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New Methods for Sustainable Circular Buildings

J Andrade[1], C Araújo[1], M F Castro[1] and L Bragança[1]

[1] Department of Civil Engineering, University of Minho, Guimarães, Portugal

joana.andrade@civil.uminho.pt

Abstract. Cities can and should be an open field to sustainable circular guidelines since its scale complexity becomes an impact (positive or negative) over the environment as deep as its dimension. On this scenario, construction industry aims to develop products that fulfil also functional requirements and at the same time safety and durability during all the life cycle phases, promoting reversible buildings to avoid constructions obsolescence and recourses' waste. Most of the Building Sustainability Assessment methods require detail in the input data, hampering their usability at early design stages. So, the paper presents two complementary methods that are being developed to promote early stage sustainability through both sustainability design decision-making guidance and assessment of investment willingness and affordability. The first method enables project teams to compare design alternatives and verify which is the most sustainable choice and alerts them how sustainability concerns are linked to all design criteria, constraints and decisions. The second method is a cost-benefit analysis method to analyse and compare building solutions that consider the stakeholders' investment willingness and market availability. These new approaches can lead to a more sustainable built environment and contribute to more circular economy since it allows thinking on reversible and transformable buildings since the early design stages choosing solutions closer to the building stakeholders' investment willingness and the users' affordability.

Keywords: Early Stages Design, Integrated Design Process, Investment Willingness and Affordability, Sustainable Building Solutions.

1. Introduction

The building sector is one of the most resource consuming sectors in European Union. In their whole life cycle, from the extraction of materials, the manufacturing of construction products, construction, use and maintenance, buildings in the EU amount for around: one half of extracted materials and energy consumption, and one third of water consumption and waste generated. On other hand, the building sector has also a significant impact at social and economic level. This sector is estimated to be worth 10% of global GDP and employs 111 million people [1].

In the Roadmap to a Resource Efficient Europe, buildings are highlighted as one of three key sectors to be addressed. Better construction and use of buildings could help making significant resource savings: 42% of final energy consumption; about 35% of total GHG emissions; 50% of the extracted materials; and up to 30% of water in some regions [2].

2. Concept of sustainability and building industry

Sustainable Development is a concept whose importance has grown significantly in the last decades. The global economic crisis has reinforced growing environmental concerns as well as raising the awareness of the population towards a necessary and inevitable change in the values of their societies. The ease and lack of concern of people worldwide, especially in industrialised countries, is the base of this increasingly three-dimensional crisis (social, environmental and economic). In this scenario, the positivism of new initiatives aimed at changing this global attitude of the world population is highlighted.

Today there is an explosion and even trivialisation of the concept of sustainability, which seems to be omnipresent in the daily lives of today's population. The issue related to environmental issues has been widely publicised by the media and is often manipulated by advertising actors in order to achieve objectives other than those of improving the planet's environmental, economic and social condition. In this way, and to be able to witness a real change in society with the aim of improving sustainable performance, it is necessary to inform and raise awareness of the populations in a correct way [3].

2.1. Building Sustainability Assessment methods

The major reason, which promoted the development of systems to support environmental performance assessment of buildings, was that the countries were unable to say how sustainable a building was. This is also true for countries and design teams, which believed that they were experts in this field. In this regard, several countries have developed their own systems for sustainability assessment adapted to their reality and presenting them as capable of guiding the overall performance of this sector. Most of these systems are based on local rules and legislation, in locally conventional construction technologies, with the default weight of each indicator set according to the actual local socio-cultural, economic and environmental contexts [4].

Among the systems and assessment tools currently available on the market it is possible to highlight some of them for increased use and accuracy: BREEAM (Building Research Establishment Environmental Assessment Method); CASBEE (Comprehensive Assessment System for Building Environmental Efficiency); DGNB (Deutsche Gesellschaft für Nachhaltiges Bauen); Green Star; HQE (Association pour la Haute Qualité Environmentale); LEED (Leadership in Energy & Environmental Design); NABERS (National Environmental Australian Building Rating System); and SBTool (Sustainable Building Tool).

