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KEY ASPECTS FOR ECONOMIC FEASIBILITY OF IMPLEMENTING DESIGN FOR STRUCTURAL ADAPTATION IN THE AUSTRALIAN TIMBER INDUSTRY

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ABSTRACT: The global increase in timber usage is generally interpreted as a response to tackle the construction industry's major contribution to greenhouse gas emissions. Meanwhile, there is a growing concern that the expected future demand for timber cannot be met while maintaining sustainable forestry. Efforts to maximize the resource efficiency and service lives of timber products are therefore highly relevant, both to preserve biodiversity and to prolong carbon storage. One such strategy in development is to invest in a timber structure's ability to be locally repaired or adapted to changed user demands – to *Design for Structural Adaptation*. Yet, stakeholders are uncertain regarding the economic feasibility of such an investment. This study addresses this by investigating which factors are key in determining the economic feasibility of designing for structural adaptation in an Australian multi-residential light-frame timber building. A cost-benefit analysis is performed to compare a structurally adaptable building to a business-as-usual alternative, where the uncertainty of future adaptation needs is considered in the model. The results provide valuable insights for future efforts to implement adaptable timber design, as key aspects for economic feasibility are identified.

KEYWORDS: Cost-benefit analysis, Design for Adaptation, Structural Adaptability, Circular economy, Service life extension

1 – INTRODUCTION

As the construction industry moves towards a circular economy, there is an increased interest in strategies to extend the service lives of materials and products in buildings. Besides reusing individual building components, strategies for prolonged service lives on a larger scale are also gaining traction. *Design for Adaptation* (DfA) is such a strategy, where the aim is to facilitate an extended service life for an entire building [1]. Existing research on DfA can generally be classified as *functional* DfA, i.e., design to facilitate non-structural changes to a building. However, there are clear advantages to be gained by applying adaptability to a building's load-bearing structure. This is particularly true for timber structures, as service life extension of timber prolongs carbon storage and promotes sustainable forestry and biodiversity [2,3]. Still, *Design for Structural Adaptation* (DfSA) is not currently practiced in the timber industry, and development is needed in several areas before an implementation is feasible. In a study centred around the Swedish and Australian construction industries, Öberg et al. [4] found significant uncertainties for decision-makers considering adaptable structural design. Such uncertainties, particularly those regarding economic feasibility, are for industry stakeholders enough to opt out of DfSA. Thestudy reported in this paper aims to reduce that uncertainty by identifying which factors are crucial for determining the economic feasibility of DfSA for timber. In a previous study within the same project, a calculation model was developed for cost-benefit analysis (CBA) of a multi-residential cross-laminated timber (CLT) building in Sweden [5]. The results of the study are relevant to other countries in the EU, partly because of shared regulations and partly because CLT usage is relatively frequent in Europe. Australia, on the other hand, does not use CLT to the same extent. It also relies more heavily on imports to supply its domestic demand for timber [6], something that can certainly influence the profitability of resource efficiency. The current study extends the analysis from the CLT building from Öberg et al. [5] to a generic low- to mid-rise timber structure, encompassing both mass- and lightweight timber buildings. The costs and benefits

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used in this study are further based on the Australian construction industry.

The CBA model is used to identify the situations in which DfSA can be an economically feasible option. A sensitivity study is subsequently conducted to determine the crucial factors in determining the economic feasibility of structural adaptability. Lastly, a best- and worst-case scenario analysis is conducted. The results of the study contribute to the development of DfSA for timber by addressing the previously identified challenge of its economic feasibility. Key considerations are identified to advance the development and implementation potential of this resource efficiency strategy.

2 – PROJECT DESCRIPTION

This study applies the CBA calculation model developed by Öberg et al. [5] to the Australian context, to investigate the economic feasibility of implementing DfSA for timber buildings in Australia. While the original study was only focused on CLT buildings in Sweden, the current study expands the focus to include other multi-residential timber buildings as CLT is not as widespread in Australia. High-rise buildings are excluded to limit the focus to the common applications of timber construction in Australia [7]. The two alternatives to be compared in the *ex-ante* CBA model are:

- Alternative 0 (reference alternative): A low- to midrise business-as-usual (BaU) multi-residential timber building, demolished and replaced every *x* years.
- Alternative 1: A similar building as in alternative 0, but with an added investment for structural adaptability – i.e., a DfSA building.

