A Conceptual Framework to Optimise the Impact of Embodied Energy and Operational Energy in Buildings during the Design Stage

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Abstract

Since the global energy consumption is reaching unsustainable levels, the need for regulating energy consumptions has been highlighted. As revealed from literature, buildings consume approximately 50% of the global energy annually, during construction, operation, maintenance and deconstruction stages. Hence a variety of methods are followed to minimise the impacts of embodied energy (EE) and operational energy (OE) in buildings. EE impacts of buildings are becoming significant with the increased efficiency in OE consumption. Therefore, considering either EE or OE in its individuality is not a pragmatic approach. The design stage was identified as the most suitable stage for integrating energy efficiency measures, since most crucial project decisions are taken at this stage. Different professionals who can impact energy decisions were also identified. Although a multitude of research has been conducted on EE and OE individually, there seems a lack of investigations that focus on both these aspects together. Therefore, this paper sets out to develop a conceptual framework to optimise the impact of EE and OE in buildings during the design stage by reviewing secondary data. The involvement of construction professionals, barriers and strategies to optimise the impact of EE and OE are discussed and incorporated to the framework.

Keywords
Construction Professionals, Design Stage, Embodied Energy, Operational Energy

1. Introduction

Construction is a large, dynamic and a multifaceted industry which encompasses developing new structures and engineering projects (Celik et al., 2017). The construction industry accounts for around 9% of the global Gross Domestic Product (GDP), which is indicative of the economic significance of the industry in the global context (Horta et al., 2012). However, the positive impacts of the construction industry on economic growth is overshadowed by the industry's negative environmental impacts (Yusof et al., 2017). Being a large industry with wide ranging aspects, construction accounts for a significant proportion of the global energy and resource consumption (Basbagill et al., 2013). The building sector which is a major sub-sector of construction, consumes approximately 48% of the annual global energy production throughout the life cycle stages of construction, operation, maintenance and disposition, which emphasizes the need for regulating energy consumption associated with the building sector (Dixit, 2017). Lifecycle energy consumption of buildings can be divided into two main categories as Embodied Energy (EE) and Operational Energy (OE) (Iddon & Firth, 2013). Although the ratio of the general energy consumption breakup of EE to OE of buildings is found to be 16:84 (WBCSD) (as cited by Mani & Venkatarama-Reddy, 2012), the significance of EE has increased with the development of buildings which are highly efficient in terms of the OE consumption. Therefore, Birgisdottir et al. (2017) highlighted that it is important to consider means of reducing both EE and OE in parallel and according to Balouktsi and Lützkendorf, (2016), it is a challenge faced by the construction industry at present. Therefore, this paper was aimed at developing a conceptual framework to optimise the impact of EE and OE in buildings during the design stage by reviewing secondary data.

2. Research Method

Conducting a systematic literature review enriches and reinforces the research process initially. Iqbal (2007) explains that literature review is required to identify any gap in the knowledge and a successful researcher claims a gap in the existing knowledge with evidence. This paper is based on the comprehensive literature review of an on-going research. Thus, the paper elaborates the existing research gaps and way forward. Findings of comprehensive literature review presented the concepts of EE and OE, importance of design stage in achieving energy efficiency, strategies for EE and OE reductions, and role of construction professionals. Finally, relationship between each parameter discussed above were presented in a framework in order to achieve simultaneous OE and EE reduction. Mainly, literature evidence was taken referring journal articles, books, published and unpublished bibliographies, conference proceedings, industry reports and documents. During the literature survey, key terms like embodied energy, operational energy, design phase and energy efficiency in buildings were used.

3. Lifecycle Energy Consumption of Buildings

According to BS EN 15978:2011 (European Committee for Standardisation) (as cited in Giesekam et al., 2016), the building life cycle comprises of four main stages as product stage, construction process stage, use (operational) stage and the end of life stage. A further stage beyond the life cycle, referred to as “Beyond the System Boundary” has also been defined that involves re-use, recovery and recycle processes. Buildings consume energy throughout all these life cycle stages, directly for construction, operation, repair, maintenance and demolition and indirectly for manufacturing of construction materials and components (Sartori & Hestnes, 2007). This lifecycle energy consumption of buildings can be broadly classified into two as EE and OE. According to the International Energy Agency (IEA) (2016), EE is the total quantity of non-renewable primary energy demanded for direct and indirect processes involved in the creation of a building, its maintenance as well as the end of life stages. Alternatively, OE is defined as the primary energy demanded for lighting, heating, cooling and powering of building services (Giordano et al., 2017). Primarily, this is the energy consumed for maintaining comfortable internal environmental conditions within buildings. Population growth, building services enhancement, rising comfort levels along with the increase in the time spent within buildings have increased life cycle energy consumption in buildings to substantial levels (Pérez-Lombard et al., 2008). As a sector that demands significant energy requirements, the building sector also offers numerous avenues for cost effective energy efficiency improvements that would undoubtedly assist in managing the rapid increase of the global energy demand (Nii Addy et al., 2014).