SBTool is a generic framework for rating the sustainable performance of buildings and projects and authorized third parties can be allowed to establish adapted SBTool versions as rating systems to suit their own regions and building types. For instance, owners and managers of large building portfolios, can also use it to express in a very detailed way their own sustainability requirements to their internal staff or as briefing material for competitions. Lastly, it can also be an educational tool, since developing benchmarks for a wide range of issues is a useful experience for graduate and post-graduate students.

In Portugal, some tools have been developed under the structure of SBTool. There are already three available, focused on the following building types: residential buildings; office buildings; and tourism buildings. In addition to buildings a method and a tool to assess the sustainability of urban areas and urban neighbourhoods (SBTool Urban) is also under development.

2.2. International Policies

The differences between the criteria of the different assessment tools make the definition of “Sustainable Construction” subjective and difficult to compare the results obtained from each of the methods. In this context, the International Organization for Standardization (ISO) and the European Committee for Standardization (CEN) have been active in producing standards (eight and eleven respectively) for the environmental and sustainability assessments of buildings.

Considering founding programs, it is possible to highlight Horizon 2020, which is the biggest EU Research and Innovation program ever, over seven years (2014 to 2020). European Union (EU) established demanding targets to be achieved by 2020, 2030 and 2050: reduction of GHG emissions; share of renewable energy consumption; energy saving compared with the business-as-usual scenario; and share of renewable energy in transport sector.

Regarding legislation there are been published directives and standards about building materials (ISO/EN 15804), construction and demolition waste (Directive 2008/98/EC) and indoor environment quality (EN 15251). Although, related to sustainable buildings the legislation is mainly focused on energy: Energy Performance of Buildings Directive (2010); and Energy Efficiency Directive (2012).

Recently, Directive 2018/844 of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency, was published. The main objective of this new Directive is to accelerate the cost-effective renovation of existing buildings, that is to introduce building control and automation systems as an alternative to physical inspections, to encourage the implementation of the necessary infrastructures for efficient mobility and to introduce an intelligence indicator to assess the technological preparation of the building. Thus, among the changes that occur, the following stand out [5]:

- Introduction of new definitions, such as "automation and construction control system";
- Implementation, by 2050, of a long-term strategy to support the renewal of MS building parks, transforming them into energy-efficient and decarbonized real estate parks;
- To instruct the EC to act legally through actions complementing this Directive by establishing a common voluntary regime for the classification of the degree of preparedness for intelligent building applications with the definition of an indicator and a method of calculation;
- Establish mandatory periodic inspections of heating and air-conditioning installations with a rated output of more than 70 kW;
- Determine primary energy consumption in kWh/ (m^2.year) as a numerical indicator for certification purposes and to meet minimum energy efficiency requirements.

2.3. Actions for sustainable circular economy

The circular economy provides an industrial system that is restorative and regenerative by an early design stage considering the different building life cycle phases, providing a low carbon economy and a sustainable growth, maximising the benefits and reducing the costs. In addition, it also delivers dynamic and interactive services and enable expert assistance, learning, and peer-to-peer sharing experiences to reduce human error [6].

Even all these actions being carried out, the majority of buildings are still not sustainable, and there are a small number of commercial and residential buildings certified by a BSA method. The reason for this is mainly because: sustainable solutions have higher initial costs; lack of information on solutions costs and benefits; lack of public awareness; disbelief on social and economic benefits of sustainability; lack of political support/incentives. So, what could be done?

3. Methods for sustainable circular buildings

According to the Ellen MacArthur Foundation and SYSTEMIQ [7] report three main themes within built environment should be invested in to promote a circular economy, being (i) designing and producing circular building through designing and producing multi-use highly modular buildings and energy positive buildings made of durable non-toxic materials; (ii) closing building loops by ramping up recycling and re-manufacturing building materials and; (iii) developing circular cities, through integrating circularity into urban developments through innovative business models.

