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Refurbishment decision support tools review—Energy and life cycle as key aspects to sustainable refurbishment projects

Joaquim Ferreira, Manuel Duarte Pinheiro*, Jorge de Brito

Instituto Superior Técnico, Technical University of Lisbon, Av. Rovisco Pais, 1049-001, Portugal

HIGHLIGHTS

- Sustainable refurbishment as an important challenge.
- Proper decision-support methods are needed to refurbishment.
- The paper reviews 40 different methods, focusing their main common aims.
- The paper highlights the role of the energy as key factor to search sustainability.
- It also stresses the importance of life cycle approach in refurbishment projects.

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ABSTRACT

Europe is facing one of its most challenging crises since Great Depression and the construction sector is one of the worst affected. Refurbishment is therefore often suggested as one of the most useful solutions for the current real estate crisis in consolidated areas like the EU. On the other hand, it is imperative to construct buildings according to sustainable principles regarding economic, environmental and social issues. Therefore, proper decision-support methods are needed to help designers, investors and policy makers to choose the most sustainable solution for a refurbishment project, especially for energy retrofit works. This paper reviews the works relating to sustainable refurbishment decision-support tools which have already been developed. For this purpose we have analysed and classified 40 different methods, with particular focus on their main common aims. They are also compared with other classifications proposed. This paper further highlights the role of energy as a driving factor and discusses what other research developments are needed to create related tools for the future that could respond to actual construction requirements.

1. Introduction

Europe is facing its biggest financial crisis since Great Depression, and economic recovery has been successively delayed, mainly because of mistakes made by the EU Member States' governments which hugely increased their national sovereign debts in the last decade (Yurtsever, 2011). For instance, Portuguese external debt increased by a factor of 3.4 in a single decade (Rodrigues, 2011).

That debt growth was due to high public spending, sometimes on several inefficient public works policies (Greiner, 2012). Those investments were followed by the expansion of construction companies, which could even represent more than 20% of the GDP, like Portugal's situation in 2002 (Cóias, 2012). Consequently, that exponential growth in construction and buildings created an oversized stock (in Portugal there are 1.44 homes per family—INE—Portuguese National Institute of Statistics (2012a)), and the increase had to abruptly slow down (INE, 2009; Cóias, 2012).

The combination of debt and the oversized stock created a huge real estate crisis (INE, 2009; Cóias, 2012), which is threatening countless families. In Portugal, for example, the construction output decreased 18.2% in September and employment in the sector decreased 18.4% (INE, 2012b), which stresses the need for urgent action. Therefore, in some developed countries this sector must be reorganised and strategies must be prepared to reduce the social impacts of the collapse of building firms (CPCI—Portuguese Confederation for Construction and Real Estate, 2012).

However, Europe is a consolidated continent with major refurbishment needs (Itard et al., 2008). In most developed countries these works in fact represent nearly 50% of the market (Juan et al., 2009a). Therefore, Kaklauskas et al. (2011) indicated this as the most probable solution for the real estate crisis.

Apart from the economic crisis, the world also experiencing an environmental one, whose consequences are difficult to predict (Serageldin and Steer, 1994). In fact, studies report that the Earth is

* Corresponding author. Tel.: +351 218 497 650.
E-mail addresses: joaquim.ferreira@ist.utl.pt (J. Ferreira), manuel.pinheiro@ist.utl.pt (M.D. Pinheiro), jb@civil.ist.utl.pt (J.d. Brito).

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being pushed beyond its limits (Wackernagel and Rees, 1996), and the world's ecological footprint is estimated to be 1.5 planets (Ewing et al., 2010).

Thus, the major challenge for the future will be to promote the sustainable refurbishment of that consolidated stock, i.e. the creation and responsible management of a healthy refurbished built environment based on resource efficient and ecological principles (Kibert, 2008).

