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Integrating Scenarios into Life Cycle Assessment: Understanding the Value and Financial Feasibility of a Demountable Building

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Abstract: Although life cycle assessment offers insight into the long-term value of our building stock, it has become impossible to model with certainty the service life of a building. What if new lifestyles make reality diverge from the expected service life? What if the building is decommissioned very early or forced to accommodate new functions? Would the same design decisions have been made or would an alternative have been preferred? In reaction to this challenge, the present paper proposes to integrate scenario planning and life cycle assessment. Therefore, it discusses from where scenario planning originates and how it appeared hitherto in architectural design and life cycle assessment. Thereafter, it explores how assessors can profit from scenarios when raising awareness and co-creating alternatives. Subsequently, a methodological framework for effective scenario development is proposed. To illustrate the added value of scenario integrated life cycle assessments, four divergent scenarios are developed for evaluating the financial feasibility of demountable building element reuse. With this simple case study is shown how more relevant and nuanced assessment outcomes are obtained when divergent scenarios are adopted.

Keywords: scenario planning; resilience; life cycle assessment; life cycle costing

1. Introduction

When aiming for sustainable, future-proof design alternatives, not only the size of their financial, environmental or social impact is of interest, also their variability should be studied. After all, the aim of each sustainable design decision is to avoid escalations of future costs, environmental impacts or social burdens. Therefore, the management strategy of scenario planning arouses interest. By developing divergent scenarios and subjecting each alternative to those imaginable futures, alternatives' resilience can be objectified [1] (p. 352).

Life cycle assessments, including life cycle costing, 'have been generally accepted within the research community as a legitimate basis to compare competing alternatives' [2] (p. 368). They allow one to look beyond the initial impact as the sole design criterion and to make better informed decisions. Moreover, life cycle assessments are relevant during building development, as well as estate management, as is explained in the ISO 15686-5 [3] and 14040-0 [4] standards.

What is needed however, is 'a platform for consideration of flexible strategies in which the specifications change during a building's service life' [5] (p. 547). After all, initial design choices are not 'repeated like-for-like throughout the study period,' but are reviewed in light of changing user requirements [6] (p. 29). Therefore, the goal of this paper is to present an assessment method that better fits the dynamic nature of the built environment by adopting scenarios.

Although scenario planning has been used for military and business purposes for decades, it is rarely adopted during a design process or construction project [7]. Nevertheless, designers themselves stated they lack the tools to make future-oriented design choices in a survey about the opportunities and obstacles of implementing transformable architecture [8]. To close this gap and facilitate the adoption of scenario planning in practice, the present paper proposes a conceptual, as well as supportive method based on a thorough reappraisal of existing insights, their synthesis and their proof-of-concept by a concrete case study.

Before adopting scenarios, it is valuable to understand their strength and to review the way they have been used before during building design and life cycle assessment. Therefore, the first section of this paper explores the state of affairs and added-value of scenarios. Thereafter, a framework for integrating scenario planning in life cycle assessment is developed. Finally, in the third section, the case study that served as the proof-of-concept of the developed framework is presented.

2. Taking a Scenario-Based Approach

Like life cycle assessment, scenario planning is a well-developed and broadly discussed method. Although the available literature about scenarios is vast, it is valuable to review their history and current use before adopting them. Therefore, this section tackles scenario planning's origin, form and use and discusses its potential in the context of life cycle assessment.

2.1. Origin, Form and Use of Scenarios

Since scenario planning evolved from a military prognostication technique in the 1940s to a planning strategy by the 1990s, it has been implemented in many forms and to various extents. However, in the context of life cycle assessments, it was rarely adopted.

2.1.1. Scenarios in Business

In his book *The Art of the Long View*, futurist Peter Schwartz [9] evokes the emergence of scenario planning in business: following earlier developments during World War II, military strategist and system theorist Herman Kahn transformed it from an organization method into a prognostication technique. Later, in the early 1970s, Pierre Wack and Ted Newland, managing director at the Royal Dutch Shell Group, developed it further into a strategic business approach.

'Scenarios are not predictions' emphasizes Schwartz [9] (p. 7). In contrast, they are imaginable stories describing subsequent events, situations or any 'development from the present to the future' [10] (p. 21). Therefore, 'scenario writing is based on the assumption that the future is not merely some mathematical manipulation of the past, but the confluence of many forces, past, present and future' explains Schnaars [11] (p. 106). Subjecting design alternatives to a series of such scenarios could allow appraising the resilience of their life cycle impact.

Today, the concept of scenario planning is well developed. During a broad literature review, Bishop et al. [12] (p. 5) found no less than 'eight categories of techniques that include a total of 23 variations used to develop scenarios'. Moreover, the vast number of journals publishing about scenario planning, including *Futures*, *Foresight* and *The Futurist*, confirms that scenarios have become 'the stock-in-trade of futures studies' [12] (p. 5).

2.1.2. Scenarios in Building Design

In contrast to its popularity in business, scenario planning is hardly adopted in building design [7]. As far as known, entrepreneur Stewart Brand was the first to link both disciplines. In his book *How Buildings Learn*, he devotes a complete chapter to the notion of a 'scenario buffered building' [13] (p. 181). With the exemplary design of a radio studio, Brand demonstrates how the use of divergent scenarios can assist designers from the earliest design stages onwards.

Until today, there is little evidence that scenario planning is taught to architectural students or applied in practice. Only a few exceptions are known. Palmer and Ward [14] report for example

about their experiments with scenario-based design briefs during the architectural design studios at the University of South Australia. Further, it could be noticed that scenario planning is adopted occasionally in specific domains such as the design of healthcare infrastructure [15] and of urban neighborhoods [16].

Although they are few in number, the presented examples and theoretical approaches illustrate scenarios' added value in the context of building design. Moreover, they confirm the findings of Selin et al. [17], who identified nine features that design practice and scenario development have in common. These features include for example the iterative nature of both disciplines, their inherent user focus and discursive, as well as material implications.

2.1.3. Scenarios in Life Cycle Assessment

In the literature on life cycle assessments, scenarios are frequently mentioned. Nevertheless, they are rarely used to identify robust, futureproofed or resilient design choices. A possible reason for this mismatch might be found in the definitions given by the European standards on sustainability [18,19]. They state that a scenario 'shall not include processes or procedures that are not in current use' [19] (p. 27). A confined interpretation of this statement probably results in scenarios that tend to minimize uncertainty rather than trying to anticipate it.

For example, many life cycle assessments evaluate different technical service performances [20], water and energy supply and use rates [21], repair and replacement routines [22] or end-of-life options [23]. Such what-if analyses, as promoted by Björklund [24] and successfully adopted by for example Häfliger et al. [25], bring insight to the variability of the assessment's outcomes, but not necessarily to the robustness of the evaluated design alternatives.