The theoretical buildings are located in an unspecified Australian metropolitan area, and all costs are expressed in Australian Dollars. The calculation model is based on the assumption that when structural obsolescence occurs, the DfSA building is adapted while the BaU building is demolished and replaced with a new one [8]. However, while structural obsolescence is known to occur at times, there is a lack of data showing how often it happens and what the statistical risk for structural obsolescence is for a timber building. This issue is navigated by stating that structural obsolescence occurs on average every x years and subsequently investigating for which values of x DfSA would prove to be the more profitable option. Each variable, such as the construction costs or building size, is given a range of plausible values. The effect of each variable on the break-even point for *x* can then be studied. The calculations aim to determine the highest value of *x* for which Alternative 1 is more beneficial, and how it varies when different input variables are changed.

To investigate this break-even point, the relevant factors determining the economic feasibility of the alternatives (e.g., building size, construction cost, etc.) are identified. Each factor is further given a range of plausible values. A baseline value within the range is also defined. With an upper, a lower, and a baseline value defined for each factor, a sensitivity study can be conducted in the form of a one-factor-at-a-time (OFAT) analysis. A separate analysis is conducted for each factor, where it is varied from its lower to its upper value while all other factors are kept at their baseline value. As such, the impact of each variable on the break-even point for x can be determined. A best- and worst-case scenario analysis is also conducted, where all factors are set to their extreme values to either increase or decrease the break-even point for *x*.

3 – EXPERIMENTAL SETUP

3.1 CALCULATION MODEL

A comparative cost-benefit analysis is conducted by calculating the Net Present Value (NPV) of the chosen alternatives. The NPV represents the net value of an alternative, including all relevant costs and benefits expressed in monetary terms and discounted based on when they are expected to occur. They are discounted as time goes on to account for the fact that it is economically preferable to postpone costs and expedite benefits [9]. The basic calculation of a project's or investment's NPV found in Equation (1):

$$NPV_i = \sum_{t=0}^{T_{tot}} \frac{1}{(1+r)^t} (B_{it} - C_{it}) \qquad (1)$$

where t is the time at which a given cost or benefit occurs, T_{tot} is the time horizon of the project, B_{it} and C_{it} are the benefits and costs, and r is the discount rate.

Equation (1) was applied and adjusted by Öberg et al. [5] to fit the two alternatives and include the average structural obsolescence rate x as a variable. The adjusted equations are shown in Equation (2) and (3). Both equations are explained and motivated in further detail in the original paper [5].

First, the NPV of Alternative 0 is calculated as:

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$$NPV_{alt.0} = \sum_{t=0}^{100} \frac{B_1}{(1+r)^t} - \sum_{n=0}^{n_{obs}} \frac{B_1}{(1+r)^{nx}} + \frac{V_{T_{tot}}(R_{alt.0})}{(1+r)^{T_{tot}}} - \sum_{n=0}^{n_{obs}} \frac{C_1}{(1+r)^{nx}} - \sum_{n=1}^{n_{obs}} \frac{C_3}{(1+r)^{nx}} \quad (2)$$

where B_1 is the monetary benefits of building use per year, n_{obs} is the number of occurrences of structural obsolescence within the time horizon of 100 years, x is the average rate at which the structural obsolescence occurs, $V_{Ttot}(R_{alt.0})$ is the residual value of Alternative 0 discounted to the time horizon ($t = T_{tot}$), C_1 is the construction cost, and C_3 is the demolition cost.

Second, the NPV of Alternative 1 is calculated according to Equation (3):

$$NPV_{alt.1} = \sum_{t=0}^{100} \frac{B_1}{(1+r)^t} - \sum_{n=0}^{n_{obs}} \frac{B_1}{(1+r)^{nx}} - C_1 - C_2 - \frac{C_3}{(1+r)^{T_{tot}}} - \sum_{n=1}^{n_{obs}} \frac{C_4}{(1+r)^{nx}} \quad (3)$$

where C_2 is the DfSA realization cost and C_4 is the adaptation cost.