However, refurbishment projects are usually characterised by high levels of uncertainty and risk due to lack of information and the complexity of tasks (Lee andGilleard, 2002; Juan et al., 2009b; Juan, 2009). Furthermore, the decision-making process involves a wide range of conflicting interests, including social and heritage related tasks, financial investment constraints and environmental issues (Martinaitis et al., 2007; Nair et al., 2010).

Therefore, decision-support tools are needed to help investors and policy makers to choose the most profitable solution. Consequently, there has been a major development of methods designed to provide the best rehabilitation measures that take an environmental and/or economic approach (Juan et al., 2009b).

The aim of this paper is to review, analyse and compare the developments in decision support tools for refurbishment in order to identify the approaches, potential improvement areas and future research needs.

2. Refurbishment decision process

It is not easy to define the refurbishment concept's boundaries. In fact, it can vary from a simple repair like painting façades to a more complex process that includes structural reinforcement works (Caccavelli and Genre, 2000; Konstantinou and Knaack, 2011). Moreover, refurbishment project clients and aims are very diverse and can range from a single family looking for indoor comfort's increase to a major investor looking for a total refurbishment in order to maximize profits and ease of sales (Juan et al., 2009a; Martinaitis et al., 2007; Nair et al., 2010).

Therefore, decision-support methods must be adapted to clients' needs (Vasconcelos et al., 2012). Juan et al. (2009b) state that a considerable number of those methods have been developed to assess conditions and support the decision-making process. However, empiricism still plays a relevant part in decision-making (Gontijo and Maia, 2004).

Even so, every decision-making process incorporates the phases shown in Fig. 1; it can be more or less formal, or more empirical or more scientific related, based on past experiences (Ma et al., 2012).

Fig. 1 enables six areas to be selected where research can create a formal model to support decision-making during refurbishment designs and projects:

- objectives and criteria,
- diagnosis,
- weighting,
- quantification and evaluation of criteria,
- mathematical optimisation,
- modelling.

Although one of the first steps in the decision process is the diagnosis, we can say that the first key step is related to the objectives and criteria, since all the other phases, including diagnosis, are adapted to these strategic aspects. In fact, when modifying the objectives and criteria the final solution is also changed, so this strategic area is in fact the rational heart of the entire process.

Next, diagnosis should reveal the real state of repair of the building and thus its refurbishment needs, and the site's advantages and limitations, thereby creating inputs for the body of the model. A thorough analysis is required to find how to do it, what data should be obtained, what its limitations are, how to standardise the process and, finally, how to transform the engineering results into proper inputs of the model.

Another field of research, with possible repercussions on the optimal solution, is the weighting process. In fact, a different way of weighting underlies each tool, based on a distinct family of weighting methods, mainly divided into monetary and non-monetary valuation methods. Each has advantages and disadvantages, which highlights the need to make the right choice to achieve the initial objectives (Ahlroth et al., 2011).

At the same time, criteria have to be quantified and adapted to the existing possible inputs given by the diagnosis; this requires separate consideration.

The procedure can continue with an accurate mathematical optimisation, ideally using the least time-consuming technique. Alternatives are very wide-ranging, from the classical weighted-sum to neural networks using genetic algorithms (Magnier and Haghighat, 2010). This step therefore needs its own development. However, it could be optional decision-making processes do not need to have a ranking list, they can simply look at and appraise different scenarios.

Furthermore, the procedure needs an interface and a model to allow data entry and the running of all the other phases. This is the model mentioned before, which aggregates all the previous fields and addresses the initial goals.

Finally, refurbishment is a very heterogeneous and complex task that is affected by uncertainty from many separate sources (Juan et al., 2009b; Juan, 2009). Indeed, all the six last steps can be affected by various uncertainties, making this the seventh step that needs further research to minimise the risk of socio-economic loss.