Although other life cycle assessments such as by McLaren et al. [26], Hellweg et al. [27] or Collinge et al. [28] have adopted increasingly dynamic service life models to evaluate the variability of life cycle impacts, and inspiring theories have already been proposed by Fukushima and Hirao [29], as well as by Mahmoud et al. [30], a practical method for integrating scenario planning in life cycle assessment, relating to the designers' insights and their needs, has not yet been developed. This paper has the ambition to fill this vacuum.

2.2. Role of Scenario Planning

Going back to the founders of current scenario planning practice such as Schnaars [11] and Schwartz [9], whose work has been the subject of frequent smaller refinements for example by Korte and Chermack [31] or Bradfield et al. [32], a literature review allowed discerning three reasons for adopting scenarios.

2.2.1. Raising Awareness

Being narrative by nature, scenarios have the power to communicate design problems and proposals [17]. Schwartz [9] argues for example that in contrast to graphs and equations, stories open people to multiple perspectives, help them to cope with uncertainty and allow them to describe and envision events. Especially, ideas that are 'too complex or imprecise for conventional languages of business and science' can be communicated using 'the language of stories and myths' he writes [9] (p. 40).

As a consequence of scenarios' communicative power, they have the potential to raise awareness and bring new insights [7]. This is not only true in business [33] (p. 70); also in the context of building design, the scenario planning process raises awareness. Brand [13] (p. 183) states for example that 'the job of scenario planning is to question whether a building is really needed at all' and to criticize the design brief clients propose.

2.2.2. Co-Creation

If one wants scenarios to have ‘the power to break old stereotypes’, they have to be developed and approved by all stakeholders [9] (p. 234). ‘Scenario making is intensely participatory, or it fails’ [Ibid.]. Two design methods, one by Herthogs et al. [16] and another by Astley et al. [15], take advantage of this participatory continuum between scenario planning and building design. Both demonstrated the added value of adopting scenarios during workshops in which various stakeholders participated.

First, the Lab for Urban Fragment Futures (LUFF) aims at introducing the idea of future adaptability during the early stages of urban development projects [16]. Therefore, Herthogs et al. propose design charrettes with various stakeholders during which the participants are invited to ‘refurbish’ the design proposal under discussion. Therewith, they take into account a set of scenarios describing changes in, for example, the users’ space requirements and mobility. In doing so, participants gain insight into the resilience of the considered proposal and in the potential of the project’s so-called transformational capacity.

Furthermore, clinicians, well aware of their day-to-day routine, are not readily able to pinpoint how their work environments change. For that reason, Astley et al. [15] developed another technique. Their method uses scenario-based discussions as a systematic tool to guide decisions about existing and future healthcare infrastructure. The feasibility of the technique was observed during service re-organization projects within six English Foundation Trust hospitals and supported by additional case studies elsewhere in Europe.

2.2.3. Decision Making

Although scenario planning is essentially a qualitative procedure, it is worthwhile to describe and express scenarios in numerical terms, like life cycle impacts. Such a quantification can be ‘fed into computational models to generate simulation outcomes’ [30] (p. 803). For example, in the case of life cycle cost analysis, the generated net present value would not only allow comparing the expected life cycle cost of the considered alternatives, but also the variability of that cost could be compared. Consequently, even translated into numerical terms, scenarios can support the design process [34].

Given the explorations above, it was possible to identify scenario planning as a promising approach regarding the evaluation and development of future-proof design alternatives. On the one hand, scenario planning allows considering the uncertainty about the service life of buildings and gaining insight in the resilience of the proposed alternatives. On the other hand, scenario planning is well known and demonstrated already its added-value for qualitative building design during a select number of theoretic reflections and case studies. To support the further adoption of scenarios by researchers, assessors and designers, the next section proposes a practical method for integrating scenario planning in life cycle assessment.

3. Framework for Developing and Implementing Effective Scenarios

For the development and use of divergent scenarios during life cycle assessment, a framework that is conceptual, as well as supportive is presented in this paper (Figure 1). It departs from the eight-step plan for scenario development created by Schwartz [9] and is adjusted to the specificities of buildings. It discusses the importance of deliberate scenario development, identifies critical uncertainties in the built environment, involves the understanding of building user requirements and reveals the life cycle options the evaluated design alternatives offer.

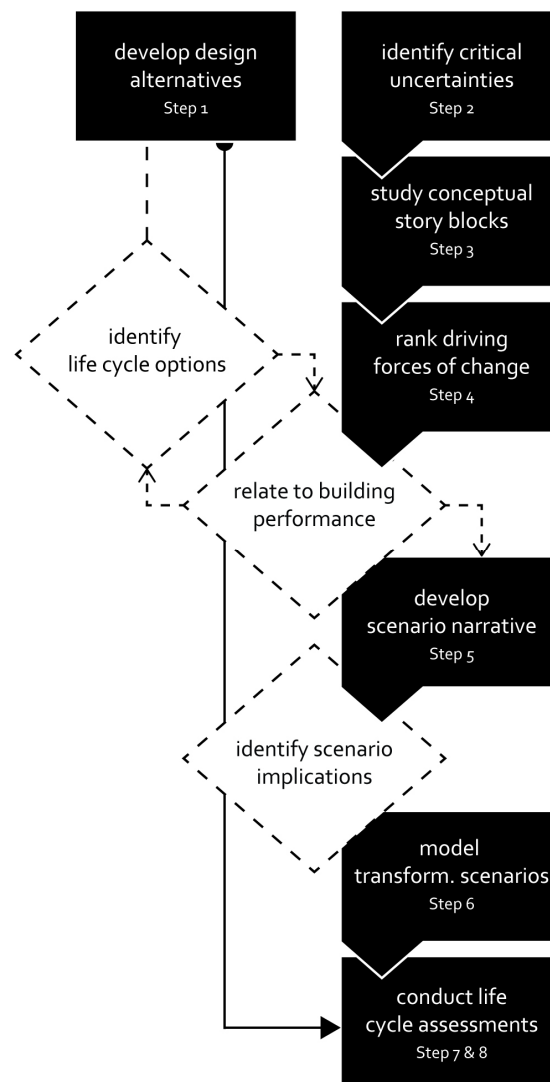


Figure 1. The proposed method to integrate scenario planning in life cycle assessment, shown here as a flowchart, departs from the eight-step plan created by Schwartz [9] and is adjusted to the specificities of the life cycle assessment of building design alternatives.

3.1. Importance of Deliberate Scenario Development

According to Pesonen et al. [10], there is no universal answer to the question of what good scenarios are. Nonetheless, Schnaars [11] emphasizes that scenarios should be developed deliberately, as the effectiveness of plausible and surprising ones is very different. Scenarios can be distinguished in two ways.