The first of these topics directly relates with building design. Besides, in order to implement this concept and make it sound, decision-making support tools are required to aid in building design. Such tools help practitioners implementing new design solutions towards circular economy and sustainability.

Accounting for sustainability concepts should occur as early as possible in the building design process, as any other project required aspect, to increase the probability of succeeding in the sustainable design [8]. It is essential to define key goals and establish targets to which design alternative solutions can be evaluated and compared to. This enables the identification of measurable criteria to assist designers defining the solutions that would accomplish the project goals, with minimal environmental impacts and costs. Also, if the goals are not easily measurable and understandable, limitations and inefficacy to their achievement could occur [9]. Most of the existing building sustainability assessment (BSA) methods are not applicable during early design, as they require a certain data detail that is not available early in the project [10].

Moreover, it is essential to bear in mind the economic viability of the design solutions under study. Even if a solution has a high performance with low environmental impact and could drive a low life cycle cost, it cannot be considered sustainable nor economically viable if stakeholders are not willing to pay for it. Several studies had already addressed the economic viability of building solutions [11] and the stakeholders' willingness to pay for sustainable solutions [12]. However, there is a lack of a comparative methodology that takes this parameter into account.

Take into consideration the abovementioned it is of major importance to consider the stakeholders' opinion on the process of comparing building solutions, because it leads to the selection of solutions that best suits their interests. Therefore, in this work two novel methods are presented. The first is a design support tool which enables designers to set sustainability goals early in the project and aids them to attain for those, allowing the comparison of alternative solutions. The second consists in a cost-benefit analysis method, where the selection of best building solution is according not only to LCC and solutions performance, but also to stakeholders' desire/willingness to invest in sustainable solutions.

3.1. Early stage design method for building sustainability

The decision-making support method intends to assist early-stage design on pursuing a building's life cycle sustainability. The main aim of the method is to aid designers define sustainability goals and accomplish them through guidance, and evaluation and comparison of design solutions performance. It intends to make designers aware that all design criteria, constraints, and decisions relate to sustainability concepts.

To cope with that, the method was developed with two main approaches: (i) quantification and (ii) decision-making. The first enables measuring the potential impacts of design alternatives within all the sustainability indicators and their burden to the whole building sustainability. The second provided critical information for the decision-making process, by comparing design alternatives performance. Both viewpoints contribute to ameliorate the built environment sustainability and to endow designers with sustainability awareness.

Additionally, the method has following premises: (i) be simple and easy to use; (ii) be in line with international standards for sustainable construction; (iii) embrace the three sustainability dimensions; (iv) allow simultaneity of quantitative and qualitative criteria and; (v) give required guidance to understand the implications of sustainability in the design [13].

Considering the abovementioned, existing BSA tools and international standards were reviewed as well as relevant literature on the topic and questionnaires were applied to understand the designers' perspectives. From that research and data analysis resulted the sustainability matrix to include in the decision-making method. The sustainability matrix is organised in a tree structure, with the following broad categories:

- Materials and resources – comprise the materials life cycle environmental impact and the efficient use of resources;
- Wellbeing – consisting in inhabitants' health and comfort indicators and in the building's functionality;
- Life cycle costing – covering investment, operational and end-of-life costs;
- Location – encompassing the site conditions, ecology and social constrains;
- Technical and management – accounting for project quality and management.

Each of these categories is further divided into indicators and sub-indicators, fulfilling nineteen indicators and thirty-nine sub-indicators. Designers can select the indicators and sub-indicators to assess and in which order. Unlike other BSA tools, this method does not weight nor aggregate results. These are presented individually, as mid-point indicators. Figure 1 presents the method's workflow. Objectives can be defined first and then, to each indicator, the design solutions' performance can be estimated or given guidelines to achieve desired levels and compared. The comparison of alternative solution enables designers to identify the one that best fits their goals and with higher performance.