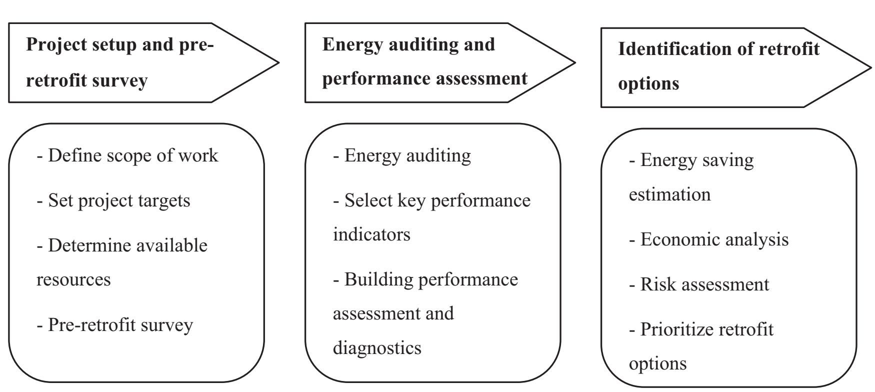

Fig. 1. Key phases of refurbishment decision-making process (adapted from Ma et al., 2012).

For instance was the diagnosis very (or nearly 100%) accurate? Were any data not collected?

Concerning the anomalies detected: will the cost of the refurbishment procedures and equipment fluctuate? Will there be delays in the deliveries and the project? How might these be related to a possibly inaccurate diagnosis?

Uncertainty even plays a part in the objectives and criteria phase: will the criteria chosen really meet the objectives? Are the objectives adapted to market purposes? Furthermore, the weighting process is always affected by subjectivity.

Finally, errors of measurement, calculation and other random errors are also possible in the mathematical calculations of the model, in optimisation and in the quantification of criteria.

3. Decision-making tools to support refurbishment

A large number of decision support systems were identified in this search, covering 40 different systems for the refurbishment of buildings. An initial analysis of these systems is summarised in Table 1, comparing them in terms of type of building (residential or service; refurbished or new) and their principle purposes (economic and environmental).

Some work has already been done on classifying decision support tools. One of the most used classifications was proposed by Kolokotsa et al. (2009) and is related to each tool's methodology, according to the scheme in Fig. 2.

This classification is very useful when studying each method's algorithm or optimisation applicability. However, when looking for object applicability, Table 1 showed that it is possible to consider another division into five distinct groups, according to common aims and objects. They are

- general methods,
- improve energy and/or CO_2 emission performance,
- purely economic analysis,
- LCA methods,
- sustainable assessment methods.

This division can supplement that of Kolokotsa et al. (2009). While the last shows the methodology approach in an algorithm theory analysis, the first looks at the objectives' field, creating an interrelated approach.

For the classification proposed the first group contains all the methods that apply to situations that are flexible enough to incorporate different criteria based on the client's needs, and therefore it was called general methods group.

Kaklauskas et al. (2005) created a multivariant design and a multicriteria analysis of building refurbishment. It is a very comprehensive method that calculates the significance, the degree of utility and the renovation priorities, selecting the optimal solution according to the customer's requirements. Thus, it is possible to introduce different criteria related to the economic, qualitative, technical, technological, ecological, climatic and social dimensions. Finally, the mathematical algorithm developed was designed to give a 0–100% ranking of each alternative scenario.

It was improved with an online transposition in the Kaklauskas et al. (2007) tool, with four principle aims: (1) to search for construction products and services for the refurbishment under assessment; (2) to compare different alternatives; (3) to assess the different stages of alternatives; and (4) to enable assessment after purchase.

Based on this method, Multi-Attribute Market Value Assessment (MAMVA) was created and it also allows experts to define new criteria and their weights, with the possibility of modification, case-by-case. The criteria are then grouped in a decision-making matrix to determine the significance, priority and market value of various alternatives, considering the whole life cycle of a project, including all related interest groups (Kanapeckiene et al., 2011).

Finally, Thompson and Bank's (2010) work is interesting for its further analysis on optimisation algorithms because of their use of system dynamics. However, as their paper's scope does not extend to the objectives under discussion it is not further analysed here.