3.1.1. Predictive versus Surprising Scenarios

When scenario planning has the intention to verify the feasibility of an established plan or transition towards a specific objective, adopting predictive scenarios is purposeful. Such scenarios consider ongoing evolutions and allow determining key indicators for the plan's further execution. Kahn and Wiener [35] call such scenarios surprise-free or baseline scenarios.

If in contrast, the goal of scenario planning is to evaluate and compare the resilience of design alternatives, it is necessary to go further and confront those alternatives also with less predictive scenarios (Figure 2). Such stress-tests require surprising assumptions, but allow revealing unknown

vulnerabilities. They come with a warning however: the change they include should never be so dramatic that no response is engendered at all [9].

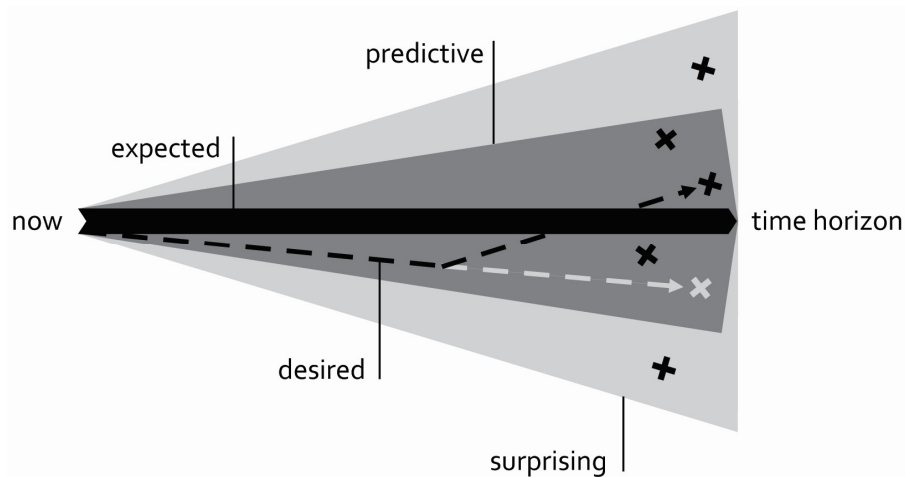


Figure 2. As represented in this scheme, an effective selection of scenarios includes predictive, as well as surprising ones. After all, the desired scenario might change in an unpredictable way within the considered time horizon. Image adapted from Hancock and Bezold [36].

3.1.2. Normative versus Explorative Scenarios

Subtler, but not less important, is the difference between normative and explorative scenarios. Proceeding from a fixed target, normative scenarios explore how that target could be reached [37]. They are typically developed during ‘back casting’ exercises. Such scenarios are useful for verifying the feasibility of reaching well-defined targets, but being procedural by nature, they provide little insight in the consequences of different design aspects.

Alternatively, to trigger more surprising insights, it is useful to consider the development of explorative scenarios. Such scenarios proceed from the question “what could happen” and consider factors that lay beyond the control of decision-making actors. Consequently, ‘explorative scenarios are mainly useful in the case of strategic issues’ [37] (p. 727). Being contextual by nature, they allow evaluating the robustness of alternative design choices.

3.2. Identifying Conceptual Story Blocks

In addition to the scenario development methods by Linneman and Kennell [38] and Wack [39], one of the most adopted methods was established by Schwartz [9]. His eight-step plan has been the subject of frequent refinements [32] and is adopted also in the present framework for its comprehensiveness and proven validity.

3.2.1. Identify Predetermined Elements and Critical Uncertainties

In his first step, Schwartz discusses the collection of elementary information. It includes the goal, scope and boundary conditions of the previewed assessments. In the case of a design project, these are the relevant design alternatives, their characteristics and the related impact figures. Schwartz’s second step is to unveil predetermined elements and critical uncertainties. They form the conceptual story blocks of the scenarios and relate the assessments directly to the context of the project and the insights of the designers.

First, predetermined elements include slow-changing phenomena such as demography. Additionally, they include constrained situations such as the path-dependency of nuclear energy [40]. These uncertainties are often referred to as the ‘known unknowns’. Second, critical uncertainties are factors that determine the success of the alternative under assessment. Their identification might be

based on stakeholders' experiences or on sensitivity analyses during earlier studies. Examples are user behavior influencing the effectiveness of energy measures [41] and building components' service life being crucial for their reuse potential [42]. These conceptual blocks are the 'unknown unknowns'.

In his third step, Schwartz emphasizes the importance of understanding the effect of predetermined elements and critical uncertainties. In the context of building design, many research reports offer that understanding. For example, demographic studies bring reliable insights to people's continued ageing, households' declining size and population's growing diversity [43] (p. 164).

3.2.2. Detect and Rank Driving Forces by Importance and Uncertainty

From a thorough understanding of the selected story blocks, it is possible to identify the forces that drive them and rank these forces by importance and uncertainty. Driving forces include external factors, as well as intrinsic characteristics. For example, both the amount of rainfall (external force) and the installed amenities (internal force) determine the chance of flooding (critical uncertainty) [9] (p. 106).

Changes in driving forces lead to different futures and thus diverging scenarios. Schwartz organizes drivers in five categories: social, technological, economic, political and environmental. Various construction-related alternatives for this categorization can be found in the literature on adaptable architecture and Open Building [44]. For example, in the tradition of Maury [45], three types of change are discerned, including changes in a building's functions, in the capacity of its systems and in the flow of its users. However, of all available categorizations, the user-related dimensions of performance defined by Iselin and Lemer [46] are preferred for the present framework. These dimensions distinguish functional, technological, economic and social drivers, as is illustrated in Annex 1.

After the driving forces of change are identified, it is time to rank them. This is Schwartz's fourth step. He stresses that the goal of this ordering is to 'identify the two or three factors or trends that are the most important and uncertain' [9] (p. 228).

3.2.3. Relate Driving Forces to Building Performance and User Satisfaction

Not every change entails a building alteration however. Alterations are assumed to occur only if changes result in a significant mismatch between the users' requirements and the buildings' performance [44]. To be able to model the effects of changes in drivers, first the concepts of requirement and performance are defined. Thereafter, it is questioned which mismatches trigger an alteration.

Almeida et al. [47] state that every building envisions the fulfilment of requirements. They include needs and obligations specified or implied by users, governments or other stakeholders [48]. Depending on the building's performance, i.e., the way it can be used, it does fulfil those requirements [49]. To describe a building's performance, several tools are at hand. For individual indicators, quantitative metrics and qualitative criteria can be used. They are discussed in standards such as the ISO standard on houses [50].