4. Embodied Energy (EE) vs. Operational Energy (OE)

The general understanding is that OE accounts for a significant portion of the energy build-up in buildings when compared to EE. This has resulted in building energy efficiency decisions to be more focused on reducing OE consumption at the detriment of EE considerations (Dixit et al., 2012). Recent years has seen the development of a number of legislative frameworks for improving the energy efficiency of the European built environments which are specifically focused on minimizing the OE consumption (Giordano et al., 2017). According to the author, Energy Performance of Buildings Directive (EPBD) in Europe requires new buildings and properties used by European public authorities to be NZEBs by 31st December 2018, and all new buildings to be NZEBs by 31st December 2020. These targets have been fixed considering the OE requirements leaving out the EE component.

With such policies promoting buildings with low OE, the significance of EE is predicted to increase (Iddon & Firth, 2013). Reports compiled by the “Government Construction Strategy and Government Response to the Low Carbon Construction Innovation and Growth Team” in UK, has recognized the need for an in-depth investigation on EE impacts, which indicates a shift towards EE considerations (Iddon & Firth, 2013). Even though the total energy consumption of modern buildings in absolute terms have decreased as a result of efficient OE reduction measures, the percentage of EE has increased which indicates that EE would play a significant role in ensuring energy efficiency of built environments in the future (Koezjakov et al., 2018). Nevertheless, minimum action has been taken on the legislative front, to regulate EE (Iddon & Firth, 2013). A similar situation is evident in the Sri Lankan context as well, with little to no consideration being provided for regulating EE associated with buildings (Fernando & Jayasena. 2008). These facts emphasize the need for identifying measures to reduce both EE and OE simultaneously.

However, achieving simultaneous reductions in both EE and OE was found to be difficult. Research has identified that most measures adopted for achieving OE reductions, results in an increase of EE. For example, insulation is widely used to regulate the OE demand in buildings, but most insulation material was found to have high levels of EE. This results in a substitution effect where the reduction in OE is counteracted by a subsequent increase in EE, making it difficult to achieve simultaneous EE and OE reductions. This issue has been identified by researchers in the field of energy efficiency and potential measures for achieving simultaneous EE and OE reductions are being considered.

5. Significance of the Building Design Stage in Achieving Energy Efficiency

Most crucial decisions in any construction project are taken during the building design stage, and such decisions will determine the ultimate outcome of the project (Braganca et al., 2014). The decisions taken during the early design stages can have a critical impact on the development of sustainable built facilities (Basbagill et al., 2013; Hakkinen et al., 2015). According to Braganca et al. (2014), projects which are well planned, with sustainable criteria integrated at the early design stages have a greater potential to reduce negative impacts and are also benefited by reduced implementation costs as expressed graphically in Figure 1.

