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Citation for the original published paper (version of record):

Öberg, V., Jockwer, R., Goto, Y. et al (2025). Design for Structural Adaptation: economic feasibility of an implementation for Swedish timber
buildings. Building Research and Information, 1(18).
http://dx.doi.org/10.1080/09613218.2025.2478063

Building Research & Information

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/rbri20

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BUILDING RESEARCH & INFORMATION
https://doi.org/10.1080/09613218.2025.2478063

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Design for Structural Adaptation: economic feasibility of an implementation for Swedish timber buildings

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ABSTRACT

As the construction industry is progressively adopting circular economy principles, there is an increased interest in prolonging the service lives of buildings by designing them to be adaptable. This is particularly relevant for timber buildings, as extended-use phases promote prolonged carbon storage and sustainable forestry. Applying the concept of Design *for Structural Adaptation* (DfSA) to load-bearing timber may grant such benefits, yet it is uncertain whether there are motivations for stakeholders to apply the concept on an industrial scale. In particular, the economic implications of implementing DfSA for timber are currently unclear. This study addresses this uncertainty by investigating the economic feasibility of applying DfSA to a theoretical multi-residential cross-laminated timber building in Sweden. A model for comparative cost–benefit analysis was developed and applied to two alternatives: a business-as-usual building and one designed for structural adaptation. A sensitivity analysis was performed to explore the factors determining the economic feasibility of DfSA, and a best- and worst-case scenario was developed. The results showed that a low investment cost for DfSA is the most crucial factor in determining its economic feasibility.

ARTICLE HISTORY
Received 16 October 2024
Accepted 27 February 2025

KEYWORDS
Design for adaptation; structural adaptability; cost-benefit analysis; timber structures; service life extension

Introduction

The global rise in timber demand is often attributed to the growing efforts to mitigate the construction sector's substantial impact on greenhouse gas emissions. In addition, mass timber construction is often suggested to be advantageous in comparison to steel or concrete with regard to energy efficiency due to the lower thermal conductivity of the structural components. While timber is generally considered to be a more sustainable structural material in these regards, values such as preserved biodiversity and prolonged carbon sequestration are crucial for a holistic approach to sustainable construction (Arehart et al., 2021; Imai et al., 2009). Hence, the increased timber demand calls for resource efficiency strategies for timber from sustainably managed forests. One such strategy is to invest in a timber structure's ability to accommodate for future needs of structural changes – to *Design for Structural Adaptation* (DfSA).

There is an increased awareness that to enable life extensions for contemporary buildings, one needs to incorporate adaptability strategies already in the design phase (Akanbi et al., 2018; Eberhardt et al., 2022; Gerding et al., 2021). DfSA is motivated by this need, with a special focus on the need for structural adaptability. DfSA aims at avoiding or postponing structural obsolescence, which can be the cause of demolition. Structural obsolescence implies that the building's structure is no longer able to fulfil the owner's demands on it. The possible causes of this can be sorted into either ability changes or demand changes (Öberg, 2024). The former includes, for instance, damages due to unforeseen events such as fire or long-term structural degradation due to moisture leakage. The latter instead includes external factors, such as the demand for different building functions in a certain location. The idea of DfSA is that a structurally adaptable building would facilitate changes in response to ability and demand changes. Thus, when structural obsolescence occurs, a building that would otherwise have been demolished and replaced would instead be adapted. This would save money and resources, reduce waste, and limit greenhouse gas emissions. If implemented for timber buildings, DfSA can have additional benefits such as prolonged carbon storage.

Though DfSA for timber may offer environmental benefits through resource efficiency, the specific benefits for decision-makers are uncertain as it has not yet been

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implemented. Moreover, industry decision-makers are often risk-averse when faced with innovations that incur higher investment costs. In an interview study by Öberg et al. (2024), industry stakeholders were found to be hesitant regarding the financial feasibility of implementing DfSA based on the assumed increased investment at a project's start. While some previous research on building adaptations indicates possibilities for long-term economic benefits (Itard & Klunder, 2007; Pereiro et al., 2023; Shahi et al., 2020; Wilkinson et al., 2009; Yiu & Leung, 2005), other research works conclude that the financial cost of rehabilitation often tips the scale in favour of new construction (P. A. Bullen & Love, 2010; Newman, 2021). For Business-as-usual (BaU) buildings, the main factor influencing the economic feasibility of building adaptation seems to be the extent and complexity of the needed adaptation work (Alba-Rodríguez et al., 2017; P. Bullen & Love, 2011; Caruso et al., 2020). There is a lack of studies exploring the long-term economic effects of investing in a building's adaptability, particularly for load-bearing timber structures designed for adaptation. Pereiro et al. (2023) conducted a study in which an adaptable (or 'reconfigurable') industrial steel structure was compared to one with welded connections. The results showed economic profitability for the adaptable structure after three reconfigurations. Yet, the situation may be different for timber, not to mention if the focus is on extensive adaptation needs that would cause demolitions of entire BaU buildings. If there is a significantly increased initial investment for DfSA, decision-makers may opt out as it is not certain that the investment will be returned later in the building's service life. Even if an adaptation is assumed to occur eventually, the cost of adapting the DfSA building is not certain. It is, simply, unclear how designing and constructing a timber building for structural adaptation will impact the project at a later stage.

This study aims to reveal this impact by determining the economic implications of implementing DfSA for a Swedish timber building. The study further identifies important considerations for the future development of the concept, to promote the economic benefits for stakeholders. This is done by developing a cost–benefit analysis (CBA) model and applying it to a multi-residential cross-laminated timber (CLT) building in Sweden. A sensitivity analysis is subsequently conducted to determine which factors have the highest impact on the results. Lastly, a best- and worst-case scenario is developed to investigate the highest and lowest potential in terms of the economic feasibility of DfSA.

It should be noted that the chosen methodology is a theoretical approach to a problem that would certainly be affected by practical factors on a case-by-case basis. For instance, the cost of a given project would be greatly influenced by the specific design and construction approaches of its involved actors – as would the possibilities for implementing DfSA. As such, an alternative approach would have been to conduct case studies of specific buildings where all such factors are considered. Such studies may provide more precise results related to very specific building types and practical approaches. They may also show the impact of different approaches to implementing DfSA, which as of yet is a relatively unexplored research topic. Instead, this study takes a generalized approach in pursuit of broadly applicable results regarding what determines the economic feasibility of DfSA in timber buildings. The effects of different practical approaches are considered only as monetary variations in the sensitivity study.

Methods

Cost–benefit analysis framework

To assess the economic feasibility of implementing DfSA in a building, it can be compared to a scenario where a similar BaU building is demolished and replaced every time structural obsolescence occurs. The main obstacle in such an assessment is that the statistical risk of structural obsolescence in Swedish buildings is currently unknown. This study navigates this issue by setting up the structural obsolescence occurrence rate as a variable, x. It should be noted that x is the *average* occurrence rate. In reality, structural obsolescence is not likely to occur at regular intervals. Yet, for the long-term perspective of this study, an average value is deemed appropriate. An analysis can subsequently be performed to find the break-even for x – i.e. how often does structural obsolescence need to occur on average for DfSA to be a more economically feasible option?

