OPTIMIZATION AND LCSA-BASED DESIGN METHOD FOR ENERGY RETROFITTING OF EXISTING BUILDINGS

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ABSTRACT

This paper aims to provide a framework for integration of life cycle sustainability assessment into design process. For this purpose, at first the meaning of efficiency will be defined mathematically by proposing a set of equations. The equations will be designed to be capable to measure life cycle values and costs and able to provide a comparative index for each design alternative applicable in an optimization process.

Finally, in order to evaluate the performance of our proposed integrated design-assessment framework, a set of design variables of a building envelope such as geometry and construction materials will be selected as optimization variables. By using parametric design software and simulation tools such as Rhino-Grasshopper and Energy plus, our proposed framework will be applied on a hypothetical case study, then the results and future development and research directions in this field will be discussed.

Key Words: LCSA, Optimization, Energy retrofit, Building

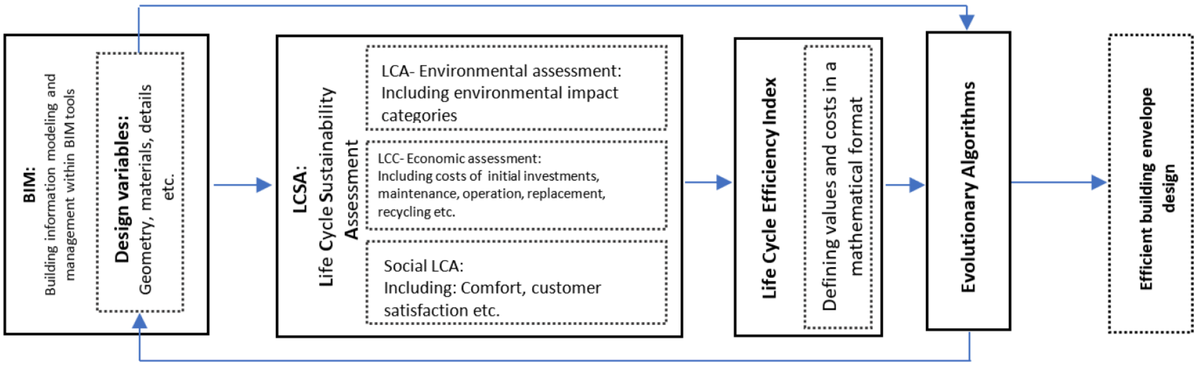
1. INTRODUCTION

The considerable share of energy consumption in existing buildings which is estimated around 40 percent of total energy consumption and noticeable environmental impacts in this sector (Iribarren et al. 2015), alongside the fact that a large proportion of existing building in Europe were constructed before 1950s with low energy efficiency (Vilches et al. 2017) and the reports which show that the renovation rate in building sector is only 1.2 % per year (European-Commission, 2015) indicate that there is a huge potential for reducing the environmental impacts of built environment by energy retrofitting existing buildings. Building envelopes are critical components which can considerably affect the energy performance of buildings (Hay and Ostertag 2018). Designing efficient envelopes both for new and existing buildings can significantly reduce the energy consumption and environmental impacts of buildings (Kheiri 2018). Therefore, in order to achieve sustainability goals in the building sector, designing efficient envelopes have a high importance and priority in energy retrofit interventions.

To answer the question of sustainability in building sector, it is required to have a comprehensive approach for building performance assessment capable to evaluate various sustainability criteria such as environmental, economic and social aspects, over all phases of a building life cycle (Jensen et al. 2018). Life cycle sustainability assessment (LCSA) is a method capable to quantify the environmental impacts, economic and social aspects of products or services with a whole life cycle perspective (Geng et al. 2017) however few studies have addressed to all three main areas of sustainability (Invidiata et al., 2018) and most of them have only focused on environmental or economic aspects (Gilani et al. 2017). Integrating life cycle sustainability assessment and optimization into design process is a new research topic, few studies have been published in this subject and further studies should be carried out in future. Research works performed by Holberg and Ruth (2016), Lobaccaro et al. (2018), Jusselme et al. (2018) and Amini Toosi and Lavagna (2018) are some of few papers published in this subject in recent years.