The application of fuzzy set methods to the problem of refurbishing rural buildings (Zavadskas and Antucheviciene, 2007) and to determining the best way to reuse historical buildings (Wang and Zeng, 2010) is relevant to the methodology and the algorithm overview.

As far as energy and CO_2 are concerned, there are several simulation based methods for minimising the operational energy and consequently the CO_2 related emissions (Balaras, 2002; Ferreira and Pinheiro, 2011). Some methods even separate CO_2 emissions from energy consumption (Diakaki et al., 2010; Liu et al., 2010; Chantrelle et al., 2011). Indoor environmental comfort is also assessed (Magnier and Haghighat, 2010; Balaras, 2002; Caccavelli and Gurgerli, 2002; Flourentzou et al., 2002; Jaggs and Palmer, 2000; Parc Scientifique de L'EPFL-PSE, 2004; Chantrelle et al., 2011), since it is a measure of performance that can easily quantify the real thermal energy needs and the real users' acceptance of indoor environmental conditions (Bermejo et al., 2012).

Software is also available, such as TOBUS (Balaras, 2002; Caccavelli and Gurgerli, 2002; Flourentzou et al., 2002) and EPIQR (Jaggs and Palmer, 2000; Parc Scientifique de L'EPFL-PSE, 2004), and several other works including multi-objective analysis (Magnier and Haghighat, 2010) and genetic algorithms (Caldas and Norford, 2002; Znouda et al., 2007; Chantrelle et al., 2011). Finally, we found an economic complementary approach, generally focusing on investment and operational costs (Juan, 2009; Gorgolewski, 1995; Diakaki et al., 2010, 2008; Jaggs and Palmer, 2000; Parc Scientifique de L'EPFL-PSE, 2004; Znouda et al., 2007; Liu et al., 2010; Chantrelle et al., 2011).

Since LCA is being widely used to assess the global environmental performance of buildings (Sharma et al., 2011; Sartori and Hestnes, 2007; Ramesh et al., 2010; Ortiz et al., 2009), there has been a natural evolution of decision-support methods towards embracing all entire life cycle impacts, generally considering

- embodied energy,
- operational energy consumption,
- construction phase environmental impacts.

Moreover, some methods are even more complete, considering a larger range of impacts, like acidification and eutrophication (Zhang et al., 2006). Others also include an economic complementary analysis based on the life cycle costs approach (Wang et al., 2005; Tsai et al., 2011).

On the other hand, as mentioned earlier, there are some purely economic methods that indirectly consider the minimisation of environmental impacts but whose primary focus is financial savings. Apparently, it seems that they are overlapping the Energy/CO_2 and LCA classes, because these methods may consider economic analysis too. Nevertheless, the purely economic methods aim to minimise costs from a purely financial perspective, not from a stated environmental one. Therefore, they were assessed separately from the others. On the whole, they aim to reduce overall costs, generally considering the investment cost and HVAC operating costs (Martinaitis et al., 2007; Wright and Loosemore, 2011; Alanne, 2004).

In a more integrated analysis, it was also possible to find some sustainable assessment methods that include multi-objective approaches (Juan et al., 2009b, 2010) or use appropriate software (Dascalaki and Balaras, 2004; Balaras et al., 2005a, 2005b). In fact, since BREEAM's first appearance in the early 90s, the development of such tools has been growing rapidly worldwide (Nilsson et al., 2008; Ding, 2008), because of their labelling

Table 1
Comparison of different decision support tools.