A schematic illustration of this comparison is shown in Figure 1. The cumulative cost of the BaU alternative starts with a construction cost (C_{constr}). The cost of the DfSA alternative starts higher due to an added realization cost (C_{DfSA}). When structural obsolescence occurs, a cost is added to both alternatives. For the BaU alternative, this is the cost of demolishing and replacing the building ($C_{dem} + C_{constr}$). For the DfSA alternative, there is instead a cost of adapting the building (C_{adapt}). This cost should be smaller than that of a full building replacement, as the purpose of DfSA is to make adaptations the less expensive option. Thus, the slope of the DfSA curve is smaller than that of the BaU curve. The DfSA option does, however, start at a higher cost due to the above-mentioned sources of increased

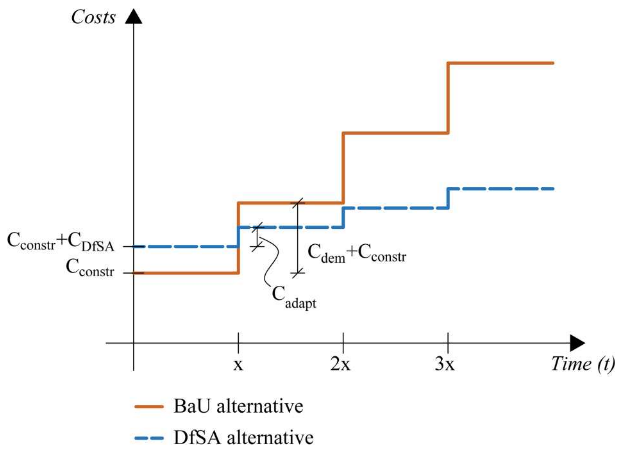

Figure 1. Schematic comparison of costs for a DfSA building compared to a BaU alternative, where *x* is the average occurrence rate of structural obsolescence.

investment cost. Because of this, the break-even point cannot be reached until the first occurrence of structural obsolescence. To ensure that the increased investment is returned as soon as possible, at the time $(t) = x$, the sum of the investment and the cost of adaptation should be lower than the summed cost of demolishing and replacing the BaU building.

Naturally, Figure 1 shows a simplified model that leaves out some important criteria. First, it does not consider that an avoided cost in the present is more valuable than an investment that will be returned in full in the future. The DfSA investment cost may enable cost savings at $t = x$, but the BaU alternative frees up that capital to be invested somewhere else from $t = 0$. That investment may then have time to generate more revenue in the years leading up to the structural obsolescence. Second, the DfSA building's end-of-life is disregarded. While it may have a longer use phase, one should assume that this option will eventually include a demolition cost. Third, the model does not consider the monetary benefits of the buildings and how they might vary between the alternatives. Fully replacing a building would increase the owner's ability to fulfil the current demands on the building. For instance, a modern apartment building could generate more revenue once built, as a higher rent could be demanded from the tenants. Apartment buildings also tend to decrease in value with age (Bokhari & Geltner, 2018), though it should be noted that there is a significant market value for a certain type of older apartments.

To reflect on these factors and create a more realistic model of the problem, a cost–benefit analysis model was developed. CBA is a method to evaluate the net impact of a project, based on its benefits and costs (Johansson & Kriström, 2018). This is done by expressing costs and benefits in monetary values, even for non-financial factors such as environmental values and human well-being. Yet, as the motivations for this study lie in stakeholders' concerns for financial profitability, the included costs and benefits are chosen from a business economic perspective. Such a method could be called a cost-revenue analysis rather than a cost–benefit analysis. However, the former typically has a shorter studied period and focuses on one single investor. As this study investigates the investment of DfSA from a long-term perspective, the original investor may change during the studied period. The CBA is based on the assumption that the revenue gained from selling a DfSA building would reflect its future life extension potential. Thus, the focus does not lie on one single investor, but instead on the society of Swedish building investors and developers. Even so, the developed CBA model may be expanded to include externalities such as carbon emissions or waste production.

The chosen approach for CBA also has some similarities with a life-cycle cost (LCC) analysis. This method also takes a long-term approach, by compiling all costs for a project in its lifespan. Still, it was not considered necessary to include all costs in the analysis since some of them (e.g. the land property cost) were assumed equivalent for both alternatives. Hence, a comparative CBA was considered the most suitable approach.

For the purposes of this study, an *ex ante* CBA was deemed appropriate. This approach is used when the purpose of a CBA is to assess different projects or policies before their potential implementation (Boardman et al., 2014). An *ex ante* analysis aims to decide which alternative to implement with respect to how it affects society. Two alternatives were chosen for consideration: A reference alternative (Alternative 0) and an Alternative 1.

Alternative 0 is a scenario where a BaU multistorey residential CLT building is built, used for *x* years, and then demolished and replaced with a similar building. This cycle is repeated until the end of the CBA's timeline is reached.

Alternative 1 is a scenario centred around a building of the same size and structure as in Alternative 0, where DfSA has been implemented. Instead of being demolished and replaced, it is adapted every *x* years until the end of the CBA's timeline. Thus, Alternative 1 is centred around one single building throughout the timeline.

The choice of structural system and building function was based on several factors. First, a BaU light-frame single-family house can already be considered adaptable, to an extent. In addition, the environmental and economic costs of replacing such a building are considerably lower than those for a multi-residential building. Thus, the market for DfSA likely lies in larger multistorey buildings. Second, compared to other options for large timber structures (e.g. post-and-beam systems), CLT can be considered more resource-intensive. Thus, resource efficiency is particularly important for CLT structures. Third, while CLT has been used in Sweden since the early 2000s (Swedish Wood, 2019), its usage is still in development. Thus, there are opportunities to influence building practices in a way that might not be possible for more traditional building materials. Lastly, a residential building was chosen as it represents one of the main uses for CLT in Sweden.

Beyond limiting the scope to multi-residential CLT structures, this study does not specify a structural layout for the studied buildings. This was motivated by the aim of scalable and broadly applicable results. Certainly, the structural layout of a building may affect the cost of constructing or adapting it. In this study, such cost variations are represented in the sensitivity analysis.

Though Swedish krona (SEK) is used in Sweden, the costs and benefits of the study are converted to Euro to increase the study's international comprehensibility. While Sweden is not a member of the Eurozone, it is part of the EU. EU regulation applies to Sweden as well as most countries using the Euro. The choice of Euro as the studied currency can therefore enhance this study's relevance and scalability to other countries within the EU.

When conducting a CBA, monetary values and the discount rate need to be expressed either in nominal or real terms. Either approach results in the same answer as long as nominal and real values are not mixed (Boardman et al., 2014). If nominal values are to be used, an expected inflation rate needs to be applied to the future costs and benefits based on when they are expected to occur. In the CBA of this study, the moments in time where costs and benefits occur are variable. Hence, this approach was not deemed appropriate. Instead, real values are used. This entails that the present value of a cost or benefit is used even if it occurs in the future when inflation has increased the nominal value of it. The real value of a future cost or benefit does not represent the actual amount of money that is lost or gained, but instead the value of the lost or gained purchasing power.

Four cost categories and one benefit category are considered in the CBA model of this study. These variables are shown in Table 1.

Table 1. Costs and benefits to be included in the CBA model.

Type	Variable	Description
Costs	C_1	Cost of new construction
	C_2*	Additional construction cost of DfSA*
	C_3	Cost of demolition
	C_4*	Cost of adaptation of a DfSA building*
Benefits	B_1	Benefit of building use per year

*Only applicable in Alternative 1.