2. RESEARCH METHOD

A Framework for integrating life cycle sustainability assessment into designing efficient building envelope is presented in figure1. The framework is comprised of different steps in an iterative process. First, the definition of efficiency should be determined according to the project targets. For this purpose, the efficiency should be defined by a quantitative method.



[Figure. 1] Conceptual framework for integrating LCSA into designing efficient building envelope

$$Life\ Cycle\ Efficiency\ Index_{\,j} = \sum\nolimits_{i=\,Production\ Phase}^{End\ of\ life\ Phase} (Values\ increment_{ji} + Costs\ decrement_{ji}\,) \qquad (1)$$

Equation1, presents a mathematical definition for Life Cycle Efficiency Index (LCEI).

Where: I: the different stages of the building's life cycle J: the building, product or scenario under assessment

Life cycle efficiency index is defined by values and costs. The values and costs should also be defined and presented in a dimensionless format. The environmental (LCA), economic (LCC) and social aspects (S-LCA) will be analysed according to European standards and guidelines. Values and costs will be calculated by equation 2 and 3 To make the values and costs dimensionless, the existing performance of the case study could be considered as the baseline.

$$\text{Values increment}_{\text{j}} = \left[CFTWt\left(\frac{\text{Thermal Comfort}}{\text{Baseline Thermal Comfort}}\right) + \cdots\right] \qquad (2)$$

$$\text{Costs decrement}_{\text{j}} = \left[\text{EnvWt}\left(\frac{\text{Baseline environmental impacts value}}{\text{Environmental impacts}_{\text{j}}}\right) + ICWt\left(\frac{\text{Baseline global costs value}}{\text{global costs}_{\text{j}}}\right) + \cdots\right] \quad (3)$$

Where: CFTWt, EnWt, ICWt: weight of Comfort, Environmental, Energy, global costs, respectively.

In this paper, thermal comfort is defined as value, and as S-LCA indicator since it is directly affect the inhabitants' satisfaction level. Thermal comfort will be evaluated and reported as percentage of comfortable time according to adaptive thermal comfort theory. The costs are defined in terms of environmental impacts and life cycle costs. The environmental impacts will be calculated according to EN 15978, the CML LCIA method is considered and

7 midpoint indicators corresponding to 7 impact categories will be evaluated (table 3). The environmental impacts will be assessed both for materials and total energy consumption (heating, cooling and lighting) of the thermal zone. The thermal zone geometry will be defined parametrically in Rhino-Grasshopper and the operational energy demand, thermal comfort will be analysed by Honeybee plugin (using Energy plus live connection). The LCA, LCC and S-LCA as well as proposed equations will be defined in Grasshopper and will be inserted in the optimization process by Galapagos component.

3. RESULTS

According to above-mentioned methodology, a simple thermal zone is defined parametrically. The boundary conditions of all surfaces (walls, roof and floor) are set to outdoor condition. Table 1 and 2, present the geometric and physical properties of the thermal zone. In order to avoid any complexity in results, a very simplified thermal zone is modelled in this case study. Structural parts and window frames are excluded and the thermal bridge effect is not analysed. All the walls, roof and floor are modelled as components with two construction layers (EPS insulation and concrete).

[Table 1] Geometric description of the thermal zone

Location	Geometry		Life Span	Zone program	Temperature set points		Illuminance required	Fuels	
Milan-Italy	Floor area (m)	10*10	30 years	Residential	Heating	20 C	300 lux	Heating	Natural Gas
-	Height (m)	3	-	-	Cooling	25 C	-	Lighting/ Cooling	Electricity

[Table 2] Construction layers and materials used in the thermal zone

	Construction layers (from inside to outside)	Thickness (m)		Density (kg/m3)	Thermal conductivity (W/m-K)	Specific heat (J/kg-K)	WWR		Boundary condition	
Floor, Roof	EPS insulation	Variable a 0.1 m b		20	0.035	1300	0		outdoor	
	Light concrete	0.1		1500	0.5	1100				
Wall	EPS insulation	South	Variable a 0.1 m b	20	0.035	1300	South	Variable a 0.1 b	South and north	outdoor
		North	Variable a 0.1 m b				North	Variable a 0.1 b		
		East	Variable a 0.1 m b				East	0	east, west	outdoor
		West	Variable a 0.1 m b				West	0		
	Light concrete	0.1		1500	0.5	1100				
glass	U value is 3.3 W/m2-K, Solar heat gain coefficient is 0.6, Visible transmittance is 0.65									

Only insulation thickness of walls, roof and floor, and window to wall ratio of south and north wall are defined as design variables in this study. In this study LCA, LCC and S-LCA are weighted equally.