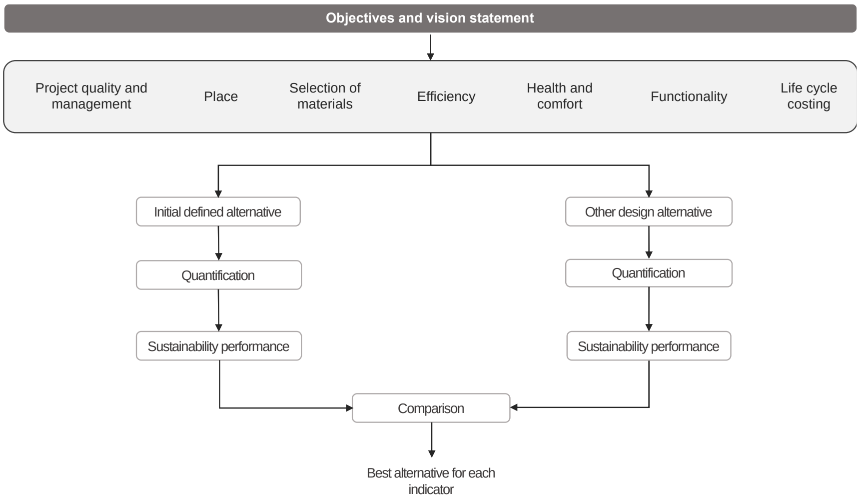

Figure 1. Early design sustainability support tool workflow

3.2. Cost-Benefit Analysis (CBA) method

The CBA method aims at comparing the sustainability performance and costs of different building solutions. The method uses a visualization approach by a bi-dimensional graphical representation (Figure 2); where the horizontal axis depicts the Sustainability Level (SL), the vertical axis represents the LCC, and the A point shows the solution. The cheaper solutions will appear at the bottom in the graph, while the solutions with better sustainability performance will appear in the rightmost.

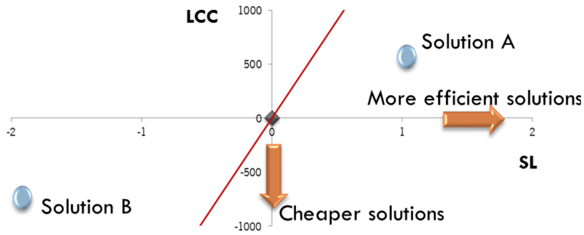

Figure 2. Graphical representation of the Cost-Benefit Analysis method

Equation 1 presents the building's LCC assessment according to the European Commission Delegated Regulation No. 244/2012 of 16 January 2012 (EU 2012) proposed method.

$$C_g(\tau) = C_I + \sum_j \left[\sum_{i=1}^{\tau} \left(C_{a,i_{(j)}} \times R_d(i) - V_{f,\tau}(j)\right)\right] \quad (1)$$

Where: τ - Period; Cg (τ) - Global cost over the calculation period; CI - Initial investment cost for the measure j; Ca,I (j) - Annual cost during year i for measure j; Rd (i) - Discount rate for year I; Vf,τ (j) - Residual value of measure j at the end of the calculation period.

In this method the sustainability assessment is carried out through the evaluation of seven key indicators. These were defined after analysing several European Sustainable Building assessment methodologies, European projects and ISO and CEN Standards. The following indicators were chosen: energy consumption, water consumption, building material LCA, thermal comfort, acoustic comfort, lightning, and indoor air quality. Each design solution is then analysed from a LCC perspective. In the end, the global solution assessment is achieved by a multi-criteria analysis.