DM tool	Building[a] (R/S)	Refurbishment or new (R/N)	Environment[b]	Economy[c]
Gorgolewski et al. (1995)	R (apartments)	Refurbishment	En	LCC
Gorgolewski et al. (1995)	R	Refurbishment	En	LCC
TOBUS (Balaras, 2002; Caccavelli and Gurgerli, 2002; Flourentzou et al., 2002)	S	Refurbishment	En; EC	Inv
XENIOS (Dascalaki and Balaras, 2004)	S (hotels)	Refurbishment	En; Rnw; Wt	Inv; PB
MEDIC (Flourentzou et al., 2000)	R+S	Refurbishment	Funct	Inv; Op
EPIQR (Jaggs and Palmer, 2000; Parc Scientifique de L'EPFL-PSE, 2004)	R	Refurbishment	En (and Rnw); IEQ	Inv
INVESTIMMO (Balaras et al., 2005a, 2005b)	R	Refurbishment	En; Funct; Ft Funct; Wt; Air (and CO_2); Ef; Wst	Inv; Op; Effect
MOGA (Wright and Loosemore, 2011)	R+S	Refurbishment and new	En; Th Comf	Inv; Op
Saporito et al. (2011)	S	Refurbishment and new	En	–
Caldas and Norford (2002)	R+S	Refurbishment and new	En	–
Alanne (2004)	R+S	Refurbishment	Client definition	Inv; Op
Kaklauskas et al. (2005)	R+S	Refurbishment	Client definition	Client definition
Pushkar et al. (2005)	R+S	Refurbishment and new	LCA (Eco-Indicator 99)	–
Wang et al. (2005)	R+S	Refurbishment and new	LCA (En)	LCC
Wetter and Polak (2005)	S	Refurbishment and new	En	Op
Juan et al. (2006)	R	New	Geom	Inv
Zhang et al. (2006)	R+S	Refurbishment and new	LCA; Mt and R; St; Conv	–
Kaklauskas et al. (2007)	R+S	Refurbishment and new	Client definition	Client definition
Martinaitis et al. (2007)	R	Refurbishment	En; Funct	CCE; LCC
Zavadskas and Antucheviciene (2007)	S (rural buildings)	Refurbishment	Client definition	Client definition
Znouda et al. (2007)	R+S	New (applicable in refurbishment)	En	Inv Op
Diakaki et al. (2008)	R+S	Refurbishment and new	En	Inv
Juan (2009)	R+S	Refurbishment	–	–
Juan et al. (2009a)	R	Refurbishment	–	–
Juan et al. (2009b)	R	Refurbishment	Sf; Us; Cv; IEQ; En; Wt; Hlth	Inv; NPV; LCC
Lee et al. (2009)	R+S	Refurbishment and new	LCA; En; CO_2	–
Diakaki et al. (2010)	R+S	Refurbishment and new	En; CO_2	Inv
Juan et al. (2010)	S	Refurbishment	St; En; Wt; Mt and R; IEQ	Inv
Li et al. (2010)	R+S	Refurbishment and new	LCA	–
Liu et al. (2010)	S	Refurbishment and new	En; Air	NPV; Inv; Op
Magnier and Haghighat (2010)	R	Refurbishment (and new)	En; Th Comf	–
Thompson and Bank (2010)	R+S	Refurbishment and new	Client definition	Client definition
Wang and Zeng (2010)	S (HB-historic buildings)	Reuse selection of HB	St	–
Crawford et al. (2010, 2011)	R	Refurbishment and new	En (in LCA)	–
Ferreira (2010) and Ferreira and Pinheiro (2011)	R	New	En; Th Comf	–
Kanapeckiene et al., (2011)	R+S	Refurbishment and new	Client definition	Client definition
MultiOpt: Chantrelle et al. (2011)	R+S	Refurbishment	En; $LCCO_2$; Th Comf	Inv
Mora et al. (2011)	R+S	Refurbishment and new	LCA; Ft Funct	–
Tsai et al. (2011)	R+S	Refurbishment and new	$LCCO_2$; En	LCC
Srinivasan et al. (2012)	R+S	Refurbishment and new	En (in LCA)	–