The indexes in table 2 (a and b), refer to the different single- variable optimizations in which some parameters are kept fixed while the other is taken into account as a variable. For instance, in the first optimization the thickness of insulation is the variable while WWR of south and north wall are kept equal to 0.1.

The optimization process is performed in four times (3 single- variable and 1 multi-variable). In order to understand the influence of each variable on the optimization objective, only one parameter is set as variable and others are kept constant in optimizations 1 to 3 (according to the table 2). In the last optimization all input parameters are set as design variables at the same time.

[Table 3] Environmental and economic data of material and energy used in LCA and LCC calculations

	Environmental data							Economic data
	GWP(kg CO2 eq)	ODP(kg CFC-11 eq)	AP(kg SO2 eq)	EP(kg PO4 eq)	POCP(kg C2H4 eq)	ADP elements(kg sb eq)	ADP fossil fuels(MJ)	Material price (installation included) (^)
Materials								
EPS (1 kg)	4.612979	1.2E-07	0.016389	0.002747	0.006862	7.58E-07	99.10928	40.9 per 1m2 with 20 mm thickness. 1.23 will be added for each 10 mm.
Glass (1 kg)	36.31064	4.12E-06	0.282713	0.051654	0.011638	0.000137	410.641	22.69 per 1mm
Energy								
Natural gas (1 MJ)	0.073375	5.78E-09	0.00019	1.47E-05	1.45E-05	2.71E-08	1.149727	0.0731 per 1 kWh

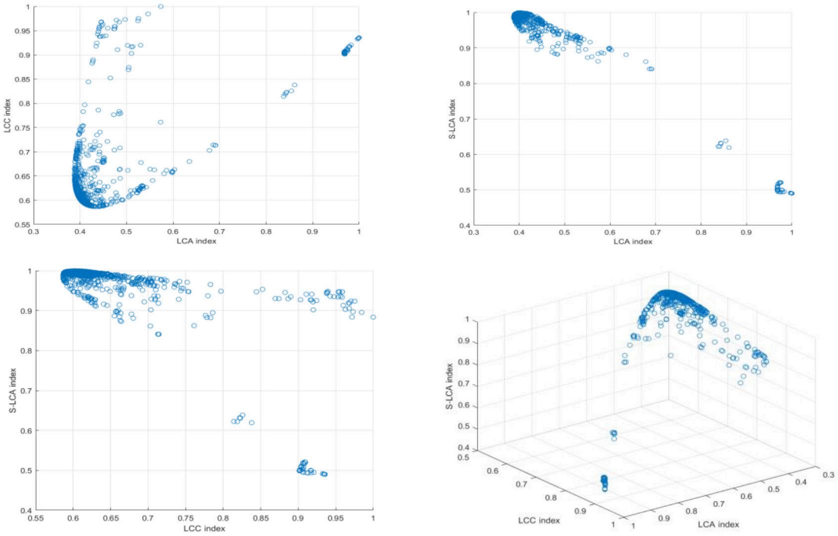
Electricity (1 MJ)	0.150662	1.96E-08	0.000656	0.000172	3.31E-05	7.11E-08	2.000522	0.2142 per 1 kWh
Normalization								
N values	5.79E13	1.61E8	3.83E11	1.22E12	2.80E11	4.39E8	4.5E14	-

Since in this study, only insulation thickness and window to wall ratio are taken into account as design variables and will affect the comparative results, these materials and energy consumption are considered in LCC and LCA calculations. The environmental and economic input data of materials and fuels are presented in table 3. The environmental impacts are calculated by SimaPro, based on Eco-invent database, the normalization values are taken from the document published by EU (Sala et al. 2017). The price of materials and installation costs are taken from the price list published by municipality of Milan (Premia, Adulti, & Anni, 2017).