To know which mismatches eventually trigger an alteration, the concept of user satisfaction can be adopted when modelling the scenarios, i.e., the degree to which users perceive their requirements are met [48]. Therefore, a large portfolio of short- and long-term occupant feedback techniques evaluating comfort, satisfaction, behavior and expectations is available, but requires further development [51]. Alternatively, stakeholders must agree on minimum performance indicators during the scenario development process.

3.3. Elaborating Scenario Narratives

Now, all story blocks are collected and understood, time has come to elaborate the scenarios and 'weave the pieces together in a form of a narrative' [9] (p. 230). Therefore, this method introduces the idea of life cycle options and adopts the concept of story plots.

3.3.1. Identify and Select Life Cycle Options

As discussed in Section 3.2.3., changes in key drivers do not always trigger a building alteration. After all, there are many ways to deal with change. As in stock trading, these possibilities can be referred to as the options a building offers. Taking into account the predetermined elements, critical uncertainties and different driving forces, a series of options can be selected to constitute a scenario.

In addition to real options such as selling or letting a building [52], a life cycle option can be the possibility to refurbish the building or to expand it [53]. The more options a building facilitates, the more future-proof it is expected to be. Like in stock trading, each building option has its cost, but avoids the risk to be confronted with escalating expenses in the future. Several studies already developed methods to assess the value of such options [54]. Numerous authors also discuss all sorts of options including Maury [45], Slaughter [55], Friedman [56] and Scheider and Till [57], whereas departing from the comprehensive categories defined by Glogar [58] and Durmisevic [59], Annex 2 was developed to support their identification.

The life cycle options a building offers are determined by the adopted design strategy. Such strategies are widely discussed in the context of the Open Building movement [60]. For example, a multi-purpose building facilitates changes without physical alterations. Within such a building, activities can be easily reorganized due to the building's generic layout, versatile services and multi-functional spaces [61]. Alternatively, an adaptable building facilitates future refurbishments. As the components of such a building can be disassembled and reconfigured, alterations allow maintaining users' satisfaction in a material efficient way [62].

3.3.2. Selecting Scenario Plots and Developing Narratives

The fifth of Schwartz's eight steps is to select one or more scenario logics. These logics are 'the plots that best capture the dynamics of the situation and communicate the point effectively' [9] (p. 230). They are the scenarios' backbone tying together the life cycle options. In his book, Schwartz discusses some typical plots such as the winners and losers plot, the challenge and response plot and the evolution plot.

When selecting plots, Schwartz warns about two pitfalls: selecting too many plots and too evident ones. The number of plots is discussed frequently in the literature. For example, Linneman and Kennell [38] (p. 146) recommend to 'develop at least three, but no more than four scenarios'. They argue that too many scenarios are overwhelming and hamper their understanding. However, if a limited number of scenarios is selected, Schwartz [9] (p. 147) warns about selecting too evident plots: 'it is easy to offer a bland assortment in which one represents the high road, one the low road, and one the average of the two'. Though, 'people not familiar with scenarios [. . .] will be tempted to identify one of the three as the middle or most likely scenario' [9] (p. 233). Consequently, 'the advantages of the multiple-scenario methodology will be lost' [Ibid.].

In the context of building design, few concrete and inspiring scenarios are at hand. The scenarios Brand [13] developed remain strategic and include few life cycle options, while those of Friedman [56] include many options, but are not divergent. Therefore, in the last section of this paper, four exemplary scenarios are presented.

3.4. Quantifying Scenarios

When different scenario narratives are developed from the most important and uncertain key drivers of change and expressed in terms of life cycle options, it is necessary to structure them so they form input for the life cycle assessments. This fleshing out of scenarios is Schwartz's sixth step.

3.4.1. Identify Scenario Implications

Although Schnaars [11] emphasizes that the strength of scenario planning lays in its qualitative evocation of how the present might evolve into the future, it is necessary to quantify scenarios to

support a design with assessment outcomes. Pesonen et al. [10] see three implications that support the quantification of scenarios: technological, contextual and value implications.

First, technological implications are reflected in the alternatives' service lives. After the introduction of life cycle options, they include not only a series of recurring interventions, such as maintenance and repair, but also changing component quantities and reuse. After all, different life cycle options will give rise to the addition and removal of building elements during subsequent transformations. Second, contextual implications are reflected in the characterization of the life cycle options' impact. After all, important key drivers for change might entail different energy mixes, labor conditions or materials prices. Third, value implications of scenarios are reflected in the weighting of the life cycle impacts. This can be done through the selected discount and inflation rates and the environmental impact indicators.

Given these implications, the life cycle impact of a design alternative cannot be calculated with conventional assessment formulas, i.e., by multiplying its element's quantity by a fixed annual impact per unit. After all, such a constant value per unit can no longer be determined. In reaction, a new calculation method was developed by Galle et al. [63].

3.4.2. Model Transformation Scenarios

During conventional life cycle assessments, building alterations are modelled as reoccurring interventions, e.g., a space repartitioning by disassembly and remounting a dividing wall every five years [64]. Such refurbishments do not result however from scenarios built with key drivers for change and a variety of life cycle options.

The scenarios that result from the steps above can only be defined at the building level. To support the translation of a life cycle scenario into an inventory (i.e., the calculation input), digital modelling methods such as BIM are promising. In this regard, Van Nederveen and Gielingh [65] (p. 674) state: 'buildings are considered as temporary configurations of components and materials'. Therefore, 'object based, parametric design technologies become more important than ever before' [Ibid.]. Based on the resulting inventories, the seventh step of Schwartz's scenario planning process can be undertaken: the assessments returning the life-long impact of each design alternative for every scenario.

As the studied scenarios include the interests and insight of the stakeholders that defined together the critical uncertainties, as they consider the options designers introduced in each alternative and because these scenarios are not predictions, but imaginable futures, the resulting outcomes foster better-informed design decisions.

Moreover, as Schwartz's eighth step says [9] (p. 231), the findings of scenario planning include also the 'selection of leading indicators and signposts' for monitoring the actual service life of the eventually preferred design alternative. Consequently, not only during the building's design stage scenarios are of value, but also during the following life cycle stages, they support building designers, owners and users.

4. Proof-Of-Concept Case Study

In this section, the adaptable renovation of an apartment building is studied. The conducted analyses illustrate how scenario-based life cycle assessment can offer insightful results and concrete design advice. After considering the project's context, as well as the analysis' scope, it was possible to develop effective scenarios and to study the robustness of the design alternatives.

4.1. The HoZe Refurbishment Project

The HoZe building is located on the Hoogbouw square in the Belgian municipality Zelzate. The nine-story high housing block is owned by VMSW (Vlaamse Maatschappij voor Sociaal Wonen), the Flemish Society for Social Housing. Today, the building's renovation is necessary to meet the society's standards [66].