Both alternatives consider a one-year loss in benefits from building use for every occurrence of structural obsolescence. The NPV of Alternative 0 also includes a residual value, which is excluded from Alternative 1. This is because the adaptable building is assumed to be demolished at the time horizon, at which point it is 100 years old. The BaU alternative, on the other hand, involves several buildings since structural obsolescence is assumed to cause a full building replacement. For certain values of x, Alternative 0 will include a relatively new building at the end of the timeline. In these cases, it is not realistic to claim that the building will be demolished at $t = 100$. Instead, the remaining service life of the final BaU building constructed within the time horizon is included in $NPV_{alt.0}$.

Another noteworthy difference is that $NPV_{alt.1}$ only includes one occurrence of C_1 and C_3, respectively. This is because this alternative only includes one building, and thus only one construction and demolition cost. In Alternative 0, these costs may occur several times within the time horizon.

Lastly, Alternative 1 includes costs C_2 and C_4. These are the DfSA realization cost and the adaptation cost, respectively. These are not included in $NPV_{alt.0}$, as it is a BaU alternative where no adaptation occurs.

One factor not represented in Equations (2) and (3) is the value depreciation rate. This rate considers the yearly loss of value for a property. A high depreciation rate benefits the BaU alternative, as it is replaced every x years. The baseline value of the depreciation rate d is 0% in this study; therefore, it is not included in these equations. In the sensitivity study, Equations (2) and (3) are adjusted to include the depreciation rate as it is incrementally increased up to 2%. For nonzero value depreciation rates, the benefit of building use decreases on a yearly basis until the building is replaced. Hence, the benefit of building use in Alternative 0 reverts to its original value every x years. As the DfSA building in Alternative 1 is never replaced, its monetary benefits of building use decreases continually throughout the timeline. This is illustrated in Figure 1. The adjusted equations for $NPV_{alt.0}$ and $NPV_{alt.1}$ are described in detail in [5].

3.2 INPUT DATA

Table 1 shows the factors included in the study along with an overview of their value ranges for the sensitivity analysis. While there are other possible costs and benefits through a building project's phases, they are disregarded in this study as they are assumed not to have a significant impact on the break-even point for x. For instance, costs for land acquisition and damage evaluation are assumed to be equal or very similar for both alternatives and are hence excluded from the CBA.

The chosen values for each factor are motivated in the following subsections.

Building size

The Australian Bureau of Statistics (ABS) classifies mid-rise apartment buildings as having up to eight storeys [10]. While the total floor area of eight-storey apartment

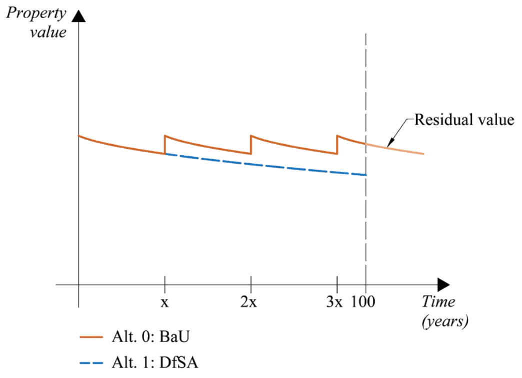

Figure 1. Illustration of the value depreciation rate's effect on the property value of Alternatives 0 and 1 for x *= 30 years. Figure from [5].*

Table 1. Overview of input data.