One-factor-at-a-time analysis

To assess which input variables have the most significant effect on the break-even point, a sensitivity analysis was performed. The one-factor-at-a-time (OFAT) method was considered a suitable approach for this sensitivity analysis. The following factors were investigated in the OFAT analysis:

- Building size
- Cost of new construction (including design costs)
- DfSA realization cost, i.e. the additional construction cost to facilitate structural adaptation
- Cost of demolition
- Cost of adapting a DfSA building
- Discount rate
- Monetary benefits of building use
- Value depreciation rate, i.e. the rate at which the monetary benefits of building use decrease each year after construction

Other factors were disregarded in the study because they were deemed to not have a significant effect on the break-even point. For instance, damage evaluation costs in the case of structural obsolescence due to fire or moisture accidents were disregarded as such activities would occur equally in the two alternatives. Any additional evaluation related to the preparation of structural adaptation was considered to be included in the cost of adapting a DfSA building. The cost of land and operational costs were disregarded on the same basis; it was assumed to be equal in both alternatives.

Three different values were chosen for each factor (excluding the value depreciation rate): a baseline value based on reference projects found in existing literature, a lower value to represent the lower limit of the factor, and an upper value to represent the corresponding higher limit. The lower and upper values were chosen to form a range of plausible values for the variable. This was also done for non-monetary variables, e.g. building size and discount rate.

The value depreciation rate was not given a lower value. It is difficult to predict the value depreciation of a property or even declare that the value will decrease at all. Thus, the baseline value for this factor was set to 0%. In its OFAT analysis, the variable was increased incrementally towards its upper value to determine the progression of the break-even point.

For the remaining OFAT analysis, all factors were kept at the baseline value except for the one in focus. The break-even point was noted for the factor's lower and upper values. It should be noted that some variables affect both alternatives, but a combination of different values in the two alternatives was never investigated. For instance, the scenario with a low construction cost in Alternative 0 was only compared to the scenario with the same low construction cost in Alternative 1. The reason for this is that except for the added adaptability in one alternative, the two scenarios should be based on identical buildings built at the same time. Thus, the construction cost (excluding the added cost for DfSA) would be the same.

Best- and worst-case scenario analysis

After the OFAT analysis, an additional analysis was performed to investigate the lowest and highest plausible break-even point for x. In this analysis, two scenarios were designed: a best- and worst-case from the perspective of economic feasibility for the DfSA alternative. For each scenario, the variables were set to either favour or disfavour the DfSA alternative. In the best-case scenario, that entailed a high construction and demolition cost, low costs for DfSA realization and adaptation, and a low discount rate. The lower value was chosen for benefit B_1 since value depreciation has a more significant negative effect on the DfSA alternative than the BaU. For the worst-case scenario, the opposite ends of each variable range were chosen: a low construction and demolition cost, high costs for DfSA realization and adaptation, a high discount rate, and a high yearly benefit value. In both scenarios, the building size was kept at the baseline value of 10,000 m^2. Lastly, the effect of an increasing value depreciation rate was investigated for both scenarios.

Calculation model

To perform a CBA and assess the expected benefits and costs of a project, a net present value (NPV) is calculated. This value represents the net monetary value of a project, where each cost and benefit has been weighted based on when it is expected to occur – i.e. they are discounted as time goes on. The idea stems from opportunity costs and the fact that it is preferable to receive a benefit sooner rather than later, while costs are preferably postponed (Boardman et al., 2014). To account for this, a discount rate is applied in the calculation of the NPV:

$$\mathrm{NPV}_i = \sum_{t=0}^{T_{\mathrm{tot}}} \frac{1}{(1+r)^t}(B_{it} - C_{it}) \quad (1)$$

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

To model a comparative cost–benefit analysis, the studied timeline needs to be specified. This studied period is often referred to as a time horizon. An appropriate choice of time horizon is crucial in this study since the two alternatives are presumed to have different life spans. A shorter one may not demonstrate the value of designing for adaptation, as structural obsolescence may not occur for many years. A very long time horizon, on the other hand, would be less realistic since the risk of types of obsolescence other than structural is disregarded in the model. A DfSA building may in practice be resilient to any future structural obsolescence, but the location or aesthetics of the building may become undesirable if enough time passes. 100 years was deemed an appropriate time horizon for this study. Multi-story timber buildings tend to be placed in urbanized places, so the location is assumed to not become obsolete within that period. While the aesthetics of the building may become unmodern, it is assumed that refurbishments such as façade replacement can postpone aesthetic obsolescence for 100 years. However, after this period, the DfSA building is assumed to be completely replaced due to some obsolescence that structural adaptability cannot resolve. Consequently, there is no residual value associated with Alternative 1 beyond the system boundary. Alternative 0, on the other hand, has a residual value that should be added when the assumed lifespan of the last building has not been spent at the 100-year mark. This is illustrated in Figure 2.

Within the time horizon of the CBA, structural obsolescence is assumed to occur every x years. From x, the number of occurrences of structural obsolescence within the time horizon can be calculated as:

$$n_{obs} = \left\lfloor \frac{T_{tot}}{x} \right\rfloor \quad (2)$$

Where $\left\lfloor \frac{T_{tot}}{x} \right\rfloor$ denotes the result of the time horizon T_{tot} (100 years) divided by x, rounded down to the nearest integer.

The following two sections describe the CBA calculations for Alternatives 0 and 1 respectively. These calculations were used for every analysis where the value depreciation rate is set to 0%. For a nonzero

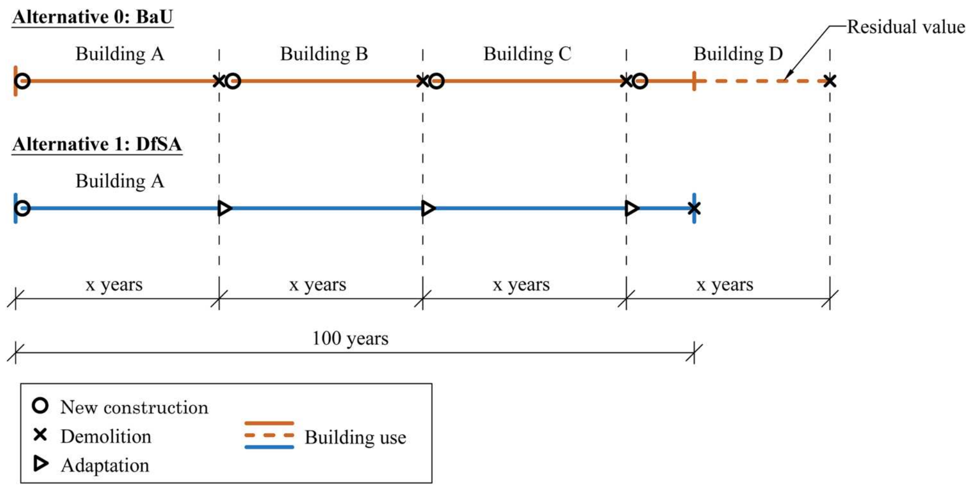

Figure 2. Graphical representation of the two alternatives within the time horizon of 100 years.

depreciation rate, the CBA model was altered as described in the final subsection of this section.