4.1.1. Goal and Scope Definition

For the renovation, VMSW commissioned the architectural office KPW to redesign the building. Ambitiously, KPW stated in their proposal: ‘this renovation is committed to develop a sustainable envelope and infill that serve as a resilient building in interaction with its neighborhood’ [67]. Other areas of improvement include energy performance, wheelchair accessibility and user comfort.

In the context of the policy-oriented research project ‘Design for Change’, KPW’s design process could be observed from the problem statement in November 2013 till the building’s technical development in March 2014 [68]. During three design meetings and intermediate correspondence, different design proposals were confronted with the key concepts of adaptable building design, and demountable and reusable building elements were developed [69]. To evaluate the elements’ environmental and financial impact and thus the feasibility of their reuse, first, conventional life cycle assessments were conducted.

However, the architects were not interested in the element’s individual impact. As they developed a ‘family tree’ of compatible dwelling types by which one apartment unit could easily be transformed into another, they wondered: is it necessary to anticipate every possible transformation, or is a focused use of demountable elements less risky? Such questions can only be answered if divergent scenarios are considered during the life cycle assessments.

4.1.2. Identifying Conceptual Story Blocks

Based on demographic studies by Deboosere et al. [43], various story blocks could be identified. Considering the particularities of social housing, three predetermined elements have been observed:

- a constant demand for social housing,
- a steadily decline of the average household size and
- an increasingly super-diverse society.

Additionally, three critical uncertainties were identified considering surveys about housing ideals, pathways and types by Luyten et al. [70], as well as the interests of the designers:

- the household sizes that will apply for social housing,
- the requirements per household size and
- the variability of those requirements over time.

Other uncertainties, including a radical change in functional requirements or urban codes affecting the usability of the building, were discussed with the designers and building owner for creating awareness. Nevertheless, they considered only the uncertainties above as relevant story blocks for the aspired life cycle assessments.

For these predetermined elements and uncertainties, two drivers are considered. First, the acceptance of new housing concepts will determine whether the composition of households remains traditional and continues to rely on relationship and parenthood or whether it changes considerably and embraces for example co-housing, assisted living facilities or home-based care. Second, peoples’ willingness to relocate and their possibility to do so will determine how frequent new households will enter an apartment. With new households, the composition and the requirements would change, affecting the preferred number of spaces per apartment, the level of privacy, and so on.

4.1.3. Developing Scenario Narratives

From the two driving forces, four scenarios can be sketched. Arranging the forces in a two by two matrix results in four imaginable futures developed during discussions between the designers, building owner and the authors that provided the consultancy (Figure 3).

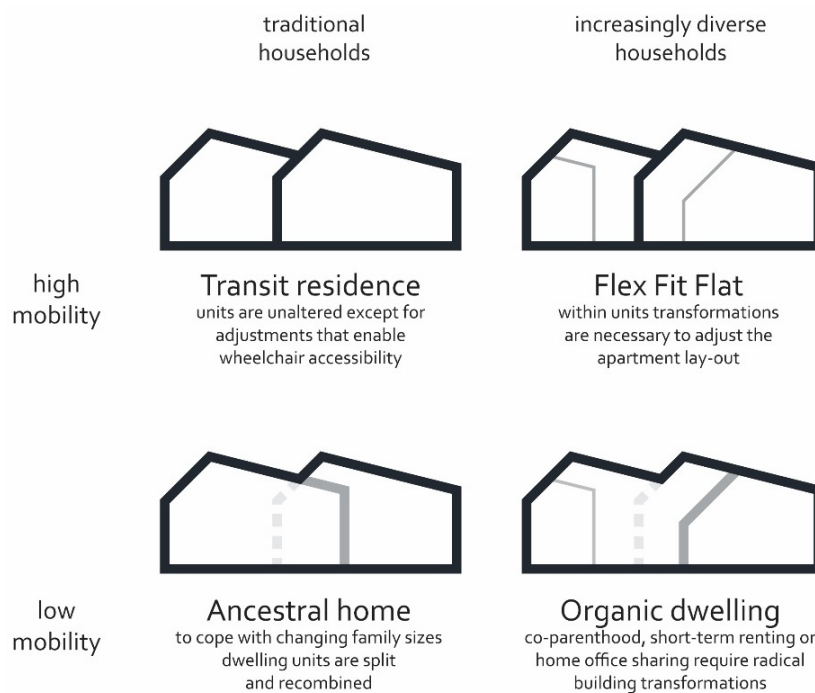


Figure 3. Organizing the identified key drivers for change in a matrix, i.e., household diversity horizontally and household mobility vertically, returns four divergent scenarios. As an example, they are presented here by a short description and a small figure.

The first scenario is that of the transit residence. In this case, households' mobility is high, while their composition remains traditional. When one family moves out, it is likely that the next one has similar requirements. Consequently, the dwelling units remain unaltered except for necessary refurbishments of technical services and occasional adjustments to enable wheelchair accessibility.

The second possible future is that of the flex fit flat. In this case, households' mobility is high and their composition increasingly diverse. If the building already contains a broad range of dwelling types, new households will easily find a suitable unit. Nevertheless, within some units, alterations are necessary to create an apartment layout that fulfils new privacy and accessibility requirements.

The third scenario is that of the ancestral home. When households remain rather traditional and their mobility is low, requirements change together with the family's evolution over time. The transformation of children from toddlers to adults will result in gradually changing needs for space and privacy. Simultaneously, caring facilities for people willing to age in place will be necessary.

The fourth scenario is that of the organic dwelling. When households' mobility is low and their composition increasingly diverse, the users' requirements can change radically. Co-parenthood, short-term renting (cf. airbnb.com) and home office sharing (cf. hoffice.com) are illustrative. These changes give rise to new unit types and alterations amongst neighboring units.

4.1.4. Quantifying Scenarios Implications

For fleshing out scenarios, all life cycle options must be considered. Possible apartment alterations are laid out in a 'family tree' of dwelling units developed by KPW. For each type of unit, characterized by the number of bedrooms and number of residents (for example Type 3/5 of three bedrooms for five residents), VMSW defined minimum space and accessibility requirements [66]. Through these guidelines, it is possible to describe all four scenarios as a sequence of apartment type transformations (Figure 4).