Variable	Lower value	Baseline value	Upper value
Building size (*A*)	$A_\ell = 600\text{m}^2$	$A_b = 7{,}000\text{m}^2$	$A_u = 15{,}000\text{m}^2$
Cost of new construction (C_1)	$C_{1.\ell} = 1{,}554\ \text{A\\$/m}^2 \cdot 1.50 \cdot 0.95 \cdot A$	$C_{1.b} = 2{,}883\ \text{A\\$/m}^2 \cdot 1.60 \cdot A$	$C_{1.u} = 4{,}212\ \text{A\\$/m}^2 \cdot 1.70 \cdot 1.05 \cdot A$
DfSA realization cost (C_2)*	$C_{2.\ell} = 0.02 \cdot C_1$	$C_{2.b} = 0.14 \cdot C_1$	$C_{2.u} = 0.40 \cdot C_1$
Cost of demolition (C_3)	$C_{3.\ell} = 1\ \text{A\\$} \cdot A$	$C_{3.b} = 35\ \text{A\\$} \cdot A$	$C_{3.u} = 0.30 \cdot C_{1.b}$
Cost of adapting a DfSA building (C_4)*	$C_{4.\ell} = 0.50 \cdot C_{4.b}$	$C_{4.b} = 44{,}000\ \text{A\\$}$	$C_{4.u} = 100 \cdot C_{4.b}$
Discount rate (*r*)	$r_\ell = 2.6\%$	$r_b = 4.8\%$	$r_u = 7.0\%$
Benefit of building use per year (B_1)	$B_{1.\ell} = 0.50 \cdot B_{1.b}$	$B_{1.b} = 166\ \text{A\\$/m}^2 \cdot A$	$B_{1.u} = 2 \cdot B_{1.b}$
Value depreciation rate (*d*)	-	$d_b = 0.0\%$	$d_u = 2.0\%$

*This factor is only applicable in Alternative 1.

buildings may vary, an upper limit estimation of 15,000 m^2 was used. An apartment building containing five average sized apartments was used as a lower limit for this factor. The average size of a new Australian apartment was 108 m^2 in 2019 [11], resulting in a total area of 540 m^2 for five apartments. This area was rounded up to 600 m^2, to include non-living areas such as hallways. Lastly, the baseline value for this factor was set to 7,000 m^2 – the rounded mid-point between the lower and upper values.

Cost of new construction

The Australian Institute of Quantity Surveyors provides information regarding the construction costs in Australia's major cities. In 2023, construction costs for low- to mid-rise apartment buildings ranged between 2,220 and 3,240 A\$/m^2 [12,13]. With a recommended error margin of 20-30% [13], the range expands to 1,554-4,212 A\$/m^2.

The construction cost should further be increased to include professional fees, required margins, and costs for marketing, sales, and financing. These may vary on a case-by-case basis. In a report on the costs of supplying residential dwellings in New South Wales, this addition was approximately 60% of the construction cost [14]. To consider the uncertainty of these costs, the lower construction cost was increased by 50%, the baseline cost by 60%, and the upper cost by 70%.

Lastly, it should be noted that reinforced concrete is the dominant structural material for Australian multi-residential buildings. Studies comparing the cost of building timber structures to equivalent concrete alternatives often find that the former is higher by a few percent [15,16]. Yet, there are also examples of timber alternatives offering cost savings instead [17]. To include these possibilities, this factor's lower and upper limits were decreased or increased by 5% respectively. The baseline value, set at the midpoint of the extremes, remained unchanged in this regard.

The resulting lower, baseline and upper values of C_1 are found in Equations (4-6).

$$C_{1.l} = 1{,}554 \frac{A\$}{m^2} \cdot 1.50 \cdot 0.95 \cdot 7{,}000\ m^2 = 15.50\ million\ A\$ \tag{4}$$

$$C_{1.b} = 2{,}883 \frac{A\$}{m^2} \cdot 1.60 \cdot 7{,}000\ m^2 = 32.29\ million\ A\$ \tag{5}$$

$$C_{1.u} = 4{,}212 \frac{A\$}{m^2} \cdot 1.70 \cdot 1.05 \cdot 7{,}000\ m^2 = 52.63\ million\ A\$ \tag{6}$$

DfSA realization cost

In the Swedish application of the CBA model [5], the value used for C_2 was not regionally tied. Instead, it was based on a study by Brigante et al. [18] which examined the cost of implementing DfA strategies. As DfSA for timber has not yet been implemented, and its related costs are currently unknown, costs related to DfA serve as the best available alternative for the baseline value of this cost. This baseline value is found in Equation (7). To account for the uncertainty in this implementation cost, the factor was given a wide range – from 2% to 40% of the construction cost C_1.