This method considers relevant aspects when comparing solutions. When a solution is cheaper and has better sustainability performance than others, it is easily concluded that it is better than others (in the graph it appears at the bottom right corner of the quadrant IV). However, when comparing alternatives in which one is more expensive but has better performance than the other, such conclusions may not be so obvious. Therefore, it is required a comparison method that accounts for the value of money or the stakeholder's willingness to invest in expensive high-performance solutions or in cheap low performance solutions. This comparison method is crucial to answer the question: To what extent is someone willing to pay for a certain sustainability performance improvement in a building?

Mathematically, this corresponds to selecting an ideal cost-benefit ratio for a given budget. In figure 2, the red line represents this ratio. This ratio can vary between stakeholders. In order to define it, stakeholders' investment willingness should be analysed to adapt the line to each stakeholder.

This will allow not only the comparison of solutions but also the selection of the one that best suits each individual. As the willingness to invest in sustainable measures can diverge for different investment or desired sustainability levels, the line can take a linear or non-linear shape.

4. Case Study

It was considered a typical Portuguese single-family building (Figure 3). The building has two bedrooms and a total built area of 110 m^2. Hypothetically, it is located in Lisbon at an altitude of 71 m, and the objective of the analyse is to identify the best comparative solution for the improvement of energy efficiency.

The case study building solutions were defined taken into account the most common building solutions used in Portugal between 1960 and 1990. So, construction solutions considered for each building element are: wall - Single masonry Wall with 22cm with 2 cm of plaster both sides (U = 1,8 W/m^2.ºC); superior Slab - Lightweight slab (U = 2,8 W/m^2.ºC); roof - Pitched roof with lightweight slab (U = 3,0 W/m^2.ºC); ground floor - Concrete slab covered with ceramic tile (U = 1,7 W/m^2.ºC); glazing - Single glazing (6 mm) and wooden frame (U = 4,1 W/ m^2.ºC).

The building was considered to be air conditioned through mobile heating and cooling systems (COP=1; SREE=3,5), and to be naturally ventilated. The comfort temperatures recommended by the Portuguese thermal regulation were considered for the analysis of the energy needs: 18 ºC for the heating season and 25 ºC for the cooling season. The ventilation was assessed trough dynamic simulation using the *EnergyPlus AirFlowNetwork* module. The building was considered to be occupied by three persons from 7 pm to 8 am in week days and all day during the weekends.

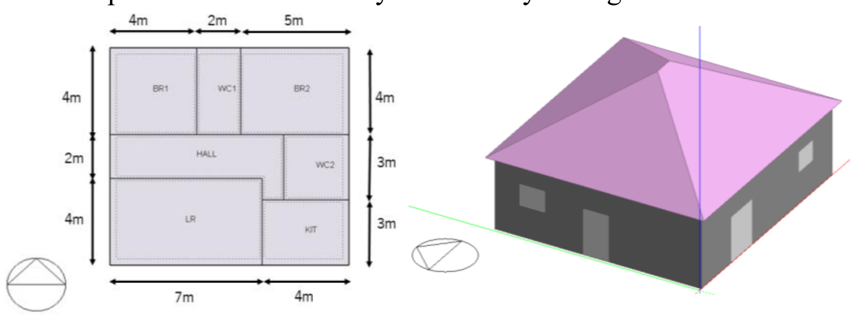

Figure 3. Case study

4.1. Rehabilitation Scenarios

Three rehabilitation scenarios were analysed (Table 1). In scenario 1 only passive measures were considered. In scenario 2, in addition to the passive measures, more efficient building systems were defined. In scenario 3 the measures from scenario 2 were combined with a heat pump. So, the rehabilitation scenarios are:

1. Application of 8 cm of thermal insulation on the extern walls (U = 0,32 W/m^2 °C), 12 cm of external thermal insulation on the roof (U = 0,27 W/m2 °C), and substitution of the glazing systems for double glazing with aluminium frame (U = 2,8 W/m2 °C);
2. Passive measure of scenario 1 plus substitution of building acclimatization equipment for an air conditioning system (COP= 4,12; SREE=8,53) for heating and cooling and of the DHW system by a gas condensing heater (COP=0,881)
3. Measure of scenario 2 with the addition of a self-consumption photovoltaic kit with a production of 1 500 W (Eren = 2 290 kWh.year, where Eren = Photovoltaic system energy production across a year. The panels were considered to be facing South with a slop of 35º).

