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Evaluating the environmental and economic sustainability of energy efficiency measures in buildings

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Abstract. It is estimated that buildings in extreme weather regions waste large amounts of money each year in thermal comfort costs, and that if addressed, significant amounts of environmental impacts would be averted. Retrofitting is considered the most immediate, pressing, and effective mechanism for reducing energy consumption and greenhouse gas emissions in the building sector. An environmental life cycle costing was applied to evaluate the sustainability of retrofitting existing buildings. A portfolio of environmental and economic impact results was developed for a baseline building and five alternative retrofitted building scenarios based on insulating the building wall. The results demonstrated a reduction in the environmental impacts and economic impacts by retrofitting the building. Improving the thermal performance of the building resulted in a reduction of environmental life cycle cost of 5%. Externality, which is primarily caused by energy usage, was the key source of the environmental life cycle cost. People in hot climate zones spend much of their time indoors, therefore, it is critical to keep comfortable thermal environment in buildings. This study provides strategically important evaluations for transforming existing buildings into more cost-effective and environmentally friendly sustainable buildings.

1. Introduction

It is known that buildings waste a large amount of money each year in energy costs, and that if addressed significant amount of greenhouse gases (GHG) can be reduced. Massive energy efficiency measure in the building sector represents a key factor for reducing GHG emissions [1,2]. Retrofitting is considered as the pressing mechanism to reduce energy consumption and carbon emissions in the building construction sector. Thermal insulation is a proven green strategy for energy reduction through improvement in the thermal transmittance (U-value) of building envelope [3,4]. The building envelope regulates the heat transfer between indoor and outdoor, and reduces the energy demand of buildings [5]. Thermal insulation materials influence both the environmental impacts of building construction and the use phase of the building [6–8]. The thermo-physical properties of the insulation material determines the thermal behavior of the building wall [1]. Enhancing the building envelope can reduce energy costs and improve thermal comfort for building occupants [5,9]. Study demonstrated that the environmental impact mainly results due to the use of the product life cycle [5]. To this effect, the operating phase significantly determines the economics of a building due to the associated operational expenditure [1,10].

Addressing the energy reducing solutions is very important; however, it is not the only parameter that should be accounted when designing a building envelope [1]. It is important to assess the economic sustainability of a building envelope design. Most life cycle assessment studies of insulation materials



examined the integrated energy and environmental impacts of insulation materials. It is critical that further studies complete these results with the economic implications of retrofitting buildings [11]. Very few studies have investigated the integrated environmental and energy performance of insulation materials [5]. However, the economic sustainability dimension of building design has been limitedly integrated to the life cycle environmental assessment.

The building sector represents a great potential for sustainability intervention due to its large amount of energy consumption and associated environmental impacts. Current energy efficiency policies and Green Building rating systems encourage retrofitting over construction of new buildings [12]. Environmental Life Cycle Costing (ELCC) results can inform designers and construction developers with the cost-effective ways of retrofitting existing buildings when designing a building. This research determines the economic sustainability of retrofitting existing buildings, examines the integrated environmental and cost effectiveness of differing insulating materials for a specified u-value, and identifies the hot spot to achieving economic sustainable buildings.

2. Methodology

2.1 Environmental modelling

A life cycle assessment (LCA) method is applied to analyze the environmental impacts of alternative thermal insulation materials for improved energy efficiency. The studied products were modelled using GaBi software [13]. This study focuses on retrofitting the building wall by applying thermal insulation materials to reduce energy consumption. Hotels are the most sensitive environments with high energy consumption; therefore, a hypothetical nine storey hotel building in the education city of Qatar was modeled as case to analyze the sustainability of retrofitting existing building external walls [3]. Using a functional unit of $1\text{m}^2\text{K/W}$ thermal resistance, this study compares the environmental impact of the most common insulation materials, namely stone wool (SW), glass wool (GW), expanded polystyrene (EPS), extruded polystyrene (XPS) and polyurethane (PU) that represent 90% of the global market with a baseline building with no insulation [11]. It is assumed that the opaque part of the retrofitted building wall will have the same U value and R-value, yet different thickness and mass value across scenarios.

External Thermal Insulation Composite System (ETICS) is the most recommended façade system for warmer climate zones like Qatar [11]. This study considered ETICS for retrofitting existing building wall. ETICS are a build-up system for envelopes composed of multiple layers, including the insulation material, wall, adhesive, and reinforcing coating. All of the life cycle activities from the production, transportation to the building site, the installation in the building, and the use and maintenance phase, to the end-of life of the insulation materials were included from a cradle to grave approach (Figure 1).