$$C_{2.b} = C_1 \cdot 0.14 = 3.11\, million\, A\$ \tag{7}$$

Cost of demolition

While demolition costs vary based on factors such as building design and weight [19], an estimated cost of demolishing a CLT building in Australia was found to be approximately 35 A\$/m^2 [20,21]. Hence, the baseline value could be determined according to Equation (8):

$$C_{3.b} = 35\, A\$ \cdot 7{,}000\, m^2 = 0.25\, million\, A\$ \tag{8}$$

This value can be compared to La Fleur et al.'s [19] findings from a life-cycle cost study of Swedish buildings, where the demolition cost for lightweight buildings was found to make up approximately 30% of an equivalent building's construction cost. This is a notable difference in cost, which may be partly explained by the fact that the Australian demolition cost of 35 A\$/m^2 excludes waste management and transportation. The cost of these factors greatly depends on the building's weight and location. To avoid underestimating this cost, the upper value of this factor was set to 30% of C_1. Since the lower value could not be decreased by an equivalent amount, a lower demolition cost of 1 A\$/m^2 was used.

Cost of adaptation of a DfSA building

Similar to the DfSA realization cost, this factor was not regionally bound in the Swedish study [5]. Instead, it was based on the estimated reparation costs for a CLT floor panel after a real-scale fire test [22–24]. The reported cost from this study – €13,490 – was doubled for the baseline value, to represent the added complexity and costs related to adaptations in a real building. The same was done for this study, except the cost was converted to Australian dollars according to the average exchange rate of 2024 [25]. The result is shown in Equation (9).

$$C_{4.b} = 22{,}123\, A\$ \cdot 2 = 0.044\, million\, A\$ \tag{9}$$

As this factor involves considerable uncertainty, a broad range was used in the sensitivity study. Like in the Swedish study, the original repair cost (here 22,123 A\$) was used as the lower value, and the baseline value was multiplied by 100 for the upper value. Though this may be considered an extreme increase, it is considered necessary to identify any effect in the results due to the relatively small baseline value.

Discount rate

The discount rate can have a significant impact on the results of a CBA. Regional or national recommendations from government agencies often guide the choice of an appropriate real discount rate. In Sweden, that recommendation is 3.5% [26], which is similar to other European countries where the recommendation often lies between 2% and 4% [27]. Australia, like several other non-European countries, recommends a considerably higher real discount rate [28]. This is because Australia applies a *social opportunity cost* approach, prioritizing alternative investment returns, whereas the Swedish approach prioritizes people's preference over time through a *social time preference* [28]. The Australian government recommends using a real discount rate of 7% and conducting sensitivity analyses at 3% and 10% [29,30]. However, they also recommend a declining discount rate for analyses with longer timelines. For analyses that include costs occurring 76-125 years in the future, the recommended real discount rate is 4.8% [29]. This was used as the baseline value for the discount rate of this analysis with a time horizon of 100 years. For this long-term discount rate, there are no recommendations regarding values for the sensitivity analysis. Instead, this study considered the effects of using a short-term discount rate by setting the upper value of this factor to 7%. For the lower value, the discount rate was decreased by an equal amount to 2.6%.

Benefit of building use per year

The mean rent of an Australian apartment in 2019 was 17,940 A\$ per year [31]. Based on the average size of Australian apartments in the same year [11], an estimation of 166 A\$/m^2 was used for the baseline value. Hence, the baseline value of this factor is determined as shown in Equation (10).

$$B_{1.b} = 166 \frac{A\$}{m^2} \cdot 7{,}000 m^2 = 1.16\, million\, A\$ \tag{10}$$

The baseline value was halved for the lower value of B_1 and doubled for the upper value. The wide range was chosen to include most rent schemes.

Value depreciation rate

It is difficult to estimate the value depreciation rate of buildings. Results from U.S.-based studies suggest that it can be approximated to 1.5% [32,33], but similar studies could not be found in an Australian context. To consider this uncertainty, the value depreciation rate in this study was increased incrementally from 0% to 2%.

4 – RESULTS

The CBA results for the scenario where all factors were set to their baseline values are shown in Figure 2. The break-even point occurs at x = 44 years. This suggests that DfSA would be economically preferable to the BaU if all costs and benefits are accurately represented by the baseline values and structural obsolescence can be assumed to occur more often than every 44 years.

Australian dwellings often have a design life of 50 years. Still, the design life of a building does not necessarily affect its actual service life. Obsolescence may occur before the design life has passed, e.g., due to unforeseen damages or changed demands. The probability of demolition for Australian buildings younger than 50 years is currently not determined. Hence, the break-even point of 44 years may not entirely rule out the economic feasibility of DfSA – although a result of over 50 years would certainly be more favourable.

