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Development of a multi criteria analysis method to optimize the sustainable architectural design of residential buildings.

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Abstract. This research is dedicated to the development of a multi criteria analysis method to optimize the sustainable architectural design of residential buildings. In this perspective, four axes have been chosen on the entire building life cycle: energy, ecology, health (including well-being) and economy. The building setting will be evaluated as its typology, its size, its construction method, the choice of the materials and of the systems implemented, since all these elements influence energy consumptions, environmental impacts, users' health and financial costs. In order to be able to compare the four dimensions of this assessment, the developed methodology is based on the translation of energy consumption, environmental impacts and health impacts into energy costs, environmental costs and health costs, which makes them comparable to the building life cycle costs. According to users' selection of the optimization axis and various optimization and design parameters, based on predefined options, this methodology will produce optimal solutions. Finally, this method will be useful for improving the sustainable performances of buildings, helping to create energy-efficient, ecological, healthy and affordable housing projects.

1. Introduction

Nowadays the architectural and urban design fields are more and more restricted by a normative framework that becomes stricter every day. Among the current standards in Europe, the EPB (Energy Performance of Buildings) Directive and its transposition by Member States into national legislation have one of the most important impacts on architectural design. It concerns more or less all the different levels of the construction but the EPB legislation only focuses on one issue: building energy consumption during its use phase. However, if reduction of energy use is a requirement, other important fields are to be considered, for instance: the choices regarding the production of sustainable energy, the embodied energy affecting ecology, the implemented materials potentially affecting occupants' health and cost repercussions generated by some sustainable options during the early design stage. Design decisions affect buildings energy consumption but have also life cycle environmental and economic impacts and have an influence on inhabitants' health and well-being. The four axes considered in this research – energy, ecology, health and economy – are thus interdependent in the architectural project. However, the means, legal or not, that are used currently to favour the design of sustainable buildings don't take that interdependency into consideration. Since these four axes are not assessed together, the interferences that can arise between them are hidden.

Moreover, the building performance is also influenced by its context (type of neighbourhood, etc.). The decisions that are made in relation to the housing context have energy, environmental, health and economic impacts. Therefore, this research takes into account two different aspects: the building and its surrounding context that we will limit here to its neighbourhood.

The tools we have at our disposal currently to study those issues are the normative framework (EPB, comfort standards, etc.), the methods for a life-cycle evaluation (LCA, LCC, etc.), the building certification methods (BREEAM, LEED, SB-tool, etc.) and the simulation-based optimization methods. The two first are too specific and don’t allow to study the four research goals and their interdependency. Building certification methods are multi-criteria methods but they don’t allow buildings optimization during their design phase. Simulation-based multi-criteria optimization is a powerful tool for buildings optimization, but its use is always limited to the optimization of only two parameters, while we study several indicators related to four design goals. In this research, we propose to develop a multi criteria methodology to help designing sustainable residential buildings. The main goal is to favour the use of a multi criteria analysis for optimizing new housing projects design, in accordance with the four previously mentioned axes (energy, ecology, health and economy).

2. Methodology of research

Based on a literature review and an analysis of the current and future standards, we choose several criteria for assessing the sustainability of a residential building, in each of the four selected research axes, including energy, environmental, health and cost impacts. Then, we proposed a methodology allowing weighting and comparison of these various criteria. Finally, we have coupled the multi-criteria evaluation method defined in the first part with the criteria weighting method and an optimisation method to generate the final multi-criteria optimisation methodology.

3. Choice of sustainable design criteria

3.1. Energy issues

In many European countries, the energy performance of residential buildings is mainly defined by the performance of their envelope and is regulated by the EPB certification. Due to the current idealization of the passive standard, some important issues have not been taken into account. Among them, there are, for instance, the amount of embodied energy and the growing use of technologies (that will have to be maintained and then replaced) [1]. A life cycle analysis of the Belgian dwelling stock [1] has demonstrated that the passive standard is not always the optimum to be reached when the whole building life cycle is taken into account, including construction, use phase, maintenance and end of life treatment. The legislation, focusing only on the reduction of energy consumption during buildings use phase, doesn't encourage architects to design sustainable buildings [2-3]. It is indeed possible to think in a different way, for instance by taking into consideration the embodied energy related to the used materials and systems or by thinking about the occupants’ behaviours and life-cycle modes [4]. Usually research about residential energy consumption is generally limited to the study of a residential building out of its context. Yet the context in which the architectural project is located is important for finding the best solutions to reduce its primary energy demand [5-6]. For that reason, aiming an energy optimization of residential buildings, it is needed to take into account the setting of the building, which implies its location, its orientation, its surroundings (urban, suburban or rural) and its accessibility in relation to the public transport modes and green mobility infrastructures.

