compare different software to select the suitable tool for early design stage; c) Investigate the limitations and possible orientations to improve this cooperated system.

2. Integrate LCA with energy optimization in the early stage

2.1. Research boundaries

Two boundaries need to be defined in the aim of this paper. The first boundary is the scope of selected design period from the whole dynamic process. According to the Chinese code *Standard of design depth in construction documentation*, design period for common projects can be carved up to: concept & schematic design, development design and construction document design. In the *Guide to Building Life Cycle Assessment in Practice* from American Institute of Architects (AIA), concept design is taken out separately. So the whole design period can be divided into: concept design, schematic design, development design and construction document design. These design stages (Figure 1) decide the embodied energy and operational energy of a building. It is usually considered that the early design stage includes conceptual and schematic design and the other phases belongs to the late stage. Decisions made in the early stage have the greatest influence because they define key parameters for the remainder of the design process (Hollberg & Ruth, 2016). What's more, it will cause a lot of troubles to change the plan in the development design and construction document design is a more detailed phase which offers even less possibilities for design changing. In practical projects, LCA is normally done by engineers or the consultant to evaluate the final design. However, engineers do not work until development design and only architects join all the four stages. In conclusion, this paper focuses on the early design stage which contains great potential for improving environmental friendliness (Figure 1).

The second boundary is the selected life stages from the whole life period of a building. With regard to EU standard *EN 15978*, the life cycle of buildings can be divided into: Production, Construction, Use and End of life. Cole & Kernan (1996) already have revealed out that raw material acquisition, production, on-site construction and operation account for 94% of an office building's life cycle energy consumption over its 50-year life expectancy. It means that neglecting the end of life brings little influence. What's more, it is difficult to consider the last stage since the start of building design because no one could tell the destructing technologies after 50 or 100 years. In another perspective, all the design phases have relationship with end of life only in quantity. How much energy consumed in the end of life stage, regard to the building itself, only decided by the volume and quantity of material used. Therefore, the reasonable research boundary in the perspective of LCA should be from product to use stage, "cradle to gate" rather than "cradle to grave". And the actions of maintenance and repairing will also be included in the use stage.

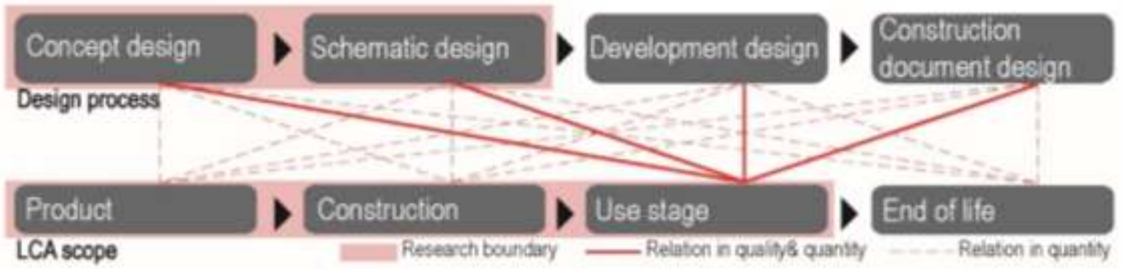

Figure 1: Research boundaries in two aspects, elaborated by the author.

2.2. Workflow of the integration

Building impacts on the environment in their life cycle correlate closely with the primary energy demand (Ramesh et al., 2010). Researchers (Sartori & Hestnes, 2007) found that strategies decreasing the operational energy raise the consumption of embodied energy and as a result, low-energy version buildings needed more embodied energy than the original ones, both in percentage and absolute value. It means that for a single nearly zero energy building, more efficient of operational energy does not necessary mean less environmental impact. In many cases, there is a negative correlation between these two objectives. Therefore, integrating LCA in the early design stage can be a possible way to balance operational energy and embodied energy content (Figure 2) and to verify the environmental impact of a building over the total life cycle. Azapagic (1999) stated that three compulsory steps are needed for incorporating LCA into systematic optimization: (1) Executing a LCA frame; (2) Conclude the multi-objective optimization issue in the LCA frame; (3) Solving the multi-objective optimization problem and selecting the optimal trade-off solution. From the perspective of designing, according to the research from Attia (2012), early design stages of NZEBs can be divided into five sub-phases: (1)

Specifying the criteria of performance, (2) Generating ideas, (3) Zones-layout design, (4) Preliminary conceptual design, and (5) Detailed conceptual design. Figure 1 already identifies that the early design stage exerts the influence over whole life time of a building, especially on the use stage, both in quantifying and qualifying aspects due to the fact that the building performance only have a direct effect on operation stage. It means that the “Use Stage” should be taken as the initial research period for optimizing and verifying, not Product Stage or Construction Stage.