The results of the sensitivity analysis are found in Figures 3 and 4. The results show that the factors demolition cost, adaptation cost, building use benefits and building size all have minor effects on the break-even point when varied. The most influential factor is the DfSA realization cost (see Figure 3b), followed by the discount rate (Figure 3f). This was also found to be the case in the corresponding Swedish study [5].

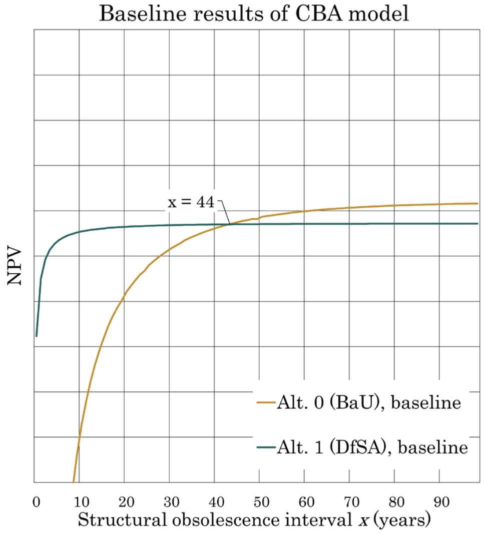

Figure 2. Results of the CBA calculation for baseline values.

A large possible span for the break-even point was found in the best- and worst-case scenario analysis and the OFAT analysis of the value depreciation rate. When applying a 2% depreciation rate to the least favourable scenario for DfSA, a break-even point of x = 6 years was found. Naturally, such a scenario would suggest that implementing DfSA would not be economically feasible in any measure. Yet, on the other end of the spectrum, a break-even point of x = 99 years was found in the best-case scenario – regardless of the assumed value depreciation rate. A closer look at Figure 4b) reveals that the "DfSA favourable" graphs do not intersect at all within the timeline. As the CBA model would not allow for a break-even point $x > 99$ years, the actual break-even point of this scenario would likely have been even greater if a longer time horizon had been chosen.

The large span of possible break-even points is the result of several uncertain factors, which cause the sensitivity analysis to include vast ranges of possible values. For specific case studies, the costs and benefits could be more accurately estimated, narrowing the span of possible break-even points.

The span of break-even points found in this study is slightly less favourable for DfSA than in the corresponding Swedish study [5]. The main reason behind this is the higher discount rate. The baseline value for the discount rate used in this study was lowered from the recommended 7% to 4.8% to consider the fact that the time horizon exceeds 75 years. Still, the baseline value is considerably larger than the corresponding Swedish value of 3.5%. It can further be argued that the BaU alternative of this study can be seen as multiple projects with a time horizon of x years – where x may certainly be less than 75 years. However, this CBA study takes a deliberate long-term approach in which the results should be comparable to the corresponding Swedish study. The recommended 7% for shorter-term investments is still included in the sensitivity study, but the baseline value of 4.8% was deliberately chosen to reflect the long-term nature of the study and enable a fair comparison to the Swedish results.

5 – CONCLUSIONS AND RECOMMENDATIONS

In this study, the CBA model developed by Öberg et al. [5] to assess the economic feasibility of implementing DfSA for timber in Sweden was applied to the Australian context. The results indicate that the most crucial factor in this regard is the DfSA realization cost, followed by the discount rate used in the CBA. This reinforces the results of the corresponding Swedish study, although the