3.2. Ecology issues

Ecology is defined as the science that studies the interactions between the living beings and their surroundings; here we will understand it as the interaction between human and his environment. In the framework of a sustainable housing, it can be considered through environmental life cycle analysis (LCA), which is regulated by European standards [7-8]. It allows to give a detailed environmental performance for any product or service and to analyse its different impacts on the environment and resources consumption during its production, use, maintenance and end of life. In Europe, the CEN standards give a detailed methodology to apply environmental LCA to buildings [9-10]. If we can find a lot of scientific references concerning buildings LCA, only a few of them take into account influences of the neighbourhood and occupants behaviours. Yet we must not underestimate, when analysing LCA results, the importance of inhabitants' way of life, their management of buildings energy systems and mobility choices [11]. An important part of the ecologic impact of buildings is due to their use phase due to factors linked to water and energy consumption that depend themselves on a great number of other factors, such as climatic zone, surrounding buildings, orientation, building dimensions, construction method, insulation level, and implemented systems. The greatest users of energy for residential buildings are the heating and ventilation systems and the production of sanitary warm water system [12]. The building and demolition phases generate only a small part of the environmental life-cycle impacts of existing buildings [11] but become more important studying life-cycle environmental impacts of new buildings with very high performance (nZEB, positive energy buildings, etc.), so that the choice of materials is important for sustainable buildings. Finally the issue of the building end of life, the last step of the life cycle, concerns the waste management and the different recycling channels as well as materials re-use.

3.3. Health issues

We spend, on average, over 90 per cent of our time indoors; most of this is now spent in our homes [13]. In the health research field, exposure-response relationships for a given risk factor are expressed in deaths or DALY (“Disability Adjusted Life Years”) associated with the risk factor. However, the World Health Organization (WHO) defines health as "a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity" [14], but this principle that a house should promote health, rather than simply prevent disease, is not considered in current regulations and standards [13]. Numerous studies have demonstrated the direct influence of comfort level in living spaces and qualities of the built environment on the health and the well-being of inhabitants [15]. Yet health impacts are rarely taken into account during the building design, even though it has been established that the building and its neighbourhood have a greater influence on the health and well-being of inhabitants than their work environment [15]. It is thus important that architects and building designers conceive their projects with inhabitants’ physical health, mental health and social well-being in mind, for example by reducing the factors generating environmental stress (noise, overheating, air pollution, etc) and social stress (insecurity, etc). Note that there is little research into the health effects of living in recent house designs. For example, health impacts related to a tight house envelope with mechanical heat-recovery ventilation in temperate climates has yet to be determined [13]. Let us mention the following design factors for healthy single-family housing design [13, 15]: importance of daylight and access to direct sunlight, comfortable thermic environment, acoustics quality, indoor air quality, openable windows, radiant heating, occupant controllable systems, enough space, views on nature or surrounding neighbourhood, security against unauthorised entry and a dwelling that is favouring social interaction while offering privacy. The contextual characteristics of a residential building (type of neighbourhood, accessibility, etc.) will also play an important role in its impact on the health of inhabitants through several factors [15]: outdoor air quality, vicinity of green areas, pleasant networks for active travel modes (like walking or cycling), housing density and typology, social interactions in the neighbourhood, access to local and healthy food.

3.4. Economy issues

The life cycle costing analysis (LCC) [16] determines the global cost of a project by taking into account the following costs: investment costs (purchase of land, architect's fees, taxes, construction costs, etc.), yearly operating costs (exploitation, maintenance, energy costs), replacing costs (if an element is faulty for instance) and end of life costs (waste management, etc.) [17]. It is the global cost of a building during its whole life cycle that must be optimized, from the early design, in a perspective of sustainable development. It allows an evaluation of the real cost that the building will generate on a lifetime period [18] rather than the investment cost that is generally the only information used during the design phase of a new housing project.

3.5. Optimization criteria and constraints

On the basis of the energy, ecology, health and economy issues discussed above, we chose optimization variables and optimization constraints. The definition of the optimization criteria has been made on the basis of current standards and well recognized assessment methods. We can cite the criteria defined by the European standards concerning the environmental LCA applied to buildings [9] and the Life cycle cost of buildings [16] but also those coming from recognized environmental assessment tools [19, 20] concerning the health impacts, resources consumption (energy, water) and waste production. In addition to the optimization criteria, some optimization constraints will need to be selected by users (architects or future inhabitants) based on predefined performance levels. The optimization criteria and constraints integrated into our method are detailed below for each axis.