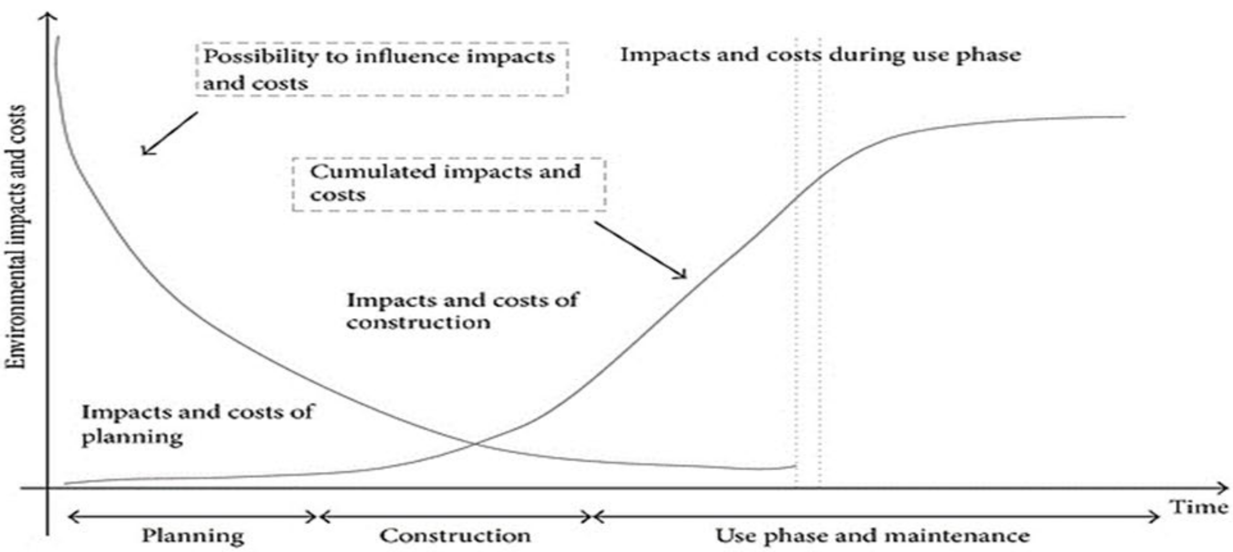

Figure 1.Impacts of design decisions on life cycle impacts and cost (Source: Braganca et al., 2014)

According to Figure 1, the possibility for influencing the impacts and costs is highest during the early design stages, and it drops considerably as the projects proceeds from the planning stages, through to the construction stages. Alternatively, the cumulative impacts and costs of design decisions are lowest during the planning stage. This indicates that early design stages provide the greatest flexibility for change and also has the lowest associated costs of change, making it the ideal stage for integrating energy efficiency measures into buildings.

Despite the significance of the design stage decisions being emphasized constantly in literature, the general practise is to consider sustainability assessments when building designs are almost finalized and the potential for incorporating changes is limited (Ding, 2008), which is a non-productive approach. With energy consumption being a major criteria in the sustainability assessment of built facilities, the necessity to provide due consideration on reducing building energy consumption during design is emphasized. This led the current research to specifically focus on the building design stage.

5.1 Design Strategies for EE Reduction

EE impacts are generally considered as those impacts that are material related which arise from the life cycle processes undergone by building materials from extraction to final disposal or reuse (Rasmussen et al., 2018). Jackson (2005) showed that a majority of the EE in a building can be attributed to its constituent materials and components. This indicates that building material can have a profound impact in determining the EE of buildings. Selection of material manufactured through less energy intensive manufacturing processes, and increasing the content of recycled, reused, natural and locally sourced material was found to provide significant EE savings (Yohanis & Norton, 2006; Venkatarama Reddy & Jagadish, 2003; Thormark, 2003). Alteration of the building form and layout plan to optimize resource use was also expressed as a design strategy for achieving EE reductions (IEA, 2016).

Regular maintenance activities and replacement of building components during repair and maintenance of a building throughout the useful life also contribute to the EE (Qarout, 2017). Therefore, building designs with low maintenance requirements and extended service lives can reduce the impact of EE. EE expended in construction and maintenance of a building cannot be recovered easily (Fuertes, 2017). Therefore, the longer a building remains functional, the efficiency of energy utilized for the construction of a building would be higher, which indicates that the useful life of a building is also a determinant of EE. As such, the reuse of existing building structures and designing for flexibility and future adaptations where possible could provide EE savings. Moreover, the energy utilized for demolition and disposal of buildings at the end of its useful life would also form part of the EE of buildings (Crowther, 1999). Buildings which are designed with disassembly in mind, can reduce the energy consumed in demolition and disposal, thereby contributing to low EE. Furthermore, procurement related strategies such as the use of collaborative contractual arrangements coupled with novel procurement approaches such as Building Information Modelling (BIM) enable procurement was also identified by researchers as a potential avenue for minimizing EE during the design stage.

5.2 Design Strategies for OE Reduction

A wide range of strategies to minimize OE of buildings are expressed in literature. Both active and passive deign measures are incorporated in delivering buildings with low OE requirements (Sartori & Hestnes, 2007). Measures such as increased insulation, recovery of heat from ventilation air/waste water, use of windows with better thermal performance and reduction of infiltration losses were identified as passive design strategies for achieving OE reductions. Further, the use of service equipment with improved energy performance, use of solar photovoltaic panels, solar thermal collectors and biomass burners etc. have been identified as active measures that contributes towards low OE.