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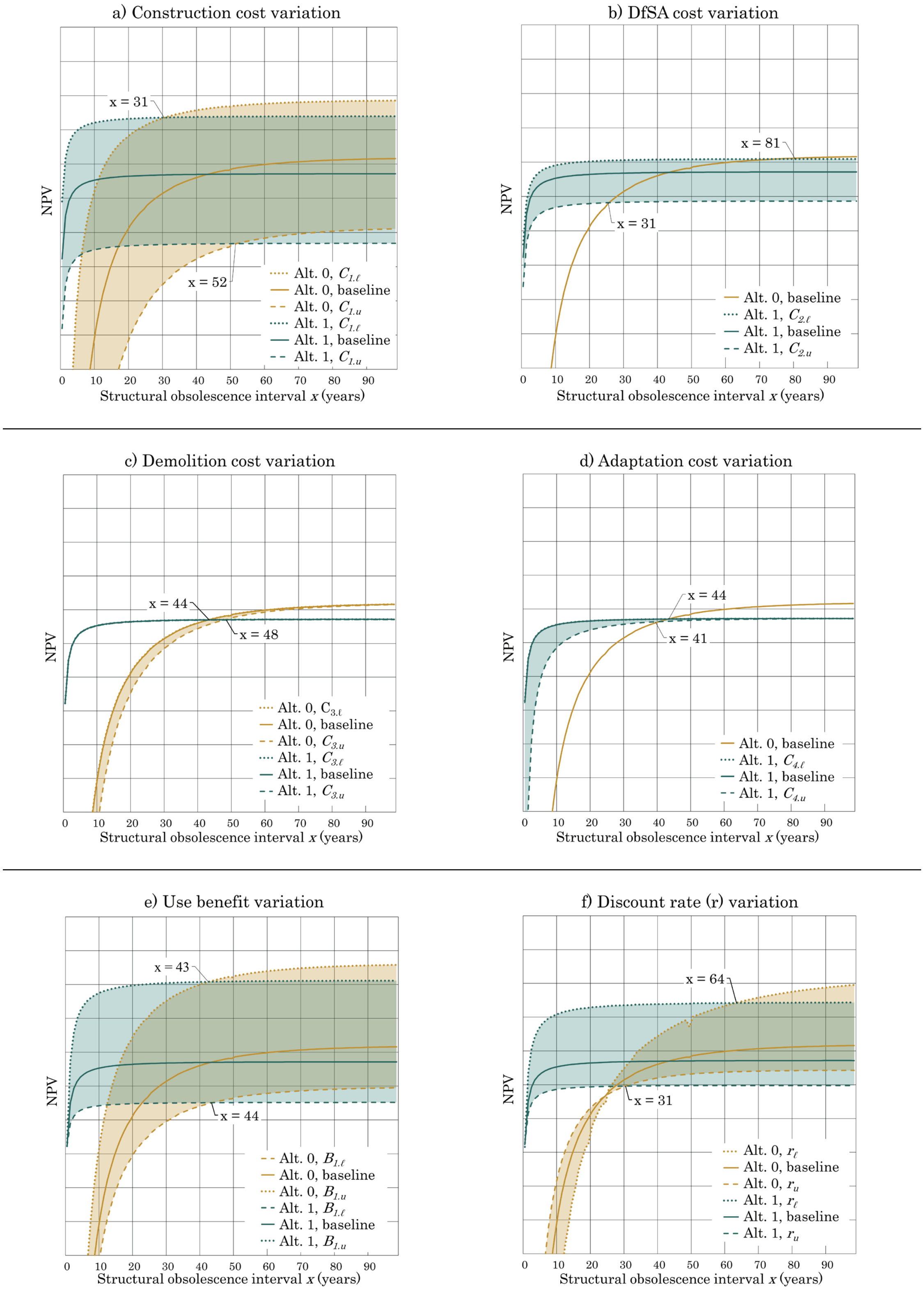

Figure 3. Results from the OFAT analysis for factors a) construction cost, b) DfSA realization cost, c) demolition cost, d) adaptation cost, e) use benefit, and f) discount rate.