Alternative 0: business-as-usual

For the BaU alternative, the cost of new construction occurs one or more times within the time horizon for any x that is less than 100 years. Each new construction except for the first one also implies an added cost for building demolition. The discount rate needs to be considered for each new addition of construction and demolition costs. The present value of cost for Alternative 0 is calculated according to Equation (3).

$$PV(C_{alt.\,0}) = \sum_{n=0}^{n_{obs}} \frac{C_1}{(1+r)^{nx}} + \sum_{n=1}^{n_{obs}} \frac{C_3}{(1+r)^{nx}} \quad (3)$$

Where n_{obs} is the number of occurrences of structural obsolescence within the time horizon, C_1 is the cost of each new construction (which will occur $n_{obs} + 1$ time within the time horizon) and C_3 is the cost of one demolition (which will occur n_{obs} times within the time horizon).

Likewise, the benefit of building use per year should be discounted. For a use period of 100 years, the discounted benefit can be expressed as:

$$PV(B_1) = \sum_{t=0}^{100} \frac{B_1}{(1+r)^t} \quad (4)$$

Where B_1 is the benefit from using the building for one year.

The demolition and construction of a new building would in practice decrease the amount of time that a building is in use. The demolition and construction time for multistorey timber buildings can vary depending on several factors, such as building complexity and size. For this model, the time needed for a new construction is assumed to be one year. The demolition of a multistorey timber building is typically much faster, lasting for mere weeks or months. Because of this, the time needed for demolition is disregarded in this model.

To consider the lost benefit of building usage during construction, Equation (5) is applied:

$$PV(B_{alt.0}) = \sum_{t=0}^{100} \frac{B_1}{(1+r)^t} - \sum_{n=0}^{n_{obs}} \frac{B_1}{(1+r)^{nx}} \quad (5)$$

Lastly, a residual value is added to represent the remaining years of usage from the last building. This is a common practice when the time horizon of a CBA is shorter than a product or project's economic lifespan (Boardman et al., 2014). The residual value is equal to the present value of subsequent benefits and costs from the project at the time horizon (Boardman et al., 2014). The following equation can be used for the total residual value of Alternative 0:

$$V_{T_{tot}}(R_{alt.0}) = \sum_{t=0}^{T_{res}} \frac{B_1}{(1+r)^t} - \frac{C_3}{(1+r)^{T_{res}}} \quad (6)$$

Where $V_{Ttot}(R_{alt.0})$ is the residual value $R_{alt.0}$ discounted to the time horizon ($t = T_{tot}$) and T_{res} is the residual service life of the building after T_{tot} has passed according to Equation (7).

$$T_{res} = \left\lceil \frac{T_{tot}}{x} \right\rceil \cdot x - T_{tot} \quad (7)$$

Where $\left\lceil \frac{T_{tot}}{x} \right\rceil$ is the result of the time horizon, T_{tot}, divided by x, rounded up to the nearest integer.

In Equation (6), the residual value is discounted to reflect its value at the time horizon $T_{tot} = 100$ years.

While the equation's sum starts at $t = 0$, this point in time does not represent the start of the global timeline but rather that of a local timeline from $t = T_{tot}$ to $t = T_{tot} + T_{res}$. To include $V_{Ttot}(R_{alt.0})$ in the NPV of Alternative 0, the value needs to be converted to a present value at $t = 0$ on the global timeline. Thus, the value needs to be discounted again, as shown in Equation (8).

Based on Equations (3–7) the NPV of Alternative 0 is calculated as:

$$\begin{aligned} NPV_{alt.0} &= PV(B_{alt.0}) + PV(V_{T_{tot}}(R_{alt.0})) - PV(C_{alt.0}) \\ &= \sum_{t=0}^{100} \frac{B_1}{(1+r)^t} - \sum_{n=0}^{n_{obs}} \frac{B_1}{(1+r)^{nx}} + \frac{V_{T_{tot}}(R_{alt.0})}{(1+r)^{T_{tot}}} \\ &\quad - \sum_{n=0}^{n_{obs}} \frac{C_1}{(1+r)^{nx}} - \sum_{n=1}^{n_{obs}} \frac{C_3}{(1+r)^{nx}} \end{aligned} \tag{8}$$

Alternative 1: design for structural adaptation

For Alternative 1, the cost of new production and demolition only needs to be added once. The initial construction cost needs to be increased, however, to include the DfSA realization cost. When structural obsolescence occurs, the DfSA building is adapted instead of replaced. Thus, the total discounted cost of Alternative 1 is found in Equation (9).

$$PV(C_{alt.1}) = C_1 + C_2 + \frac{C_3}{(1+r)^{T_{tot}}} + \sum_{n=1}^{n_{obs}} \frac{C_4}{(1+r)^{nx}} \tag{9}$$

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

The time needed to perform structural adaptations to a DfSA building is, naturally, not currently known. To be conservative, the duration is assumed to be the same as that which is needed for the full building replacement in Alternative 0 – i.e. one year. Thus, Equation (5) can also be used in Alternative 1 to express the present value of the benefits of building usage. However, no residual value is used since the building is assumed to be demolished after 100 years.

$$PV(B_{alt.1}) = PV(B_{alt.0}) \tag{10}$$

The net present value of Alternative 1 is calculated as:

$$\begin{aligned} NPV_{alt.1} &= PV(B_{alt.1}) - PV(C_{alt.1}) \\ &= \sum_{t=0}^{100} \frac{B_1}{(1+r)^t} - \sum_{n=0}^{n_{obs}} \frac{B_1}{(1+r)^{nx}} \\ &\quad - C_1 - C_2 - \frac{C_3}{(1+r)^{T_{tot}}} - \sum_{n=1}^{n_{obs}} \frac{C_4}{(1+r)^{nx}} \end{aligned} \tag{11}$$

Adjusted model to include depreciation rate

In the OFAT and best- and worst-case scenario analysis, a depreciation rate is added to the present value of B_1 in the calculation model. The property value associated with Alternative 0 is assumed to be reset at each new building replacement. For Alternative 1, the value decreases continuouslythrough the entire timeline, even though the building is adapted every x years. While renovation can increase the property value, changes or repairs of the structure are conservatively assumed to have a negligible effect on the property value in comparison to the effect of replacing the building entirely. Figure 3 illustrates the difference in value depreciation for Alternatives 0 and 1.

To account for value depreciation, the annual depreciation rate d is included in the present value of benefits. For the first use cycle of the BaU building, the present value at $t = 0$ is expressed as:

$$PV(B_{alt.0,x}) = \sum_{t=0}^{x} \frac{B_1(1-d)^t}{(1+r)^t} \tag{12}$$

Where d is the value depreciation rate.

The value at $t = n_{obs} \cdot x$ of the benefit from the last use cycle, which may be cut off at the 100-year mark, is expressed as:

$$V_{n_{obs}x}(B_{alt.0,100}) = \sum_{t=0}^{x-T_{res}} \frac{B_1(1-d)^t}{(1+r)^t} \tag{13}$$

As can be seen in Figure 3, $PV(B_{alt.0,x})$ can now be multiplied by the number of occurrences of structural obsolescence within the time horizon, n_{obs}. After that, $V_{nobsx}(B_{alt.0,100})$ is added separately. The value for each use section, except the first one, needs to be discounted