The goal of real operational energy consumption and Eco-efficiency which is the spinal column of the integrated optimization should be set up before the workflow (Figure 2) starts working. As the concept of nearly zero energy building, whose operational energy is nearly offset by the onsite renewable energy, becomes the current mainstream globally, it can be utilized as the goal of performance desideratum. Based on this prerequisites, the second objective is minimalizing the environmental footprint. The building parameters which are big contributors to better performance in concept design and schematic design (Table 1) should be scrutinized and selected. Some variables which is compulsory for simulation but problematic to be decided in the early stage, like HVAC system, can be estimated using converters according to prior benchmark studies. For the operational energy optimization metrics, there are relatively more mature studies so this paper will not talk about them in detail. Then the renewable energy production can also be simulated according to the related parameters, for instance, the area of roof which is possible for solar panels. The operational emission is decided by the real operational energy use which can easily be figured out by subtracting the renewable energy production from the predicted operational energy. If the real operational energy is not near zero, the feedback will be given for making the next iteration. If the requirement is satisfied, the workflow goes to the next step for checking the environmental impact. The embodied energy and the pre-emission which are mainly decided by the quantity and quality of construction materials could also be calculated. Subsequently, the life cycle impact assessment (LCIA) and following LCA procedures can be conducted to finish the LCA verification.

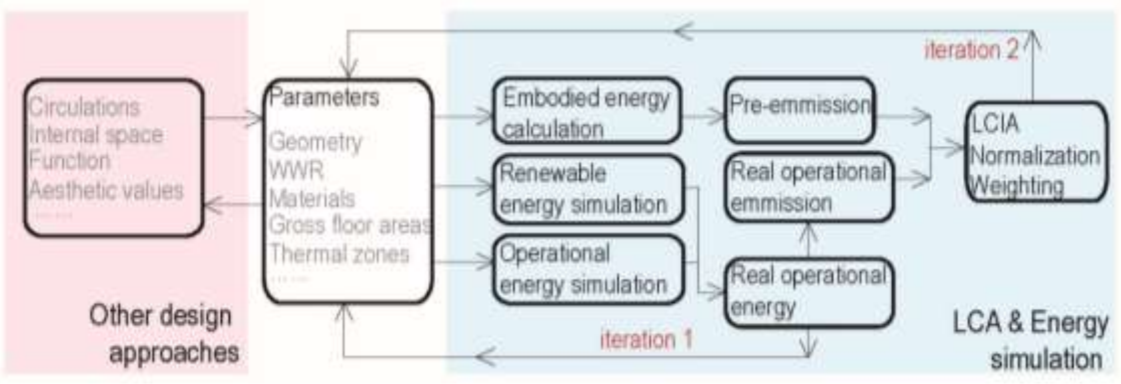

Figure 2: Coupling system of LCA and energy optimization, elaborated by the author.

Table 1: Common designing parameters in the early design stage of NZEB.

Design stages	Input Parameters
Concept design (Pre-design)	Geometry/ The site location/ Building orientation/ Floors/ Gross floor area/ Colour/ WWR
Schematic design	Material variants/ Technical choices/ Service life of the building and construction products/ Internal activities/ Thermal zones

For architects whose work is modifying the design with the LCA results, the decision is difficult to make if the result is not given in a synthesized value. Weighting is a multi-intentional driven action, incorporating social, political and moral values, which connects the quantitative results and subjective decision making. ISO 14040 and 14044 specify that weighting is an optional step in LCA and it cannot be used for comparative assertions intended to be disclosed to the public. For the construction projects in prior time, “Monetisation” and “Panel weighting” are two common weighting approaches (Finnveden et al., 2006). Monetization locates correlative precedence of an impact category in financial value and the values can be given according to expenses associated with preventing or repairing the damage. “Panel weighting” determines weighting factors by inquiring a group of people so this approach can easily be curved by the personal influences of the panellists. For the same impact category, different panel weighting system gives different weighting factors. Distinct panel weighting system has different background, for instance, the system from BEES was invented in the condition of the United States (Thomas et al., 2007). Global warming is the most important indicator in many systems. While Indoor air quality, human health, and habitat alteration in EPA panel weighting system have the highest score, so the hospital or some other projects have special demanding on the health of occupants may choose this scheme.