Research conducted by Naboni et al. (2015) recognized the higher OE reduction potential associated with the alteration of a building and its elements in terms of the form, orientation, openings and shading mechanisms. The authors further highlighted the need to consider changing energy requirements with seasonal variations, in deciding on the strategies to be used for reducing OE. Factors such as the window to wall ratio (WWR) and shading were found to have varying effects with seasonal changes where designs that increase solar heat gain in winter might result in over heating during summer. Rattanongphisat and Rordprapat (2014), studying on energy efficient buildings in tropical climates noted significant role that can be played by natural lighting and ventilation under tropical climatic conditions. The use of energy modelling and simulation software and the adoption of novel procurement approaches such as BIM enabled procurement was also found to facilitate the design of energy efficient buildings.

5.3 Classification of Strategies

Based on the strategies identified for EE and OE reduction through literature, a common categorization for categorising EE and OE reduction strategies was developed by the researcher. The categorization includes six categories as material selection related, design approach related, internal building morphology related, external building morphology related, building services related, procurement process related and renewable energy related.

6. Role of Professionals in the Design of Energy Efficient Buildings

Literature findings highlight the profound impact architectural and construction decisions have on the energy performance of buildings. However, a lack of knowledge on energy efficient building design concepts among construction professionals was identified and this was recognized as a major impediment for the integration of energy efficiency in building design. Fernando and Jayasena (2008), studying on energy efficient building designs in Sri Lanka identified that most professionals involved in building design are not concerned with integrating energy efficiency measures during building design. Further it was revealed that even though measures for OE reduction are practiced to a certain extent, EE has received almost no consideration in terms of building design. The need for a proactive approach towards developing energy efficient buildings has been expressed and professionals involved in building design can have a significant influence over the development of such buildings. The role of certain key professionals involved in building design is discussed further. The selection of key professionals was based on the traditional Sri Lankan construction project set up.

Architects: Naboni et al. (2015) studying on the energy saving potential of architectural designs found that a strong relationship exists between architectural decisions and energy saving potential. However, according to Ryghaug and Sorensen (2009), majority of architects give more prominence for aesthetics rather than for energy efficiency. Therefore the need for a shift in attitude towards achieving energy efficiency is highlighted.

Engineers - Hargroves et al. (2014) recognized engineering as a profession which can have a substantial impact in the development of energy efficient buildings. The authors emphasized that structural and service engineers can play a key role in ensuring energy efficiency in buildings, through design of structures using innovative less energy intensive material and efficient service systems with nearly zero energy demands.

Quantity Surveyors (QSs) - QSs can contribute towards delivery of energy efficient buildings through the selection of alternative procurement arrangements that facilitates energy efficient design, providing information regarding alternative design options and assessing feasibility of sustainable development options (Ma & Luu, 2013). Moreover, QSs are also encouraged to select collaborative procurement arrangements that facilitates the input of all key professionals in energy efficient building design.

7. Barriers towards the Achievement of Energy Efficiency

Building energy use has been given marginal consideration in building design, especially in developing countries (Bodach et al., 2016). Lack of government regulations on energy efficient design, unfamiliarity among professionals such as architects and engineers on energy efficient design, undermining the potential cost savings that can be achieved through energy efficient design and the comparatively higher initial costs associated with the integration of energy efficiency measures were identified as contributing factors. Moreover, issues such as the limited access to sources of finance, lack of adoption of novel technologies and the perspectives of building owners towards energy efficiency were highlighted. As emphasized by Stauffer (2009), non-collaborative design approaches also impede the development of energy efficient buildings.
Certain barriers specific to EE reduction were also identified through the review of literature. Dixit (2007) recognized the lack of accurate and comprehensive databases on the EE of building materials as a barrier for determining EE of buildings. Complexities in EE calculations was also expressed as a challenge for considering EE during early design stages (Qarout, 2017). Furthermore, the published data bases regarding material embodied energies are out of date and their applicability can be questionable with changes in manufacturing technologies and mechanisms. Dixit et al. (2012) highlighted the comparative lack of standards and regulations governing EE, as a major barrier for promoting EE reductions.

8. The Conceptual Framework

Through the literature survey, the need for reducing both EE and OE in parallel, to develop energy efficient buildings was identified. Building design stage was viewed as the most critical stage where energy efficiency measures can be incorporated to a building. Figure 2 depicts the conceptual framework developed.