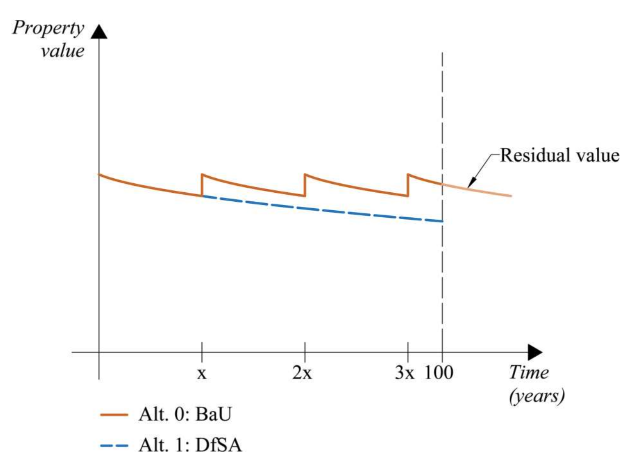

Figure 3. Schematic plot of the property value depreciation for the two alternatives, in an example where $x = 30$ years. As the value depreciates by a percentage each year, the value curves are concave.

again based on where on the timeline they occur.

$$PV_{alt.0} = \sum_{n=0}^{n_{obs}-1} \frac{PV(B_{alt.0,x})}{(1+r)^{nx}} + \frac{V_{n_{obs}x}(B_{alt.0,100})}{(1+r)^{n_{obs}x}} = \sum_{n=0}^{n_{obs}-1} \frac{\sum_{t=0}^{x} \frac{B_1(1-d)^t}{(1-r)^t}}{(1+r)^{nx}} + \sum_{t=n_{obs}x}^{100} \frac{\sum_{t=0}^{x-T_{res}} \frac{B_1(1-d)^t}{(1+r)^t}}{(1+r)^t} \quad (14)$$

To consider the lost benefit of building usage during construction, Equation (15) is applied:

$$PV(B_{alt.0}) = PV(B_{alt.0,d}) - \sum_{n=0}^{n_{obs}} \frac{B_1(1-d)^x}{(1+r)^{nx}} \quad (15)$$

Lastly, the depreciation rate is added to the residual value according to equation (16).

$$V_{T_{tot}}(R_{alt.0)} = \sum_{t=0}^{T_{res}} \frac{B_1(1-d)^{(x-T_{res})+t}}{(1+r)^t} - \frac{C_3}{(1+r)^{T_{res}}} \quad (16)$$

Based on Equations (12–16) the depreciated NPV of Alternative 0 is calculated as:

$$\begin{aligned} NPV_{alt.0} =& PV(B_{alt.0}) + PV(H_{alt.0}) - PV(C_{alt.0}) \\ =& \sum_{n=0}^{n_{obs}-1} \frac{PV(B_{alt.0,x})}{(1+r)^{nx}} + \sum_{t=n_{obs}x}^{100} \frac{PV(B_{alt.0,100})}{(1+r)^t} \\ &- \sum_{n=0}^{n_{obs}} \frac{B_1(1-d)^x}{(1+r)^{nx}} + \frac{PV(H_{alt.0)}}{(1+r)^{T_{tot}}} \\ &- \sum_{n=0}^{n_{obs}} \frac{C_1}{(1+r)^{nx}} - \sum_{n=1}^{n_{obs}} \frac{C_3}{(1+r)^{nx}} \end{aligned} \quad (17)$$

For Alternative 1, the depreciation rate is the same. Yet, as can be observed in Figure 3, the value of the DfSA building keeps decreasing throughout the timeline. Thus, the present value of the benefits for Alternative 1 is expressed as:

$$PV(B_{alt.1}) = \sum_{t=0}^{100} \frac{B_1(1-d)^t}{(1+r)^t} - \sum_{n=0}^{n_{obs}} \frac{B_1(1-d)^x}{(1+r)^{nx}} \quad (18)$$

The depreciated NPV of Alternative 1 is calculated as:

$$\begin{aligned} NPV_{alt.1} =& PV(B_{alt.1}) - PV(C_{alt.1}) \\ =& \sum_{t=0}^{100} \frac{B_1(1-d)^t}{(1+r)^t} - \sum_{n=0}^{n_{obs}} \frac{B_1(1-d)^x}{(1+r)^{nx}} \\ &- C_1 - C_2 - \frac{C_3}{(1+r)^{T_{tot}}} - \sum_{n=1}^{n_{obs}} \frac{C_4}{(1+r)^{nx}} \end{aligned} \quad (19)$$

Input data

In this section, the input variables are described, and value ranges are chosen for each one. Table 2 shows an overview of the chosen lower, baseline, and upper values. The motivation behind these values can be found in the following subsections.

Building size

The building in focus is a multi-residential CLT building, and 10,000 m^2 was deemed a suitable baseline for the heated area of such a building. The range for the variable is set from 5,000 to 15,000 m^2. This range is chosen to represent typical mid-rise apartment buildings, which remains one of the most common applications for CLT in Sweden. For all other variables in this analysis, baseline values are used. However, the baseline values for C_1 and B_1 are based on the building area, and they are therefore recalculated. $C_{2.b}$ and $C_{3.b}$ are, in turn, dependent on $C_{1.b}$, hence these variables are also affected by an area change. For instance, when the area is 5,000 m^2, $C_{1.b}$ is 5,000 m^2 · 3,418€/m^2 and $C_{2.b}$ is 14% of the resulting value of $C_{1.b}$.

Cost of new construction

In 2022, the average construction cost of a new multi-residential building was 34,596 SEK per m^2, as reported by the Swedish Construction Federation Byggföretagen (2024). This cost includes costs in the design phase, but not the land property cost. The average exchange rate for 2022 was 1 EUR = 10.6296 SEK (European Central Bank, 2024a), so the aforementioned cost can be approximated to 3,255 €/m^2. However, most of Sweden's larger multi-residential buildings are built in concrete rather than timber. While the difference in production costs between concrete and CLT buildings varies on a case-by-case basis, a majority of studies suggest that CLT alternatives add a few percent in construction costs in comparison with steel or concrete alternatives for multi-storey buildings (Ahmed & Arocho, 2021). Thus, the construction cost per m^2 from *Byggföretagen* is increased by 5% for the baseline value of C_1.

$$\begin{aligned} C_{1.b} &= 3,255\ € /\text{m}^2 \cdot 1.05 \cdot 10,000\,\text{m}^2 \\ &= 34.2\ \text{million}\ € \end{aligned} \quad (20)$$

For the lower value of C_1, the cost per square metre is decreased by 20 percentage points (from 105% to 85% of the average construction cost). The upper value of the factor is instead increased by 20 percentage points (from 105% to 125% of the average construction cost).

Table 2. Overview of chosen lower – baseline and upper values for each factor in the CBA.