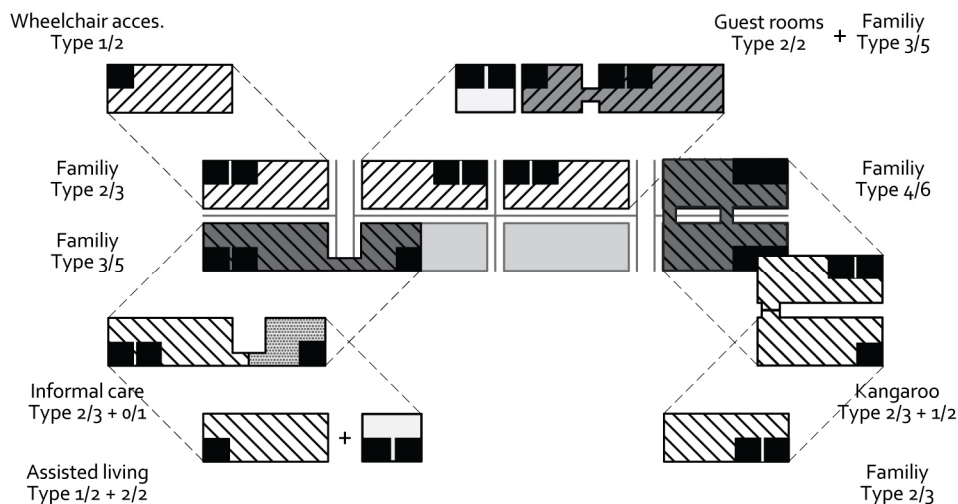


Figure 4. Projecting the organic scenario on the HoZe building shows how conventional family apartments could transform into new types such as assisted living or kangaroo dwellings. Based on a ‘family tree’ of units, this image shows all possible transformations on the first floor of the building.

The most important implication of the considered transformations is the number of building elements that is added, reused or removed every year (Figure 5). These changing quantities are managed with the use of a BIM software modelling the subsequent apartment layouts for all floors of the HoZe building in different project ‘phases’, i.e., a feature in for example the Autodesk Revit software. For each scenario, a different model is built, resulting in four separate inventories. Processing these inventories with the help of VBA scripts and Microsoft Excel sheets developed by Galle [71], it is possible to know how many elements are added, reused and removed every phase. Thereafter, their service life can be modelled and their life cycle cost calculated according to the assessment procedure of Galle et al. [63].

In contrast to the technical implication of the four scenarios, the conceptual story blocks that are defined in this case study do not give rise to changing energy, labor or materials prices. Therefore, no contextual nor value implications are considered.

4.2. Exemplary Assessment Outcomes

After defining the analysis’ purpose, developing relevant design alternatives and modelling scenarios, it is possible to carry out the comparative life cycle assessments. For illustrative purposes, a simple yet comprehensive focus on life cycle cost assessments is chosen.

According to the adopted assessment procedure [71] and corresponding standards [19], the financial impacts are sorted into distinct life cycle stages: initial construction or renovation (i.e., life cycle Stage A4-5), operational energy consumption (B1), maintenance (B2), repairs (B3), replacements (B4), simple reoccurring refurbishments (B5simpl), addition of elements during future transformations (B5/A4-5), reuse of elements during transformations (B5trans), demolition of elements during transformations (B5/C1-2), residual value of disassembled elements during transformations (RV) and demolition of elements at the end of the period of analyses (C1-2). The considered impacts include labor, material and equipment costs and are taken from the extensive database of average contractor prices in Belgium [72,73]. In the assessments below, these impacts are discounted at a nominal rate of 4% to take into account time preference, risk and loss aversion, as well as endowment and other psychological factors reflecting our economic behavior [71].

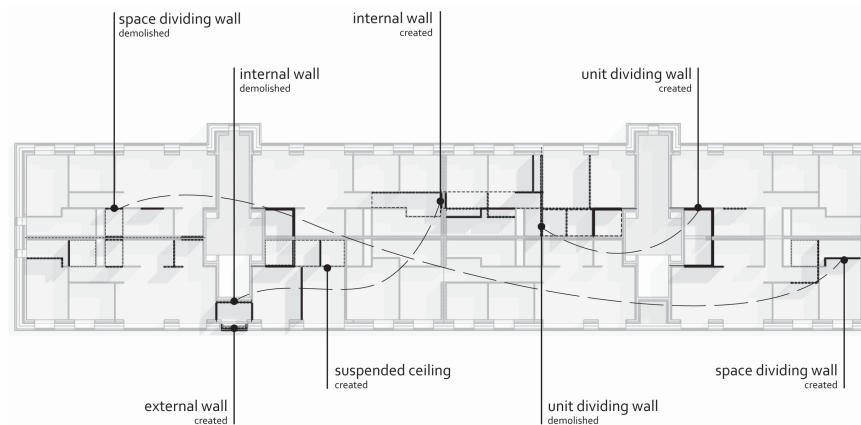


Figure 5. During a typical transformation phase in the organic scenario at the first floor of the HoZe building shown here, a range of demountable building elements such as space and unit dividing walls are removed while others are added. This is an opportunity to reuse and save materials.

4.2.1. At the Building Level

The comparison of a conventional renovation using elements that are wasted every refurbishment to a transformable renovation using demountable building elements that can be reused is conducted accordingly. It starts at the building level and considers external and internal walls, unit and space dividing walls, floors and suspended ceilings. The resulting life cycle cost of the renovation strategy using demountable elements for a period of 75 years varies around 6.5 million euros, i.e., 16% more than the conventional renovation.

At this level, the developed scenarios do not influence the preference of one renovation strategy above the other (Figure 6). Since, depending on the considered scenario, the initial cost accounts for 48 to 50% of the life cycle cost, while transformation costs have a share of only 0 to 3%, the life cycle cost of the flex fit, ancestral or organic scenario is never 3% greater than that of the transit scenario. This is the result of discounting costs and savings that are situated further in the future, as well as of the versatile plan layout KPW designed. Nevertheless, the transformation costs, including the addition of elements (i.e., life cycle Stage B5/A4-5), the reuse of elements (B5trans), the residual value of disassembled elements (RV) and the demolition of others (B5/C1-2) are 3 to 18% lower for the transformable renovation strategy. Conclusively, although the variance of the life cycle cost is lower for a transformable building than in the case of a conventional materialization, a renovation using only demountable building elements cannot be justified financially.