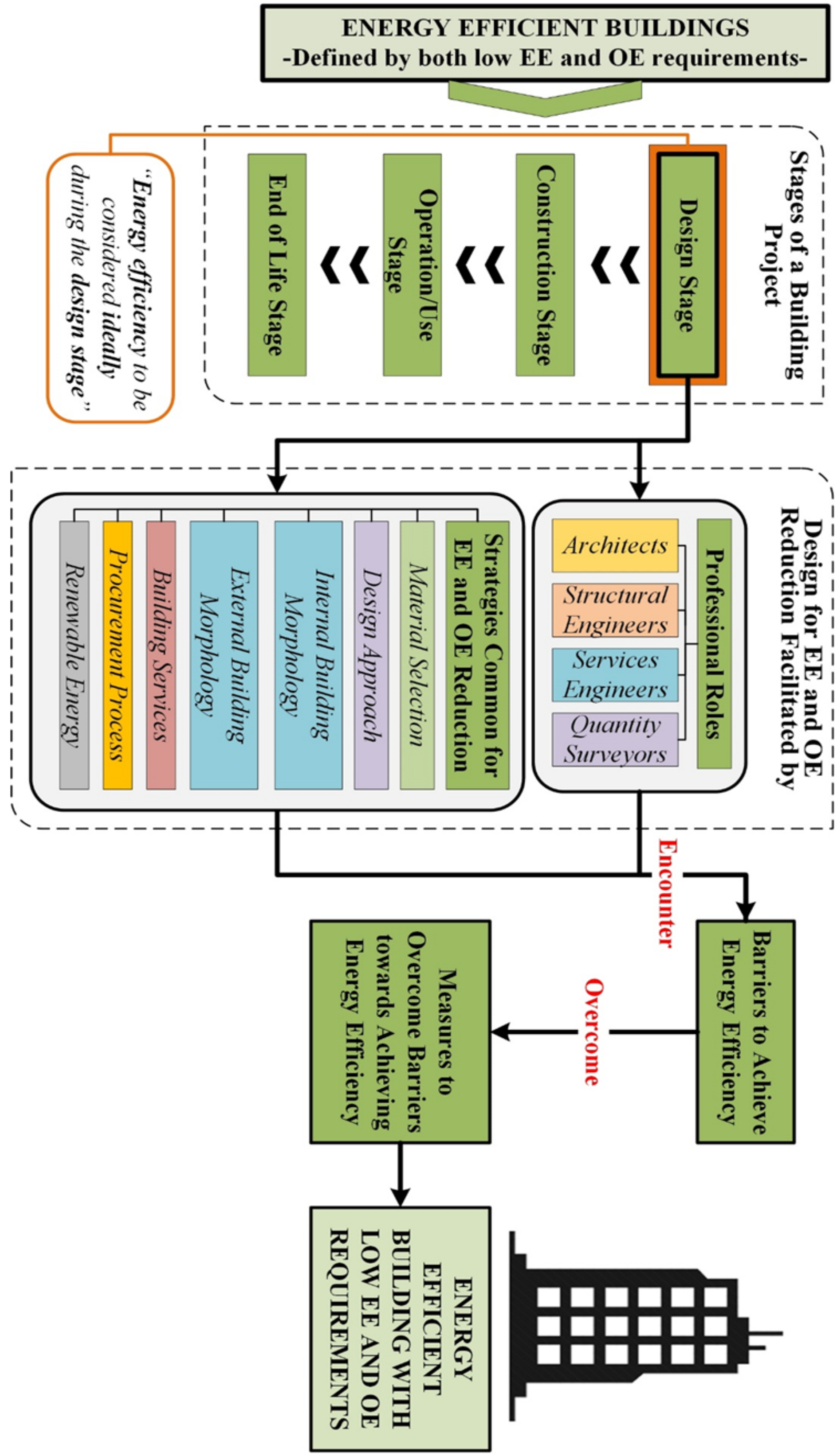

Figure 2. The conceptual framework

The requirement for construction professionals involved in the building design stage, to consider energy efficient building design concepts is paramount. However, certain barriers were identified which impede the development of energy efficient buildings with low embodied and operational energy and these need to be overcome through the implementation of enabling measures. Based on these key considerations, a conceptual framework was developed for the design of energy efficient buildings with low embodied and operational energy.

9. Conclusions and Way Forward

The limited number of research that focuses on both EE and OE reduction in parallel, bears testimony to the fact that achieving simultaneous EE and OE reductions is a difficult endeavour. This paper looks at theoretical aspects and sets the foundation for a larger subsequent empirical investigation on determining strategies for achieving simultaneous EE and OE reductions during the building design stage. As the next step of the study, the conceptual framework, can be used to develop best practice guidelines to achieve simultaneous EE and OE reduction in buildings during the design stage.

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