4.2. Results

Figure 4 presents the energy use in each rehabilitation scenario.

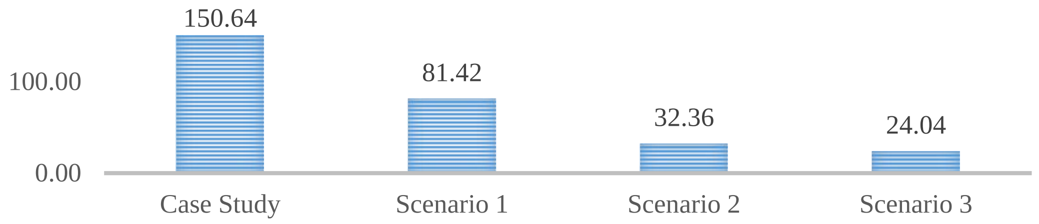

Figure 4. Energy use of each rehabilitation scenario

Considering the indicator I5 (Energy Efficiency) of Early stage design method, it is possible to estimate the total primary energy required by the building. Briefly, the indicator estimates the energy needs, using ISO 13790 general framework for the calculations for the heating and cooling needs, while EN 15316-3-1 is used for the estimation of DHW production needs. The model requires the input of the building envelope solutions – materials and thickness for each building element – and the heating, cooling and domestic hot water preparation systems – type of system. Then, the energy needs for heating, cooling and domestic hot water preparation are present. If needed alternative solutions can be tested and the performances compared.

Therefore, it was verified that the simple adoption of passive measures leads to a decrease the annual building energy use in 69 kWh/m^2.year. These passive measures combined with more efficient but conventional building system allow to decrease the energy use in around 118 kWh/m^2.year. The adoption of a heat pump, which is a more efficient but usually also more expensive equipment, allow to obtain an even better energy performance, decreasing energy use in 127 kWh/ m^2.year.

Table 1 present the economic analysis regarding the CBA method.

Table 1. Economic analysis.

Scenario	Initial cost (€)	Operational Cost (€)	Life Cycle Cost (€)	Annual savings (€/year)	Payback time (years)
Case Study	0	33 635	33 635	0	0
1	11 457	21 465	32 922	406	28
2	14 791	14 559	29 350	636	23
3	18 125	10 655	28 780	766	24

The payback time was verified to be high in all of the three rehabilitation scenarios. Nevertheless, the scenarios with the best payback time is scenario 2. It was also verified that regarding the payback time, the scenario based only in passive measures present a very similar performance than other scenarios combining these measures with more efficient energy systems.

The initial cost has a very significant influence on the economic analysis of residential buildings rehabilitation measures. Even in scenarios with relevant annual savings, the initial costs of the solutions make the return of investment only available in the last years of the life cycle.

5. Conclusions

The early stage sustainability design tool fulfils the existing gap in the BSA tools universe, as it enables considering sustainability concepts since the early design stages. This method aids the decision-making process through the comparison of design alternatives sustainability performance at the indicators and sub-indicators level. This will assure that decisions regarding sustainability concerns are made conscientiously. Acting so early in the project, not just will improve the possibilities to promote sustainability but it will also reduce the possible associated costs.

The cost benefit method aids stakeholders to easily compare building solutions and understand the benefits of their investment. Also, it encourages them to invest in high performance solutions, with higher initial costs, since the benefits of such investment, in terms of sustainability and cost savings will be easily understood. The method also allows identifying measures with low investment availability and high performance. This is important to inform the government bodies of measures and aspects for which is necessary to develop funding programs in order to improve sustainability.

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