Energy: three energy optimization indicators have been selected: life cycle embodied energy, operational energy use throughout the building service life, end-of-life energy consumption. These three indicators are expressed in terms of primary energy demand and calculated during the building life cycle [19, 20]. Their sum corresponds to the Cumulative Energy Demand in primary energy, also called Life Cycle Energy Use. The primary energy analysis makes it possible to take into account the different energetic vectors (electricity, heat) on a homogeneous basis. The analysis goes back to the upstream phase of fuels extraction (such as crude oil or uranium), or other resources (such as hydroelectricity). Constraint value: The energy constraint is the desired building energy performance level chosen by the user: EPB or passive or zero-energy level.

Ecology: eleven LCA optimization indicators have been selected, including the seven CEN environmental LCA indicators [9], but also Ecotoxicity: terrestrial and water [19], Water resource depletion [19], Ultimate Waste [20] and Radioactive Waste [20]. The seven CEN LCA indicators include: Global Warming Potential, Depletion potential of the stratospheric ozone layer, Acidification potential of land and water, Eutrophication potential, Formation potential of tropospheric ozone photochemical oxidants, Abiotic resource depletion potential for fossil resources, and Abiotic resource depletion potential for non-fossil resources. The Global Warming Potential reflects the warming potential of the various greenhouse gases, converted into tons of CO_2 equivalent over a period of 100 years. The Ozone Depletion Potential of a compound is the relative amount of degradation to the ozone layer it can cause. Acidification is linked to the phenomenon of acid rain and forest dieback; it is expressed in kg sulfate equivalent. Eutrophication potential is linked to the intake of substances acting as fertilizers (nitrates and phosphates) in surface water, promoting the development of algae, which are toxic to living organisms during their decomposition process. The decomposition of certain Volatile Organic Compounds (VOCs) under the action of the sun contributes to the formation of photochemical ozone, also known as smog, which has harmful effects to the respiratory systems of many living beings. Natural Abiotic Resources Depletion potential reflects the depletion of the environment in mineral and fossil resources; the calculation is based on the remaining stocks and consumption rate of the current economy. Ecotoxicity reflects the ultimate damage to nature in terms of biodiversity damage; it is expressed as a percentage of extinct species × m^2 × year. Water Resource Depletion quantifies total water consumption over the entire life cycle of the structure, measured in cubic meters of water drawn. The Ultimate Waste is divided into three categories: inert, hazardous and non-hazardous waste. Radioactive Waste impact includes Category A, B and C of radioactive waste; quantities are expressed in dm^3. Constraint value: The ecology constraints are related to land use (occupation and transformation) and maximum building dimensions, based on the desire of the users and the urban regulations.

Health: three optimization indicators [19] have been selected: Human toxicity: cancer and non-cancer effects, Particulate matter, Ionising radiation (human health effects). These three indicators reflect the impacts on human health, expressed in years of healthy life lost; they are expressed in DALY (Disability Adjusted Life Years). Constraint value: The health constraint is the comfort level to achieve in the building through daylighting, acoustic performance, thermal comfort, etc. chosen by the user in connection with national and international standards: 80% or 90% of satisfied inhabitants.

Economy: three optimization indicators [16] have been selected: investment costs (such as acquisition and construction costs), use and maintenance costs, end of life costs (such as collection and recycling costs). Their sum corresponds to the building global cost, namely Life Cycle Cost. Constraint value: The cost constraint is the maximum investment cost acceptable for the project.

4. Development of a multi criteria analysis method

A set of optimization criteria to assess the sustainability of a building design has been developed. In addition, we have defined optimization constraints, which are minimum or maximum values that are imposed to some building performances during the optimization process. According to the wishes of the method users (architects or future inhabitants), one or several optimization axes will be chosen in the list of the four studied fields (energy, ecology, health, economy). Following this choice, the optimization process will consist in finding one or more optimal solutions to minimize the selected optimization criteria, while ensuring that the optimization constraints are achieved. The non-selected optimization criteria will become optimization constraints, ensuring to reach at least reference values for a sustainable design. Thus considering a project according to a selected optimization field, different optimization constraints will be added. Finally, the users have to choose the design parameters of the optimization, based on a list of predefined parameters included in the method. Then, a sensitivity analysis, followed by a simulation-based optimization study or a parametric improvement study, is applied with the chosen optimization and constraint criteria. So, the optimal solution of our multi-criteria optimization method will be different following the domain(s) on which the optimization will be done as well as the choice of the performance levels for the optimization constraints and the design parameters. Figure 1 presents a graphical summary of how user choices influence the optimization results. The purpose of users' participation is to take into account the specific characteristics of each situation and to facilitate the implementation of sustainable solutions thanks to the involvement of users throughout the whole optimization process.