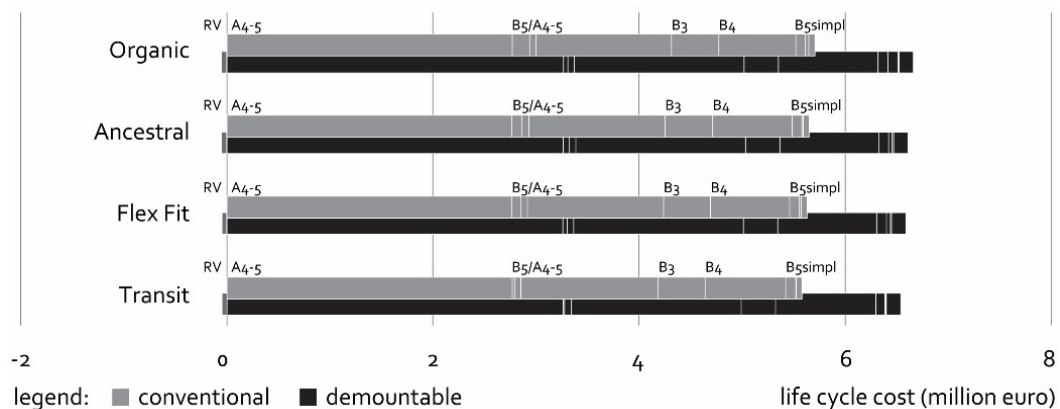


Figure 6. At the building level, the life cycle cost of the renovation strategy using demountable elements is higher than that of the conventional strategy, regardless of the considered scenario.

4.2.2. At the Element Level

To minimize the increased construction and life cycle costs, the use of demountable building elements can be differentiated by realizing them only where future alterations could occur and under the condition that their reuse results in long-term savings. Therefore, analyses per element type are required. For the illustrative propose of this proof-of-concept, only three elements are discussed.

For the floors, it is assumed that they are not the subject of future transformations in any scenario. Although the durable parquet finishing of the demountable variant results in reduced repair (−72%) and replacement costs (−49%), these savings do not compensate increased construction (+48%) and maintenance costs (+213%) (Figure 7).

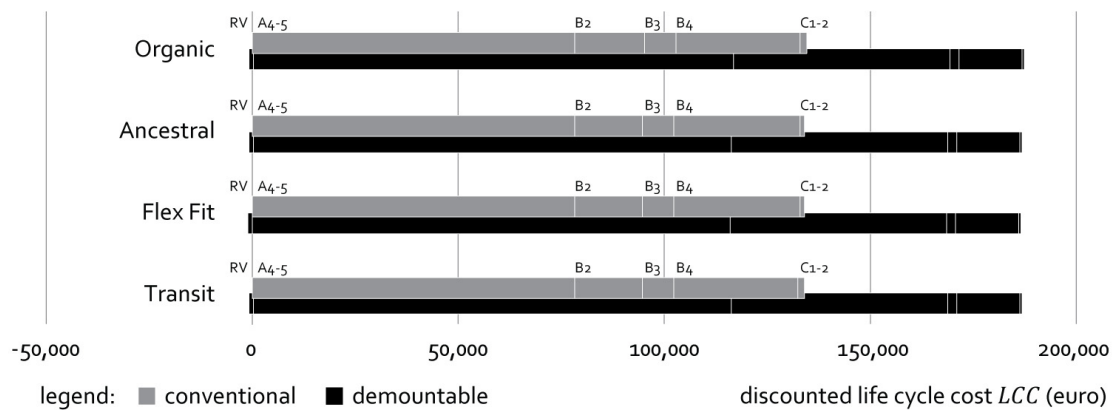


Figure 7. For the floors, the life cycle cost related to the demountable renovation strategy is significantly higher than the cost of the conventional strategy in all scenarios.

To improve their acoustic performance, internal walls are placed in front of existing unit dividing walls. The initial cost of the demountable wall variant is 3% higher than that of the conventional alternative. Nevertheless, its reuse during future transformations results in a reduction of the life cycle cost of between 1 and 3% (Figure 8).

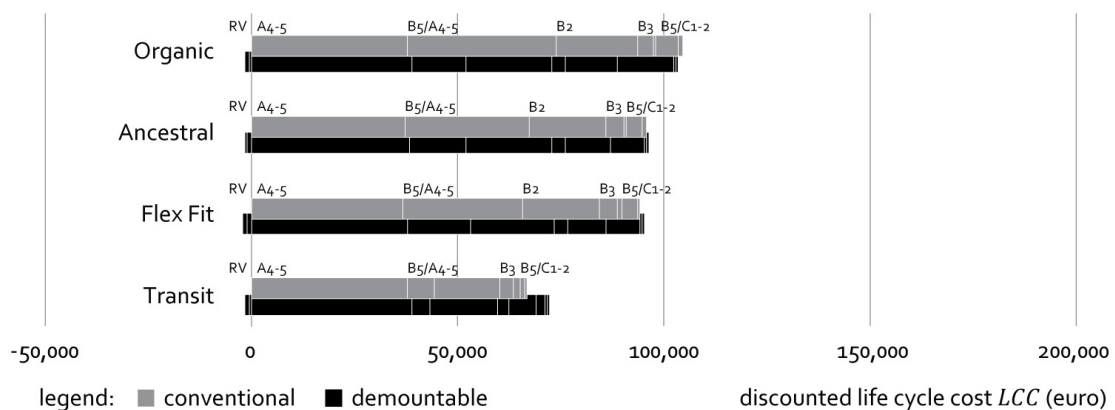


Figure 8. For the unit dividing wall, the life cycle cost related to the demountable renovation strategy is lower than the cost of the conventional strategy (including the elements' residual value), except no transformations occur (i.e., the transit scenario).

If demountable space dividing elements are used only where transformations could occur (i.e., considering the 'family tree' of unit types), the difference in life cycle cost between both variants varies from +0 to +6% (Figure 9). Imagining that this demountable variant results in an important reduction of environmental impacts, this additional life cycle cost might still be acceptable.

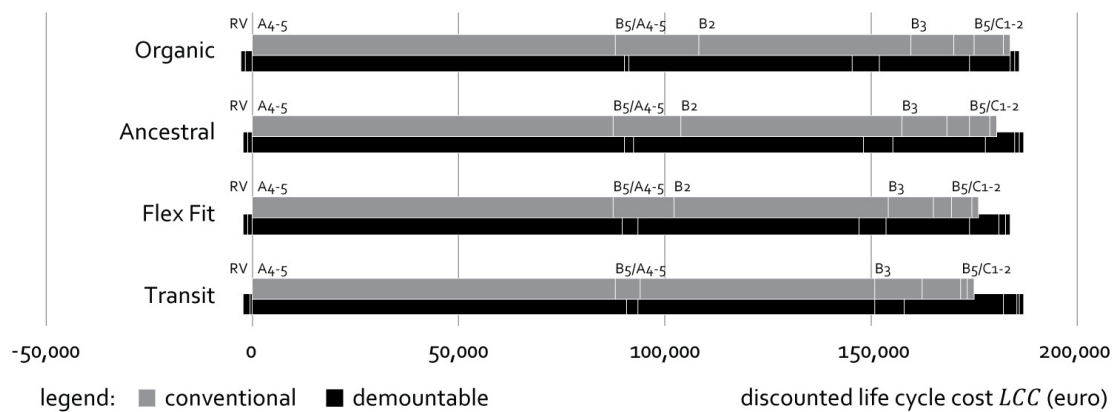


Figure 9. For the space dividing wall, the life cycle cost related to the demountable building strategy is lowest only in the scenario with the most transformations, if the residual value is included as a gain.