Variable	Lower value			Baseline value			Upper value		
Building size (A)	A_ℓ	=	5,000 m^2	A_b	=	10,000 m^2	A_u	=	15,000 m^2
Cost of new construction (C_1)	$C_{1.\ell}$	=	$0.85 \cdot 3{,}255$ €/$m^2 \cdot$ A	$C_{1.b}$	=	$1.05 \cdot 3{,}255$€/$m^2 \cdot$ A	$C_{1.u}$	=	$1.25 \cdot 3{,}255$ €/$m^2 \cdot$ A
DfSA realization cost (C_2)	$C_{2.\ell}$	=	$0.02 \cdot C_{1.b}$	$C_{2.b}$	=	$0.14 \cdot C_{1.b}$	$C_{2.u}$	=	$0.40 \cdot C_{1.b}$
Cost of demolition (C_3)	$C_{3.\ell}$	=	$0.10 \cdot C_{1.b}$	$C_{3.b}$	=	$0.33 \cdot C_{1.b}$	$C_{3.u}$	=	$0.50 \cdot C_{1.b}$
Cost of adapting a DfSA building (C_4)	$C_{4.\ell}$	=	$0.50 \cdot C_{4.b}$	$C_{4.b}$	=	27,000€	$C_{4.u}$	=	$00 \cdot C_{4.b}$
Discount rate (r)	r_ℓ	=	2.0%	r_b	=	3.5%	r_u	=	5.0%
Benefit of building use per year (B_1)	$B_{1.\ell}$	=	$0.50 \cdot B_{1.b}$	$B_{1.b}$	=	$A \cdot 180$€/m^2	$B_{1.u}$	=	$2 \cdot B_{1.b}$
Value depreciation rate (d)			–	d_b	=	0.0%	d_u	=	2.0%

DfSA realization cost

As DfSA has not been implemented for timber structures, it is difficult to assess the additional cost of applying it to a project. The most relevant study to refer to in this assessment is one from (Brigante et al., 2023), investigating the costs of implementing DfA strategies in multi-residential timber buildings. The DfA strategies from the study should, however, be labelled as non-structural adaptability measures. The three investigated strategies were (a) increased floor live load, (b) increased floor heights, and (c) the use of post-and-beam framing rather than structural walls. Though all three strategies are implemented on the building's load-bearing structure, they all aim to facilitate non-structural changes. Nevertheless, strategies (a) and (b) could also facilitate functional changes that require structural adaptations. Strategy (c) is not relevant for DfSA as the purpose is to avoid structural obstructions, and the motivation behind DfSA is that post-and-beam systems with longer spans are not always suitable or resource-efficient. Still, implementing DfSA would add costs that are not included in Brigante et al.'s study. For instance, an implementation of DfSA would affect the digital workflows for designers and engineers and increase the importance of appropriate methods for traceability (Öberg et al., 2024). Changes to the practical workflow of the building process may increase its related costs. To avoid underestimating such costs, the cost increase found from implementing all three DfA categories – 14% (Brigante et al., 2023) – is used in this example. Thus, the baseline for the cost C_2 is expressed as:

$$C_{2.b} = C_1 \cdot 0.14 = 4.5\,\text{million €} \tag{21}$$

The lower and upper values of C_2 are set to 2% and 40% of the construction cost respectively. While 2% of the construction cost may still be considered a significantly large cost, it is a deliberately conservative choice of the lower range limit. For the upper value, instead of merely increasing the factor by the same percentage points (i.e. from 14% to 26% of C_1), it is increased to the highly conservative 40% of C_1. This wide range is chosen due to the high uncertainty related to this variable.

Cost of demolition

The cost of demolition of a multistorey building largely depends on the building's design and structural material. Heavier structures tend to increase demolition costs (La Fleur et al., 2019). For three mid-1900s buildings with brick and lightweight concrete structures, La Fleur et al. (2019) found the cost of demolition to be approximately 33% of the construction cost of an equivalent new building. This study's hypothetical timber structure would likely be lighter than a corresponding brick or lightweight concrete structure, which suggests that a lower demolition cost may be chosen. Yet, the 1900s buildings from La Fleur et al.'s study presumably feature fewer and smaller windows than a modern multi-residential timber building. More windows tend to increase the demolition cost (La Fleur et al., 2019). The values found in La Fleur et al.'s study are hence seen as an adequate approximation to be used in the demonstration of this study's CBA model. The baseline for the cost C_3 is calculated as:

$$C_{3.b} = C_1 \cdot 0.33 = 10.6\,\text{million €} \tag{22}$$

This factor is decreased by 20 percentage points for $C_{3.\ell}$ and increased by 20 percentage points for $C_{3.u}$. The lower and upper range limits are subsequently rounded to the nearest multiple of ten. Thus, this factor ranges from 10% to 50% of the construction cost, resulting in a wide plausible range of demolition costs.

Cost of adaptation of a DfSA building

As DfSA has not been implemented for timber buildings, the cost of adapting a DfSA building is unknown. Because of this, the example cost for the CBA application can only be based on the cost of structural adaptations of BaU CLT buildings. However, doing this introduces some issues. First, this model is focused on adaptations in DfSA buildings that would not be possible or economically feasible in BaU buildings. If an adaptation of a DfSA building is extensive or complex enough to not be possible in a BaU building, it may be more expensive than any BaU adaptation examples. On the other hand, an adaptation that is made possible by DfSA due to an increased economic feasibility would be less expensive than an equivalent BaU adaptation. It is clear that this factor should include a wide range of values to account for this uncertainty.

Another issue is that there is a dearth of published cost assessments of BaU adaptations of CLT buildings. This can be explained by several factors. First, unplanned structural adaptations are often prompted by some unforeseen damage or deterioration (Lind & Muyingo, 2012; Steiger, 2008). For marketing purposes, the contractors and designers of the building are unlikely to offer researchers access to their damaged or deteriorated projects. Second, the specific costs of building projects are often considered classified information, and thus it is unlikely to be published. While some published information can be found on the cost of construction, it is significantly rare. The number of structural adaptation projects is very low compared to the number of new constructions, so there are naturally even fewer published studies on the cost of structural adaptations. Lastly, CLT is a relatively new structural material still gaining traction in advancing timber industries worldwide. CLT wasn't used commercially for multistorey constructions until the early 2000s. Naturally, very few CLT buildings constructed since then have had the time to age enough to develop serious structural deterioration. A similar argument can be made concerning structural damage due to unforeseen events. The small pool of existing CLT buildings and the short span in which they have existed greatly reduces the probability of finding real-world examples of such damages.

Without the ability to refer to published costs of structural adaptations of real-world multistorey CLT buildings, laboratory-based studies need to be utilized. In a report published by Research Institutes of Sweden (RISE), Brandon et al. (2021b) describe their fire tests of five real-scale CLT and glulam compartments. In a subsequent report (Brandon et al., 2021a), the repair work of one of the test floors is documented. To repair the floor, the char layer of the CLT panel was removed and replaced by glued-on lamella (Brandon et al., 2021a). Seagate Mass Timber later used the description of the repairs to assess the repair cost, including labour and material costs, to 14,205 USD (McLain, 2023). Using the average USD to EUR exchange rate of 2022 (European Central Bank, 2024b), this cost is approximately 13,490 €.

Naturally, the cost of a structural adaptation would greatly vary depending on the extent of the interventions. In the example above, only one floor was repaired in a test compartment. In a real building, structural damage may spread to adjacent floors and walls. The type of structural obsolescence that DfSA aims to solve is also of the kind that cannot be fixed by the repairs done in the RISE experiment. Aside from a larger cost for new materials, one would also need to add costs for engineering consultants. To account for this increased cost, the 13,490 € is doubled for the baseline value of C_4. This value is found in Equation (23).

$$C_{4.b} = 13,490 \text{ €} \cdot 2 = 0.027 \text{ million €} \quad (23)$$

As the baseline value of C_4 cannot be based on real adaptations of DfSA buildings, $C_{4.b}$ should not be interpreted as the estimated cost for any structural adaptation work in CLT buildings. Instead, it should be viewed as an example of what such interventions could cost. To account for the significant uncertainty in predicting adaptation costs, a vast range was chosen for this variable. The 13,490 € from the RISE study was used as a conservative choice for the lower value. For the upper value, the baseline value in Equation (23) was multiplied by 100. Since 0.027 million € makes up a very small part of the total costs of the project, such a dramatic increase was considered necessary to spot any changes in the results.