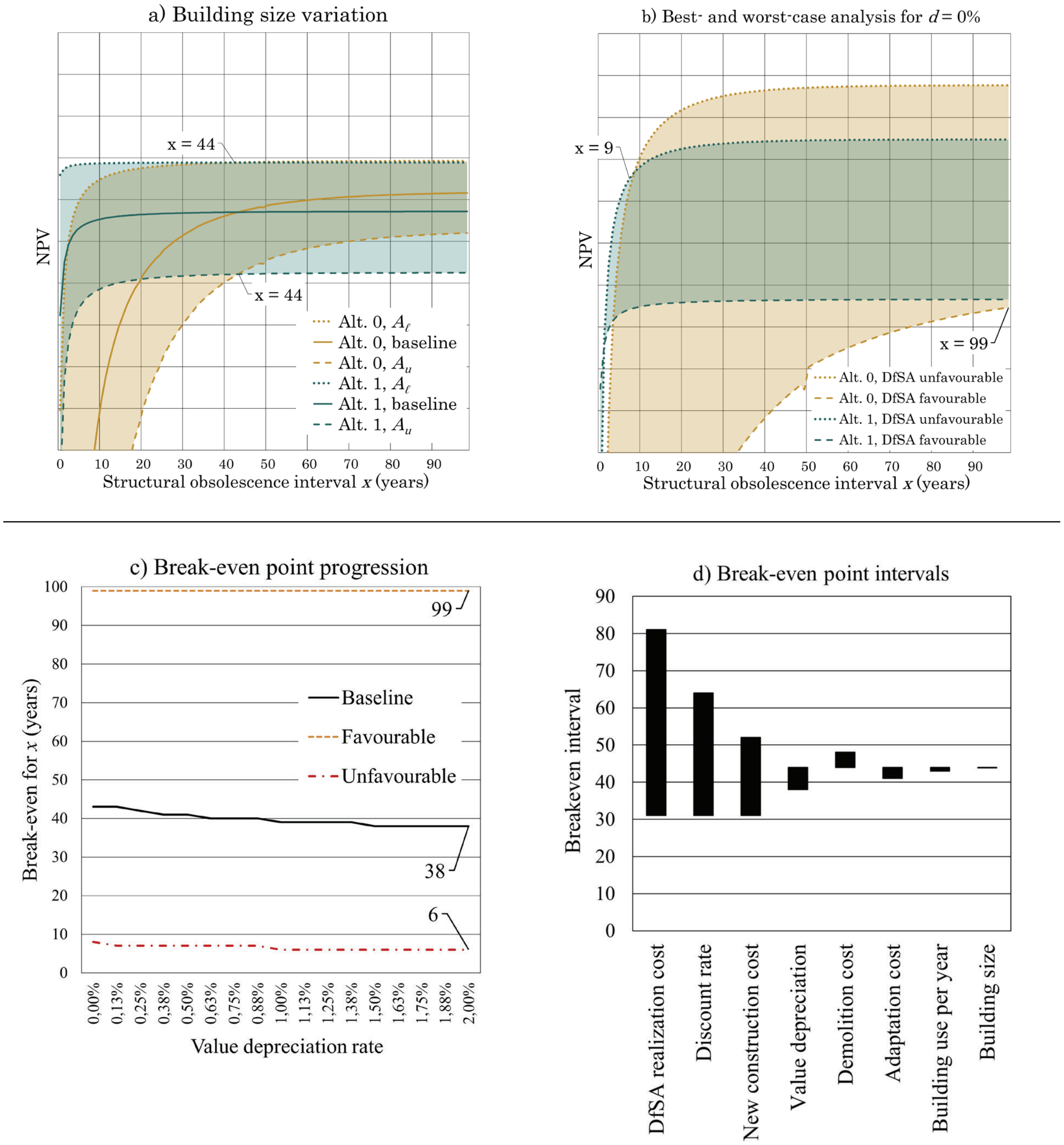

Figure 4. a) Results from the OFAT analysis for the factor building size. b) Results of the best- and worst-case analysis for a 0% depreciation rate. c) Break-even point progression for an increasing value depreciation rate. d) Break-even point intervals for all OFAT analyses, sorted from most to least impactful factors.

general economic feasibility of DfSA was found to be lower in Australia. This is mainly due to the recommended discount rate, which is higher in Australia than in Sweden. A lower discount rate benefits the DfSA alternative, as it lessens the demand for a quick return on investment. Moreover, the costs used for construction and demolition are lower in this study than in its Swedish counterpart. This further benefits the BaU alternative as the costs of replacing a building are lower.

This study provides valuable insights for the future development of DfSA, as economic feasibility is crucial to facilitate its implementation. This feasibility is analysed based on a range of economic scenarios, and the key aspects to increase the implementation potential in Australia are identified. The results can be used to further advance the development of resource-efficiency strategies for timber construction.

6 – ACKNOWLEDGEMENT

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