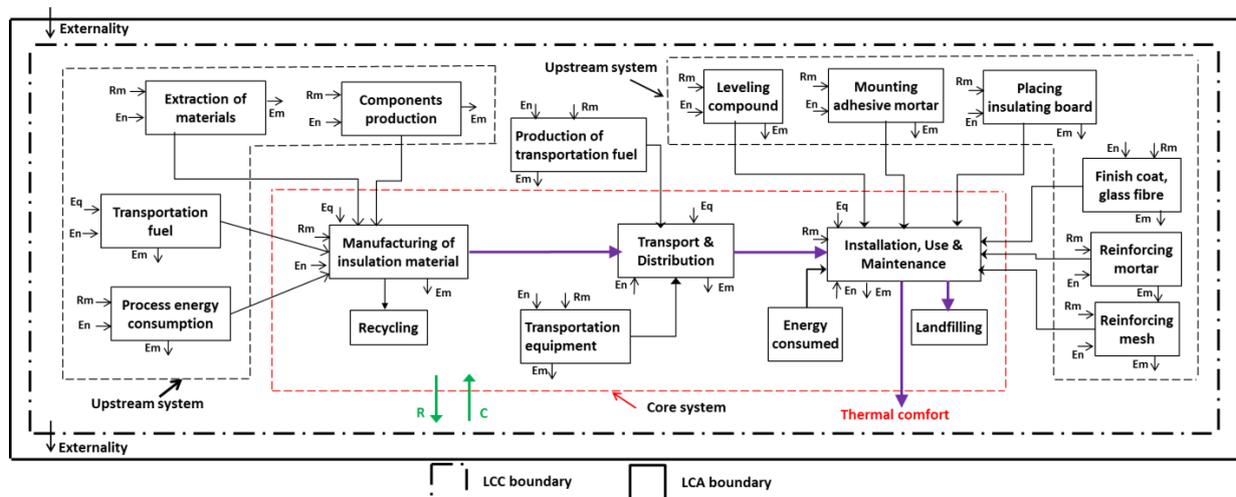


Figure 1. System boundary of building retrofitting.

Note: R: Revenue; C: Cost; En: Energy; Rm: Raw material; Em: Emission; Eq: Equipment

Environmental life cycle data were compiled for the baseline building scenario and for the retrofitted building wall scenarios based on the proposed improved U-value specifications. Energy modeling was carried out using Revit Autodesk software [14]. The amount of insulation material was quantified by relating the functional unit to the heat transferred through its surface area (A) [11]. The thermal resistance R represents the heat transfer through an insulation material. R is related to the thermal conductivity (λ) of a material and its thickness (t). Thus, R corresponds to the density (ρ) and weight of the insulation material. The life cycle reference flow was quantified per functional unit of the same R -value for all insulation materials for building refurbishment. When the U-value of the baseline building is improved from $1.532 \text{ W/m}^2\text{K}$ (i.e., $R=0.65 \text{ m}^2\text{K/W}$) to $0.34 \text{ W/m}^2\text{K}$ (i.e., $R=2.94 \text{ m}^2\text{K/W}$), the R -value for the insulating layer will be $2.29 \text{ m}^2\text{K/W}$. As such, the material required to achieve a thermal resistance of $2.29 \text{ m}^2 \text{ K/W}$ for a 1m^2 panel was quantified.

2.2 Economic modelling

The environmental modeling was followed by a life cycle costing method to analyze the economic sustainability of the case study. A LCC model analyzes all costs associated with the building scenario. A computer-based Excel spreadsheet programs have been developed to quantify the life cycle cost of alternative investments. The LCC modeling was specified with the same system boundary as for the LCA to value the economic sustainability per functional unit of $1\text{m}^2\text{K/W}$ thermal resistance (Figure 1). In this study, the LCC was analyzed based on a study period of 50 years of economic life span through 2018 to 2068. The cost per functional unit of $1\text{m}^2\text{K/W}$ thermal resistance was quantified by linking the input/output flows from the LCA model to the LCC model. The LCC for building scenarios was quantified using the present-value method. Costs can be incurred before, during, or at the end of the service period. Future costs that arise during the system's service period, including salvage values were discounted from the end of the year in which they occur to the base date [15]. The constant dollar method at 0.01% real discount rate was considered to estimate future cash flows. The life cycle cost factors for the building scenario can be categorized into investment, operating, and externality costs. Internalized costs of GHG emissions, which will be internalized in the near future, were included as externality cost.

3. Results and discussion

3.1. Environmental and economic comparison of improving the U-value

The life cycle environmental impacts per 1 m²K/W functional unit of the various building wall systems were compared using LCA. Retrofitting the building wall reduced the impact for all environmental categories when compared to the base building. On the other hand, the net present values for the manufacturing, transport, installation, use & maintenance, and end-of-life LC stages were summed up to determine the economic impact. Improving the thermal performance of the building resulted in reduced economic impact.