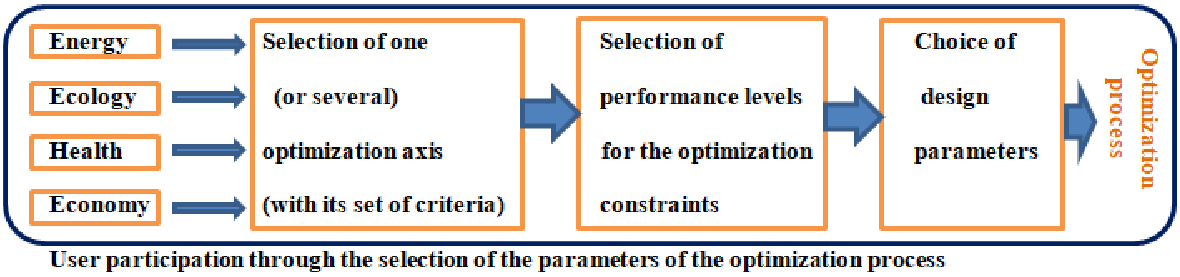

Figure 1. participation of users (architects / inhabitants) in the definition of optimization parameters

To be able to compare the results obtained by assessing the optimization criteria, a weighting method must be applied to all impacts to convert them into a global indicator that will allow their relative analysis. The method chosen here is monetization, which translates each impact in a cost value. The cost calculation will follow the Monetization method of the MMG (Global method monetize) updated in 2017 [21], which is based on a methodology developed previously [19]. Monetary values for each environmental indicator have been determined in this methodology [21] for three regions: Belgium, Western Europe, and the rest of the world. Note that the error margin related to the monetary value is low. Each value of an individual environmental indicator has to be multiplied by a monetization factor representing the cost of the damage to the environment and/or humans for avoiding potential damage or setting any damage incurred. The different life-cycle assessments can then be combined into a same optimization simulation. Table 1 shows the conversion values of some environmental impacts in environmental costs and Figure 2 gives a graphical summary of the proposed optimization method.

Table 1. Example of monetary values for four indicators [21].

Environmental Indicator(CEN)	Unit	Value € /unit
Greenhouse gas	kg CO_2 eq	0.05
Biodiversity damage	PDF.m^2.year	0.30-0.59
Energy demand	kWh	0.2
Human health	DALY	60,000

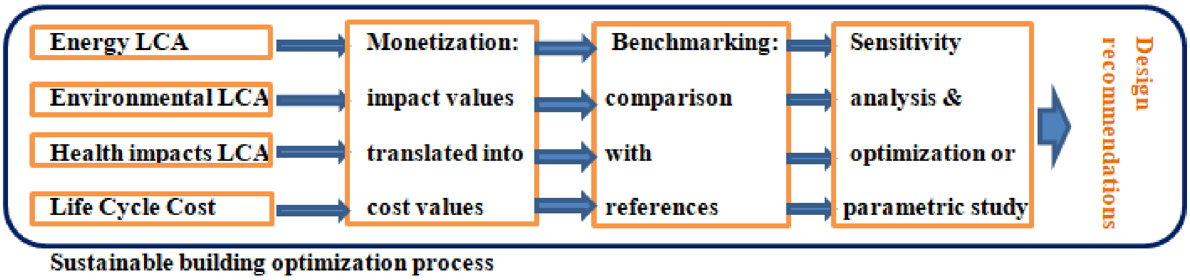

Figure 2. The sustainable building optimization method.

Once all the indicators have been translated into costs, they are compared to reference values corresponding to sustainable buildings presenting similar constraints as the case study. Then, the process of optimization continues through a sensitivity analysis, followed by a simulation-based optimization (using genetic algorithms thanks to an optimization engine) or a traditional improvement process based on a parametric study.

5. Conclusion

In this paper, we developed a multi criteria analysis method providing a global evaluation of sustainability criteria of residential buildings on their entire life cycle. The future of this research will consist in the application of the developed methodology on the design of a terraced house located in Belgium. Then, applying the method to other typical residential buildings in Belgium will allow us to generate a data basis of simulation results corresponding to a variety of different optimization choices. Finally, these results will be analysed for the establishment of a set of recommendations in order to improve the early design stage of sustainable housing design in Wallonia. This methodology could also be used in other countries to improve their new housing design or to define design recommendations to be applied from the early design phase.

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