[a] R—residential; S—service.
[b] Air—air emissions; CO_2—CO_2 emissions; Cv—convenience; EC—environmental comfort; Ef—liquid effluents; En—energy consumption; Funct—building's state of physical/functional deterioration; Ft Funct—estimated future deterioration; Geom—geometrical commercial housing conditions; Hlth—health; IEQ—Indoor Environmental Quality; LCA—Life Cycle Assessment; $LCCO_2$—Life Cycle CO_2 emissions; Mt and R—materials and resources; Rnw—renewable energies; Sf—safety; St—site assessment; Th Comf—thermal comfort; Us—use functionality; Wt—water consumption; Wst—solid waste.
[c] CCE—Cost of Conserved Energy; Effect—long term effectiveness of investments; Inv—investment costs; LCC—Life Cycle Cost; MC—Monte Carlo procedure; NPV—Net Present Value; Op—operational costs; PB—estimated payback time; Prob—probabilistic calculation.

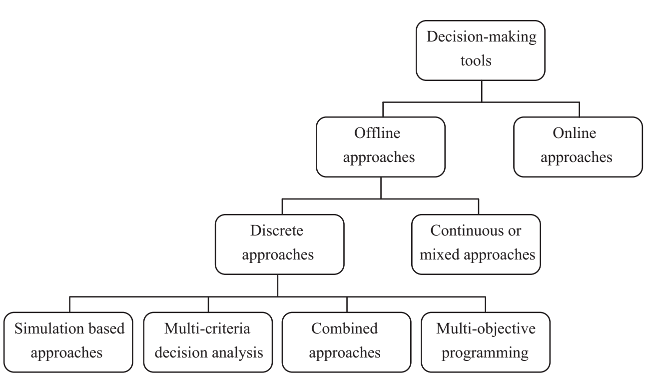

Fig. 2. Classification of decision-support methods (Kolokotsa et al., 2009).

perspective and possibility of use (Birgisdottir and Hansen, 2011; Cole, 1999).

The works in question (Juan et al., 2009b, 2010; Balaras et al., 2005a, 2005b; Dascalaki and Balaras, 2004) embrace those sustainable principles, which are broadly discussed in the existing sustainable assessment methods (BREEAM and LEED, for instance), and test several refurbishment solutions pointing out the most suitable one for each problem. They are not sustainable construction assessment and certification schemes. But they are based on such schemes' principles, and they incorporate decision-support theory, in order to create powerful tools to help designers and clients to choose the most sustainable solution.

As a last comment, there were some methods with interesting optimisation algorithms which were not assessed because their

Table 2
Method classification.

General methods	Energy and/or CO_2	Purely economic methods	LCA methods	Sustainable assessment methods
Kaklauskas et al. (2005)	Caldas and Norford (2002)	Gorgolewski et al., (1995)	Pushkar et al. (2005)	XENIOS (Dascalaki and Balaras, 2004)
Zavadskas and Antucheviciene (2007)	EPIQR (Jaggs and Palmer, 2000; Parc Scientifique de L'EPFL-PSE, 2004)	Gorgolewski et al. (1995)	Wang et al. (2005)	INVESTIMMO (Balaras et al., 2005a, 2005b)
Kaklauskas et al. (2007)	TOBUS (Balaras, 2002; Caccavelli and Gurgerli, 2002; Flourentzou et al., 2002)	Alanne (2004)	Zhang et al. (2006)	Juan et al. (2009b)
Wang and Zeng (2010)	Diakaki et al. (2008)	Juan et al. (2006)	Lee et al. (2009)	Juan et al. (2010)
Thompson and Bank (2010)	Diakaki et al. (2010)	Martinaitis et al. (2007)	Li et al. (2010)	
Kanapeckiene et al., (2011)	Magnier and Haghighat (2010)	Znouda et al. (2007)	Crawford et al. (2010, 2011)	
	Liu et al. (2010)	MOGA (Wright and Loosemore, 2011)	Mora et al. (2011)	
	Ferreira (2010) and Ferreira and Pinheiro (2011)		Tsai et al. (2011)	
	Saporito et al. (2011)		Srinivasan et al., (2012)	
	MultiOpt: Chantrelle et al. (2011)			

goals do not fit the defined purpose of this paper, i.e. their aim was not to help decision-making in sustainable refurbishment projects. They are

- Wetter and Polack's (2005) work, which developed a new precision control algorithm with faster convergence in building energy optimisation problems.
- Works by Juan (2009) and Juan et al. (2009a), which created methods to help owners to choose the most suitable contractor for the works, also enabling contractors to recognise inefficient factors, using a hybrid fuzzy set method.