3.2. Integrated environmental and economic assessment

A portfolio of the integrated LCC and LCA performances per FU were presented on a two dimensional axis to identify the sustainability balance of retrofitting an existing building (Figure 2). The results demonstrated a reduction in the environmental impacts and economic impacts of retrofitting a building. It is more cost effective and environmentally friendly when the thermal performance of a building wall is improved from a life cycle perspective.

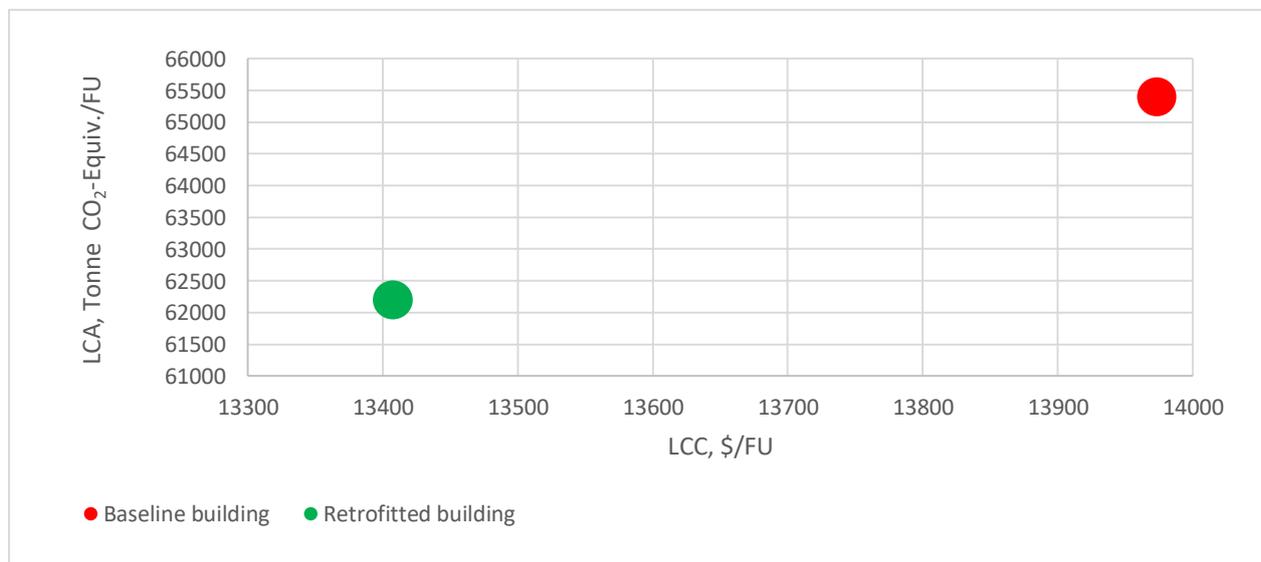


Figure 2. Integrated LCA and LCC impacts per FU of thermal comfort (\$: dollar)

4. Conclusion

Retrofitting is considered as the most immediate, pressing and effective mechanism to reduce energy consumption and carbon emissions in the building sector. This research applied an Environmental life cycle costing (ELCC) approach to evaluate the sustainability of retrofitting existing buildings. A portfolio of environmental life cycle assessment (LCA) and economic impact results were presented for a baseline building and five alternative retrofitted building scenarios based on insulating the building wall. Retrofitting the building wall reduced the impact for all environmental categories, whereas the life cycle impacts among the different insulation systems was insignificant overall. The reduction in global warming potential represented much higher when compared to the rest of environmental impacts. Improving the thermal performance in the external walls should be a consideration for climate change conscious building stakeholders. Improving the thermal performance of the building resulted in reduced environmental life cycle cost by 5%. Thus, economic sustainable buildings can be achieved by retrofitting existing buildings from a life cycle perspective. The results demonstrated a reduction in the environmental impacts and economic impacts of retrofitting a building.

All stakeholders including policy-makers, developers, and architects should account for energy efficiency measures to achieve a return on investment and to address environmental concerns. Externality, which is primarily caused by energy usage, was the major contributor to the total environmental life cycle cost. As such, insulating building walls will become more cost-effective as energy costs increase in the future from the current low prices in the state of Qatar. All building scenarios achieved their least economic impact when the C price was decreased. Decreasing and increasing the build-up cost had little effect on the total outcome in absolute values. Therefore, local standards and policy should target the processes that cause massive energy consumption in order to address environmental issues. The ELCC methodology has improved the significance of the LCA methodology for decision making by integrating economic sustainability impacts and by demonstrating the benefits of thermal improvement measures in the building construction sector. The results found in this research are valid and consistent with previous results for environmental impacts [2,3], energy consumption [1,8,10], and economic impacts [5,9].

Author Contributions: Y.W.W. designed the research, collected the data, modelled the LCA & LCC, analyzed and interpreted the results, and wrote the manuscript. S.A.G modelled the energy use, contributed to the ELCC analysis, reviewed the manuscript, and helped with manuscript improvement and data interpretation.

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