2.3. Simplification of LCA methods

Huge demand for simplified LCA approaches exists due to the gap between the LCA in theory and its practical use (Baitz et al., 2013), especially for the role of design aiding for which time saving is a compulsory quality. LCA can be divided into three types: screening LCA, simplified LCA and detailed LCA. A screening LCA study is employed for a trial overview of the environmental impacts of a building design and it can be used for internal communicating and helping architects make decisions in the early design stage (Gantner et al., 2012), however, this kind of LCA study is not able to offer explicated results. A simplified LCA study is more advanced and can be practiced for a quick assessment of a building but the challenge is to adapt the LCA methodology and simplify its use. A detailed LCA study follows the standard ISO 14040/14044 and reflects the regular approach of LCA. Apparently, in the early design stage, screening LCA is suitable for concept design while simplified LCA is more appropriate to schematic design.

To avoid misleading results in the screening LCA, care is needed to ensure that omitted building products are not significant for the chosen environmental indicators seeing that a screening study would only put the pin on main factors to the system for evaluation. In the screening LCA, for some omitted processes or beyond the focus of the study, default values can be used. Gantner et al. (2012) think it is also important to use adapted calculation rules for simplified LCAs. Compared with a screening LCA, the data used for a simplified LCA should be more representative of the product, component, element or part of a building under assessment (Gantner et al., 2012). Due to this special condition in the early design stage mentioned above, the sensitivity and uncertainty are needed for conducting the life cycle assessment. Hester et al. (2016) used Monte Carlo simulation method to reflect the design uncertainty and sensitivity of parameters contributing in the early design stage.

2.4. Software for implementing

Varieties of LCA software in the market can be divided into two categories related to the application fields: comprehensive software (for any type of sector) and ones specific for the building sector. The latter ones also can be separated into three subgroups according to the research scales: building materials, building assemblies and the whole building (Table 2). Software which can analyse a whole building is needed in the aim of this paper and most of the software for building sector can satisfy this requirement. The second key element is "visualizing the result in real time" since it is necessary to give feedback to architects for improving the design and communicating with clients regarding the environmental impacts of their choices. Some other characteristics of software also need to be considered. Almost all of the software are lack in assessing the full picture of the building life cycle for different study types and objectives (Gantner et al., 2012). The energy optimization software in the early design stage is in the same situation as LCA software. Attia et al. (2012) considered that the majority of existing tools focus on evaluating the design alternatives after the decision making, and largely overlook the issue of informing the design before the decision making. It is argued that the mismatch between the tool capabilities and the user's needs is one of the reasons why the use of simulation tools is limited in the preliminary design stage (Hopfe et al., 2006).

Table 2: Compare different LCA software for building sector.

Software	**Scale level**	**Regional application**	**Other analysis**	**Normalization weighting**	**Early stage design**
BEES	Assemblies	US	Life Cycle Costing (LCC)	YES	—
Impact	Building	Global	BIM + LCC	—	—
Gabi	Building	Global	LCC	YES	—
Athena	Building	US, Canada	—	—	Concept design
EQUER	Materials/ Building	France	Energy simulation COMFIE	?	user friendly
LEGEP	Materials/ Building	Germany	LCC	?	—
Eco2soft	Building	Global	—	—	—
BECOST	Materials/ Building	Finland	LCC	—	—
ELODIE	Building	France	—	?	—

("?" Means couldn't find specific information, "—" Means not existing or not satisfied)

Packaging LCA software and energy simulation application together is another pivotal topic of implantation. Data managers like "Building Design Advisor" actually can be used in the aim of collaborating work between LCA software and energy simulation software. ModelCenter, a software aiding in the design and optimization of systems, which can integrate standalone applications was chosen in the research (Basbagill, Flager, & Lepech, 2014). Data from different applications can be transferred automatically inside ModelCenter. So, the “optimizing workflow” doesn’t need to be optimized for avoiding transmission errors. ModelCenter can easily answer the question like "what is the trade-off between objective A and objective B.” Ideally, these two workflow circles in Figure 2 should iterate automatically to get the optimal result. However, little literature was found on the topic of automatic iteration. Most of the existing studies set up the framework but architects have to change the variables manually and compare the results by themselves.