And Flourentzou et al. (2000) created a method enabling EPIQR to predict the expected service life of building components. Thus, its analysis is indirectly incorporated in EPIQR.

Finally, Table 2 was added to this work for a simple classification of the methods discussed above.

It can thus be said that in general the decision-making process focuses on several criteria that can range from economic issues to social and environmental ones. Different variables and methods have been developed to optimise the final solution by improving its service, efficiency and/or competitiveness.

The next section discusses these works, looking at the different objectives and methods used with a view to identifying future research needs based on the works under discussion.

4. Discussion

Besides the previous proposed division into five groups of tools, a more precise analysis that considers the individual objectives stated can be undertaken. In fact, the methods share some similar goals, in which the design of low energy buildings is undoubtedly the most sought after as it is registered in more than 50% of them (considering passive and active measures).

In addition, several goals have similar emphases:

- reducing energy consumption and CO_2 emissions,
- improving indoor living conditions/comfort,
- assessing refurbishment needs,
- estimating costs,
- other environmental impacts.

Cost estimation is widely dispersed in the five different groups, ranging from a single investment or operational analysis to life-cycle cost.

In terms of methodology, most of the tools involve a multi-objective approach that usually aims to minimise the environmental impacts (energy, CO_2 emissions and/or other impacts, depending on the tool) and the cost (or maximise the profits), as these factors are normally in opposition' are normally in opposition.

Moreover, ‘other environmental impacts’ has a very large range of possibilities, such as water efficiency, eutrophication, waste or emissions. These are therefore mostly evaluated in the LCA tools (mostly regarding ISO 14040 recommendations, 1997) or in sustainable assessment methods.

However, the LCA is mostly used to assess a building's environmental impact, in spite of being a decision support tool. This could be the next step, since LCA started from a product vision before evolving into a building analysis tool (Ortiz et al., 2009), and now the first steps are being taken to incorporate it into the decision process.

Returning to the refurbishment aspects assessed, energy, CO_2, cost, comfort, health and sometimes other environmental impacts are considered in the decision-making support process. But there are other social issues that should be taken into account when assessing the quality of life and service of a building, including local amenities, transport facilities and job proximity (Pinheiro, 2010).

Indeed, these additional aspects are fundamental to the search for sustainable constructed sites since they in fact link the building and its surroundings, enabling the first to be assessed as a part of one single unit—the real human habitat (Pinheiro, 2006).

Regarding the techniques used by each tool, it can be concluded that genetic algorithms are most often used. They are characterised by chromosomes that represent one possible decision on one problem. As in Darwin's theory, a decision with a best performance has a greater probability of survival, and its performance is measured by comparing it with a fitness function (Juan et al., 2009a).

An evolutionary process is thus created by crossover and disturbed by a mutation, resulting in a new generation of chromosomes with greater probability of survival. When the chromosomes of a new generation are identical to those of the previous one the process ends, creating a solution with a high probability of being good according to the initially defined objectives (Juan et al., 2009a). Consequently, the genetic algorithms enable the assessment of very large sets of alternatives, increasing the probability of achieving the best solution, which is why their application is viewed as promising for the sustainable decision support process.

Another approach is the fuzzy set theory, where one element of a set is no longer treated in binary terms (it either belongs—1—or does not belong to the set—0), but as continuous grades of membership varying from 0 to 1—characterised as belonging function (Zadeh, 1965). Fuzzy set theory makes it possible to handle situations where elements are not completely inside or outside the set, and therefore it better represents the real world where partial truths are more common than absolute ones (Rodrigues, 2000).