Discount rate

Choosing an appropriate discount rate is important, as it can have a significant impact on the results of the CBA. Recommendations regarding this choice are often provided by government agencies. In Sweden, the real discount rate recommended by the transport administration *Trafikverket* is 3.5% (Trafikverket, 2024). It is often used for non-transport-related projects as well. The rate is roughly equivalent to the rest of Europe, where the recommended discount rates tend to vary between 2 and 4% (Groom et al., 2022). The EU recommends a declining discount rate for long-term projects (>50 years), but there is significant disagreement over how such a decline should be applied policy-wise (Groom et al., 2022). To be conservative, a constant discount rate is used in this study.

It should be noted that the discount rates described above are typically used for public sector investments. Private companies may use a higher rate due to increased demands for swift returns on investments. Still, this study takes a long-term macro-level perspective instead of focusing on the investment of one actor. Thus, the recommended 3.5% is used as the baseline value. The lower value for this factor is set to 2%, in accordance with the abovementioned lower limit of common discount rates in Europe. This is a decrease of 1.5 percentage points. Consequently, the upper value of the discount rate is increased by an equal amount to 5%.

Benefit of building use per year

The benefits of using the building for one year can be expressed in different ways. From an owner-centric perspective, the benefits may simply be expressed as the income from renting or selling the apartment units. From a social benefit perspective, the benefits may instead be expressed as the well-being granted by providing humans with homes. In the context of CBA, human well-being is often expressed in monetary terms by assessing the willingness to pay (WTP) for the benefit (Johansson & Kriström, 2018). In this simplified example, the WTP for this benefit is seen as equal to the rent or apartment price – as it is, in fact, the price that the residents are willing to pay to live in their apartment.

In 2022, the average rent was 2,070 SEK per m^2 and year for newly constructed dwellings in Swedish metropolitan areas (Statistics Sweden, 2023). With the average exchange rate in 2023 (European Central Bank, 2024a), this is 180 €/m^2 and year. Thus, the baseline for the benefit B_1 for one year of building use is found in Equation (24).

$$B_{1.b} = \frac{180\,€}{m^2} \cdot 10,000\,m^2 = 1.80\,\text{million}\;\;€ \qquad (24)$$

$B_{1.b}$ is halved for the lower value and doubled for the upper value of B_1. This results in a wide range which should include most rent schemes.

Value depreciation rate

Though property values can vary based on different factors – e.g. building maintenance, location desirability, and market trends – a general assumption can be made that the value of a property depreciates with age. While old dwellings can have a so-called 'vintage effect' – an increased property value of buildings built within a specific period and in a particular architectural style (Rolheiser et al., 2020) – such an effect is difficult to predict.

Instead, a maximum probable value depreciation rate is chosen for this study, and the effect of incrementally increasing the factor towards this value is investigated. U.S. studies suggest that such a value can be approximated to 1.5% (Bokhari & Geltner, 2018; Lopez & Yoshida, 2022). There is a lack of similar studies in a Swedish context. To counteract this uncertainty, the value depreciation rate is set to range from 0% to 2%.

Results and discussion

Baseline analysis

For the scenario where all variables were set to their baseline values, the break-even point for x was 60 years. This indicates that if structural obsolescence were to occur more often than every 60 years, Alternative 1 would be the more economically feasible choice. As can be seen in Figure 4, Alternative 0 shows a significant decline as structural obsolescence occurs with increasing frequency. In contrast, Alternative 1 maintains a more subtle and stable decline until x becomes very small. This is undoubtedly due to the significant difference in cost between replacing the building and adapting it.

Sensitivity analysis

The results of the sensitivity analysis are shown in Figures 5 and 6. Figure 5(c, d), and Figure 6(e) show

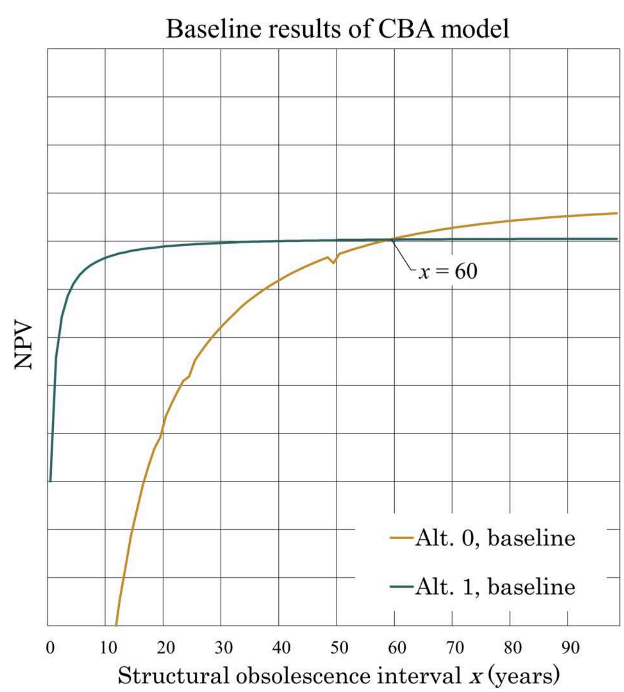

Figure 4. Results of the CBA calculation for baseline values.