Based on the presented findings, several exemplary conclusions can be drawn. From a mere financial perspective, the use of for example the demountable floor cannot be encouraged. Furthermore, the unit dividing wall has a higher construction cost, but because of the life cycle savings it brings, it should be studied how this wall's initial cost can be lowered. Further, the demountable space dividing wall has a competitive initial and life cycle cost. Its use can thus be advised.

Moreover, the life cycle cost analyses presented in this case study include transformation scenarios that are much more realistic than the continuously reoccurring disassembly and reconstruction of all elements that are considered during conventional assessments. After these imaginable futures, it appeared that the financial feasibility of demountable building elements is noticeably lower than was concluded during earlier assessments, for example by Paduart [74]. Therefore, a differentiated use and the further improvement of demountable and reusable building elements are indispensable.

5. Discussion

The principal aim of this paper was to support the integration of scenarios in life cycle assessment through the development of a conceptual, as well as supportive method that designers currently lack. Therefore, the added value of scenario planning for building designers and life cycle assessors was explored first. This exploration showed that the main strength of scenarios includes the insight they create about the long-term effects of initial design choices and about the resilience of the design alternatives at the table. Therefore, in the second half of this paper, a framework for the creation and implementation of scenarios was proposed and illustrated by a proof-of-concept case study. The framework discusses the identification of key drivers for change, their impact on user satisfaction, as well as the life cycle options a building offers.

Although the analytic approach of identifying a design's life cycle options might be inconsistent with the creative nature of the architectural discipline, it was identified in the present study as an interesting way to raise awareness about the adaptability of a building. It could identify vulnerabilities in the initial design proposals, reveal life cycle options designers were not yet aware of and give an indication of the building's transformational capacity. Nevertheless, when performing scenario-based life cycle assessments, the outcomes do not reveal instantly 'why' one design alternative is more resilient than another one. To find out, for example, if the imagined refurbishments profit from the layout's generality or the reusability of building elements, a detailed study of the assessment outcomes remains necessary. Moreover, although scenarios cover uncertainty about future refurbishments, sensitivity analyses on uncertain model assumptions, such as the discount rate, and on generalized operational data, such as maintenance and replacement frequencies, remain indispensable to verify the variability of the assessment outcomes and test its impact on the conclusions.

Further, the case study presented in this paper illustrated that with the developed scenarios, design consultants can take into account the specific plan layout of the building, its possible transformation options and the key drivers for change the stakeholders find most relevant. As the resulting assessment outcomes are based on these case-specific and realistic assumptions and because of the participative way the scenarios are developed, a broad acceptance of the resulting assessment outcomes could be realized amongst all stakeholders.

Additionally, with the adoption of the developed scenario-integrated method, researcher could understand better under which circumstances the reuse of building elements is financially feasible and environmentally advantageous. These circumstances include not only the number of refurbishments before element reuse is advantageous, but also the impact of the elements' durability, the actual material losses during reuse and the disassembly labor cost could be studied further. Consequently, with these scenario-based assessments, the well-informed and substantiated development of reusable, material-efficient and thus sustainable building elements can be supported.

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Annex 1

Drivers for change can be categorized into the four dimensions of Iselin and Lemer [46]. Their categorization is adopted for its comprehensiveness and relation with the building's performance. Per dimension examples are ordered from internal to external.

Functional drivers, related to the purpose of the building, its elements or amenities.

- Natural wear and tear, maintenance and possible (ab)use of the building.
- User and owner needs, such as spatial capacity and organization.
- Changes within the building's environment, such as climate conditions.

Technological drivers, related to the efficiency of the installed technology.

- Building components' quality, safety and effect on the environment and health.
- Technological innovations, such as the emergence of smart energy management.
- Standards on energy efficiency, accessibility or indoor comfort.

Economic drivers, related to the cost of the existing building.

- Operational expenses, such as management and maintenance costs.
- Property valuation, related to the location and eventual urban developments.
- Development of real-estate markets, including resale opportunities.

Social drivers, related to the broad influence of values, political agendas or lifestyles.

- Household and dwelling forms, such as co-parenthood, house sharing, etc.
- Cultural changes, for example in heritage or environmental impact valuation.
- Policy and legislation, reflected in building and spatial planning regulations.

Annex 2

After the work of Blakstad [44] and Tseng, Zhao and Fu [75,76], six categories of managerial options are distinguished. Although these options do not necessarily alter the building, they might have an important impact on the feasibility of the alternatives.

The option to execute a life cycle option, allows maintaining the expected quality.

- e.g., reconfiguring a demountable wall to adjust an apartment's layout
The option to defer or postpone a life cycle option, until more information is available.
- e.g., not reconfiguring a demountable wall, but find another temporary solution
The option to abandon a life cycle option, when market conditions have changed.
- e.g., replacing the demountable wall with a conventional one
The option to expand or contract an option, when technical possibilities changed.
- e.g., upgrade the demountable wall so also its insulation level could be altered
The option to switch a life cycle option, when old uncertainties changed for others.
- e.g., use the demountable wall to build a transformable cupboard
The option to renegotiate a life cycle option, when market conditions have changed.
- e.g., replace the demountable wall with an increasingly cheaper sliding door

Further, to obtain a selection of appropriate life cycle options for fleshing out life cycle scenarios, three categories of adaptations can be explored [58].

The option to adapt the requirements, after Glogar's use and utilization adaptability.

- The use is reorganized within the same building by adapting the use's structure, form or timing. Consequently, the expected level of satisfaction is maintained.

The option to adapt the expected level of satisfaction, after Glogar's social adaptability.

- The existing building and its performance is accepted possibly at the (indirect) cost of a lower level of satisfaction.

The option to adapt the performance, after Glogar's structural adaptability.

- The existing building, its elements or components are altered to adjust their performance and realize the expected level of satisfaction.

Finally, all options can be expressed at three different levels. Detailing their implications at each level will facilitate their translation into service life models and life cycle impacts [59].

Building alterations, after Durmisevic's spatial adaptability.

- location (rearrangement and reconfiguration)
- volume (expansion or contraction)
- repartitioning (splitting or merging)

Element alterations, after Durmisevic's structural adaptability.

- construct
- deconstruct
- replace
- relocate

Component alterations, after Durmisevic's material adaptability.

- elimination (old)
- addition (new)
- move (reuse)

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