The family of ‘general methods’ comprises the tools whose criteria can vary from situation to situation, with different weights according to the case being assessed. Their main advantage is their flexibility and ability to be applied to a very large range of problems with different issues and criteria, according to the client's needs. However, they always require a large amount of initial data and because they assign different weights and criteria to each case, the final result can be influenced.

All of the above tools tend to use a quantitative evaluation to minimise subjectivity and even where qualitative criteria are used they are transformed into numerical values through comparative methods similar to an analytical hierarchy process (AHP) philosophy, by mutually comparing the priorities of each pairwise action.

AHP highlights another important point of debate: the weighting process. First, a multi-objective analysis can indirectly eliminate this issue by assigning the same weight to all criteria. But some issues are always more important than others so a weighting process is normally recommended to represent the reality more accurately.

For this, monetary or non-monetary approaches can be chosen (Ahlroth et al., 2011) and enquiry analysis with representative samples is desirable (Ferreira et al., 2012). However, clients can initialise the weights relative to their own wishes and experience, with no scientific study. Furthermore, the weighting process is always affected by subjectivity, varying with

- professional experience,
- own interpretation of the enquiry sample's professional experience and the consequences of each criterion being assessed,
- type of enquiry and how it is made,
- instant predisposition to answer the enquiry,
- psychological state when answering the enquiry, which can affect some answers that might be different in other circumstances,
- time available for the enquiry that may reduce the accuracy of response over the entire process, especially important in lengthy inquiries,
- when no inquiries are conducted, subjectivity is even greater as it depends on the client's interpretation of reality.

Thus, future work on decision-support analysis should discuss this question in detail in the very first stages of the method, to reduce its impact and improve the quality of the final results.

Finally, in this new era of dissemination via the Internet some tools are being processed on the web to be freely used anywhere in the world (Kaklauskas et al., 2007; Juan et al., 2009b). Consequently, it is also expected that future research will consider this option, thereby allowing their easier distribution and use so that they can become active tools in the search for more sustainable working sites.

5. Conclusions

This review has shown that the development of decision-making tools to support the refurbishment of buildings has generated very diverse methods with distinct purposes all over the world, involving correspondingly diverse assessment criteria that are generally centred on the design stage. Energy and CO_2 efficiency are the issues most often analysed and interpreted as key factors in promoting sustainable refurbishment projects, but other concerns such as social questions, economic efficiency and environmental criteria are appearing and are also crucial to policy decision makers.

As far as methods are concerned, there has been an evolution from single-objective to multi-objective algorithms using methods like fuzzy set theory, genetic algorithms and simple weighted-sum algorithms.

Studies have been carried out on criteria weighting (an area always affected by subjectivity), focusing on the use of AHP and willingness to pay. As in other areas these studies are characterised by diverse uncertainties.

Finally, this paper has focused on an overall analysis, making it possible to determine the following needs for research:

- The evolution from an operational perspective to a life cycle approach has indicated LCA (e.g including both energy operation consumption and embodied energy) as the most promising tool to exploit in future to assess environmental aspects, so it could be introduced into new decision-making models.
- LCC could supplement LCA by enabling an economic analysis.
- As the decision-making process is usually very time-consuming it is very important to develop fast and effective methods that take advantage of already-existing computational and mathematical algorithms.
- Those tools should also include the social aspects of comfort, health, quality of life and service performance.
- Since local databases of solutions are essential, especially in relation to the relevant life cycle costs, life span period and life cycle impacts, precise work is needed in this area.
- Tools should also be thought of in a national or regional perspective, since problems may differ from region to region, from climate to climate, from economy to economy and from culture to culture.
- Finally, as far as uncertainty is concerned, Section 2 made it clear that poor decisions can be responsible for a wide range of losses, so tools that take a stochastic instead of a deterministic perspective should be considered in future.

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