3. Limitations

3.1. The assumptions related to the lifetime

The data quality of LCA is temporally and geographically related to the accuracy of sources. Temporal perspective means the data age of life cycle inventory should suitable for the current goal, not too out-of-date. Specific regional data should be used for specific project, due to geographic boundary varies project to project. From the perspective of building itself, inaccurate real life time and operational energy are other two contributors for poor data quality. Randomly chosen building lifetime or excluded interior renovation introduces a noteworthy amount of error into residential building LCA; many LCA studies do not adequately address the actual lifetime of buildings and building products, but rather assume a typical value (Aktas & Bilec, 2012). In a study (Li, 2013) the life expectancy of all the buildings in China was assumed to be 100 years, but the real average lifetime of buildings in China is only 30 years (Wang, 2010) because of intensive urban regeneration. Many case studies in the United States also used unsuitable numbers (Keoleian et al., 2001;Thormark, 2002). While the actual residential building lifetime in the USA is 61 years currently and has a linearly increasing trend (Aktas & Bilec, 2012). Furthermore the building performance condition is a dynamic state rather than a stable one, so the energy consumption during the operation period is changing all the time. Generally speaking, the building performance becomes worse as the time going by if there is no enough maintenance and retrofitting. That’s another kind of “unpredictable” data. Aiming to solve this problem, Collinge et al. (2013) developed a frame to assess the environmental impact in a more realistic and dynamic way, due to the long life span of buildings and potential for changes in usage patterns over time. However, the existing research on dynamic LCA still stays in the starting stage.

3.2. The adaptability problem of early design stage

A concept based on practicability studies is prepared during the early design stage, (AIA, 2012) but many detailed parameters are still unable to be decided at that time. Decisions and approaches improving the building performance are typically not performed until the development design stage (Basbagill et al., 2013). All that makes the energy simulation and the LCA difficult to execute because it is necessary to know the quantified inputs, like the characteristics of materials. As a result, default values or estimated ones have to be used and the inaccuracy of a result comes out. The second barrier is integrating the performance optimization with design itself. Existing MDO methods do not satisfy the need of sequential decision-making processes. MDO requires all design decisions to be made in parallel, instead of allowing designers to define variable values sequentially and thereby understand the impacts of each successive decision (Basbagill et al., 2014). So it doesn't match with the design process which needs sequential decision making. Basbagill et al. (2014) developed a new method by providing feedback to designers after every single design decision and allowing for easy modification of decisions; the methods integrates well with the dynamic decision-making processes common to the Architecture, Engineering and Construction (AEC) industry. Hester et al. (2016) used a regression-based energy metamodel to provide quantitative and probabilistic analyses for conceptual design. The third problem is that building performance optimization needs to provide the design advice without slowing down the flow of the creative generating process (Petersen & Svendsen, 2010), otherwise architects have to repeat and iterate the process for a satisfying result and they would feel being blocked.

4. Conclusions

Nearly zero energy building (NZEB) is the current global trend, however, most NZEB cases only consider the operational energy which is in a trade-off relationship with embodied energy; as a result, the actual environmental impact is not minimized. A more logical way to make design decisions is integrating LCA with the energy optimization, especially for the early design stage which has great potential to raise the environmental sustainability. Great possibility of the incorporation exits but series of problems are still unsolved. The existing mechanism of simulation is unable to describe the dynamic characteristic of building performance. Another problem is the integration with design itself. Designing is a sequential process while all the parameters need to be fixed before simulation. The performance optimization as an underlying design support method is not allowed to consume too much time and cumber the mind flow of architects. The research in a detailed evaluative tools is a crucial prerequisite for the development of multi-objective optimization as an informed design method (Petersen & Svendsen, 2010).

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