The Result showed that the S-LCA index which represent the thermal comfort level increases by insulation thickness from 0 to 0.22 m, then it gradually decreases. The optimum insulation thickness is 0.22m. Reverse relations are found for LCA and LCC indexes. The optimum insulation thickness for minimizing environmental impacts and global costs over the life cycle are 0.39m and 0.18m for LCA and LCC respectively.

According to these results for minimizing the total life cycle environmental impacts more insulation is required compared to LCC minimization. These results are directly connected to the thermal performance of insulation materials as well as their embodied environmental impact and the cost of materials and installation. However, other parameters such as annual increasing rate of energy prices and interest rate of investments affect the results over the life span of the building.

The results for WWR-Optimization are acquired in 2 different optimization processes in each of them the insulation thickness is fixed on 0.1 m and the south and north window to wall ratio is set as variable and 0.1 respectively and vice versa. The optimum WWR for south and north wall is 0.1 and 0.05 if the total energy consumption is the optimization objective. But according to S-LCA, LCA and LCC indexes, the optimum WWR for south wall are 0.07, 0.09 and 0.11 respectively. These values for optimum WWR of north wall are 0, 0.12 and 0.17 correspondingly.



[Figure 2] 3D and 2D illustration of all simulation results in multi variable optimization

The results showed that life cycle efficiency index is more sensitive on WWR of south wall in comparison with north wall and rapidly decreases by increasing WWR. This behaviour of LCEI is directly and vividly influenced by energy demand in different WWR of south wall. The optimum window to wall ratio of south and north wall are found equal to 0.1 and 0.14 respectively. Due to the significant increment in cooling energy demand by increasing south WWR and regarding that cooling energy is assumed to be supplied by electricity which is more expensive economically and environmentally compared to natural gas in this Italian case study, the optimum WWR is higher for north wall than south for maximizing life cycle efficiency index.

Finally, the multi-variable optimization is performed by 3000 simulations, figure 2, shows the result of simultaneous optimization for insulation thickness, south WWR and north WWR according to equal weighting factors for S-LCA, LCA and LCC indexes.

The important point is that the result of this multi-variable optimization is acquired in a combinational form of design variables, which allow designers to understand the performance of different design alternatives and choose each of them according to their preferences and compare them with the maximum achievable performance. The results show the combination of variables for achieving a set of optimum results could be very different. In this case study, by the equal weighting for S-LCA, LCA and LCC, minimum and maximum LCEI are obtained from 0.4951 and 1 respectively. In this range the maximum LCEI corresponds with 0.3 m, 0.22 and 0.02 for insulation thickness, north WWR and south WWR. However, there are many different combinations with less than 0.04 reduction in performance which could be chosen as the final solution in accordance with other design criteria. For instance, the values 0.26 m, 0.17 and 0.22 for insulation thickness, north WWR and south WWR will result in life cycle efficiency index (LCEI) equal to 0.9619 which has a negligible difference with maximum performance and a considerable difference in the variables combination. These results and findings also show that there is a flexibility in some design variables such as window to wall ratio if a quasi-optimization is considered in the optimization process.

4.CONCLUSION

In this paper, a new method for integrating life cycle sustainability assessment is applied into designing the external envelope of a simple thermal zone. The framework includes life cycle environmental impacts of materials and energy consumption over the life cycle of the thermal zone as well as life cycle costs (material price, installation costs and energy price) over 30 years of life span. This research is the first part of an ongoing PhD research which has been started by authors and the purpose was to show how this framework is effectively able to find the best scenarios for designing efficient building envelopes. The results showed that the proposed method is capable to perform as a decision making support within a design process and is able to find the best scenario considering various life cycle values and costs. The method is also applicable for designing different parts of building envelope and facades and for finding the optimum shape and geometry of a building facade or any components of a building. In future research works, more complicated design variables and scenarios could be taken into account and also more values and costs will be considered into defining life cycle efficiency index. The other question which will be answered in future research works is how to select the best weighting method for comparing different values and costs for each case study.

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