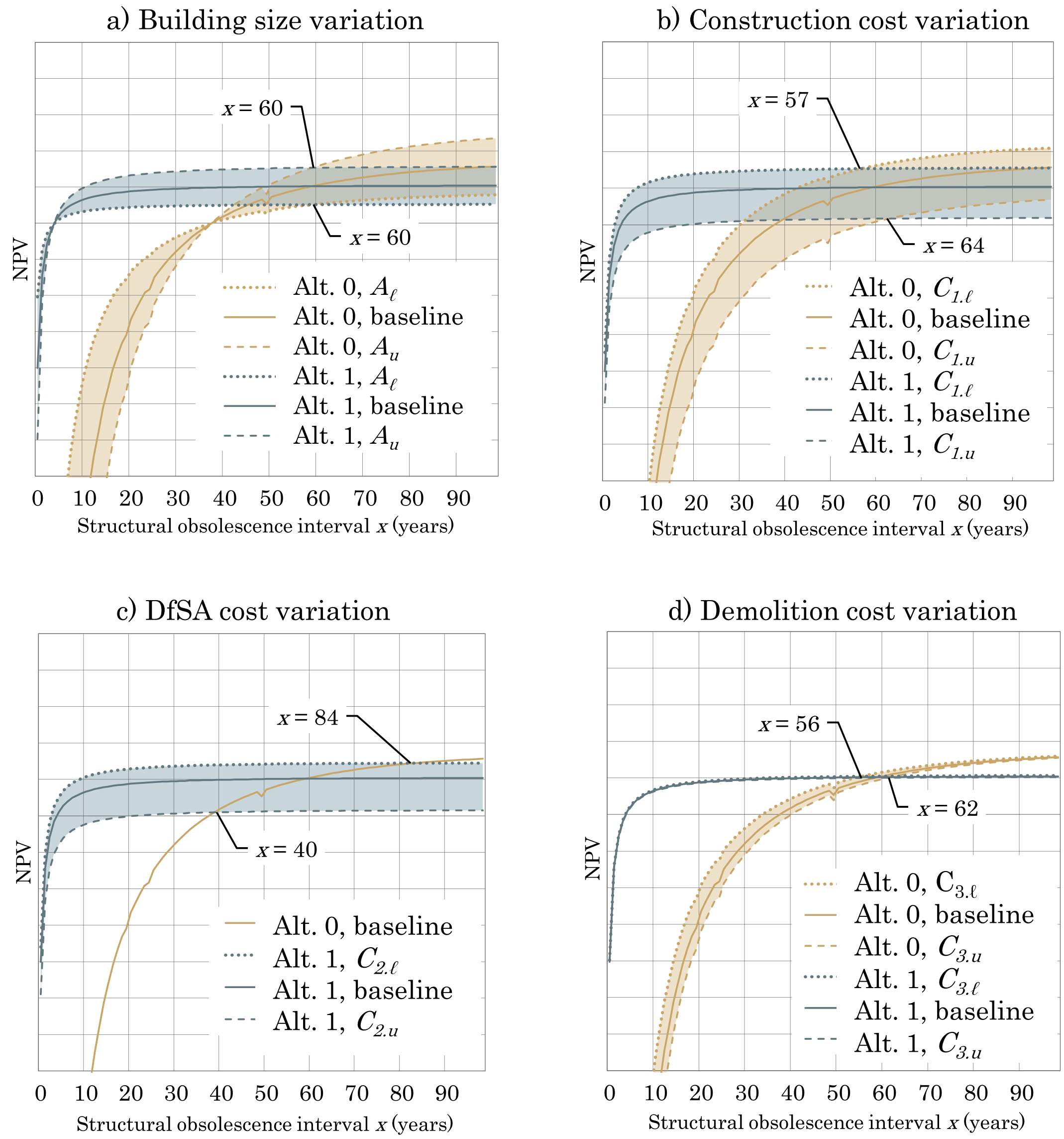

Figure 5. Results of the OFAT analysis for (a) building size, (b) construction cost, (c) DfSA realization cost, and (d) demolition cost.

the variables that mainly affect one alternative when varied. The reason is self-evident for the DfSA realization cost and the adaptation cost, as these costs are only represented in Alternative 1. For the analysis of the demolition cost, a minor change could in fact be observed in Alternative 1. Still, the demolition cost only occurs once in Alternative 1, after 100 years. Because of this, it is discounted to the degree that the difference is too small to be visible in the graph.

Figure 5(a, b), and Figure 6(g) show that while the building size, construction cost, and use benefit affect both alternatives, the factors have a minor effect on the break-even point for *x*. The discount rate, on the other hand, also affects both alternatives but has a significant effect on the break-even point. This is shown in Figure 6(f). If a low discount rate is assumed, benefits in the future are only slightly less valuable than current benefits. This increases the likelihood of a swift return on investment. A high discount rate, on the other hand, increases the economic risk of investing in DfSA as more future adaptations are needed to justify the initial investment.

As can be observed in Figure 6(f), a higher discount rate is in fact beneficial for Alternative 0 for the lower values of *x*. In general, a low discount rate can be seen as preferable as the return on investment can be expected sooner. Yet, a low discount rate also means that costs occurring in the near future are weighed

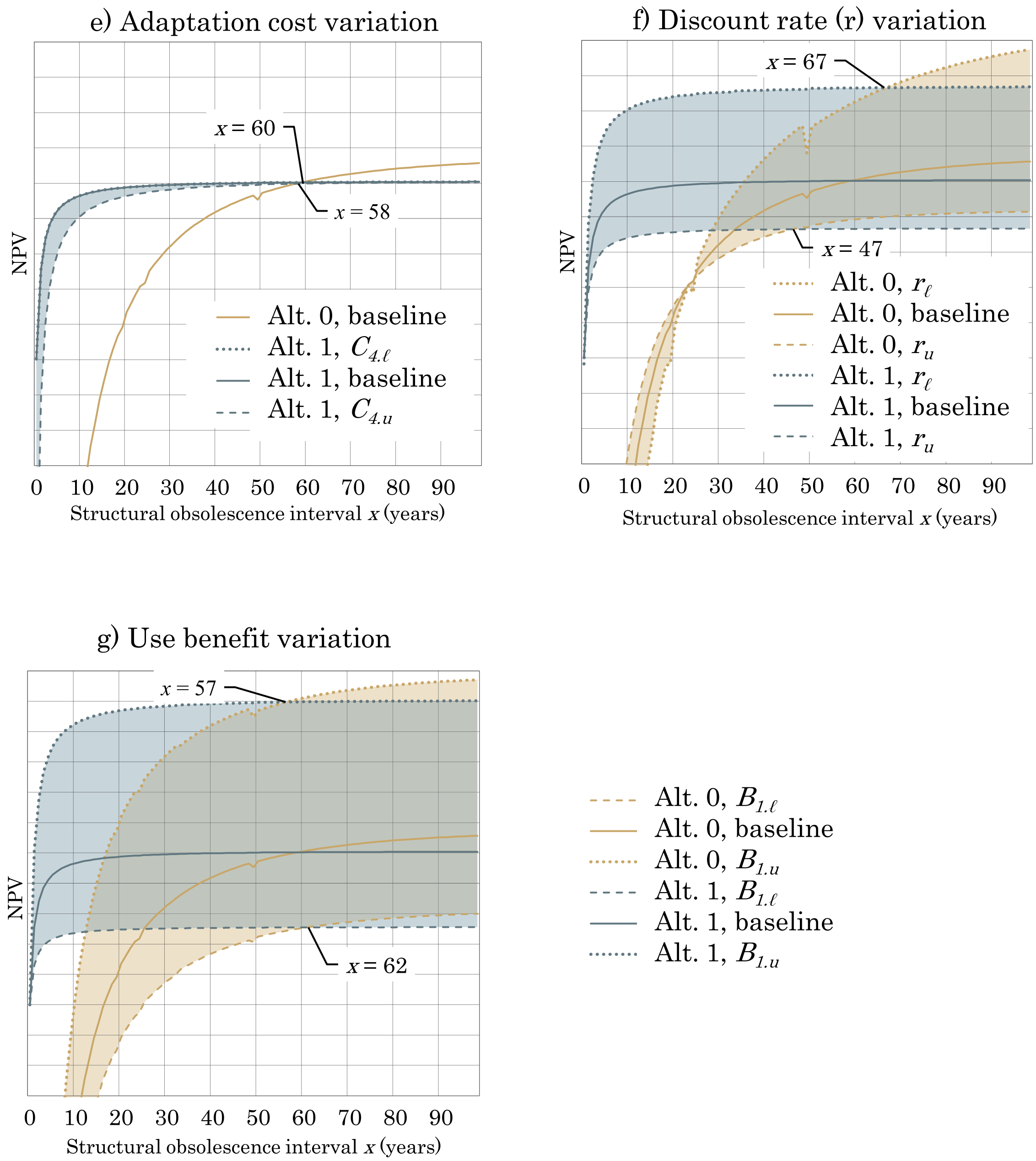

Figure 6. Results of the OFAT analysis for (e) adaptation cost, (f) discount rate, and (g) use benefit.

almost the same as current costs. For low values of x, the first costs after the initial construction occur relatively close to $t = 0$. In these cases, the benefits of a low discount rate are outweighed by the drawback of not discounting the costs to the same degree as for a higher discount rate. This effect could also be identified in Alternative 1, but only for $x = 1$ year. This can be explained by the difference in reoccurring costs for Alternatives 0 and 1. The former includes costs for demolition and construction every x years, whereas the reoccurring adaptation cost of the latter is significantly smaller. Hence, the benefits of a low discount rate far outweigh the drawbacks of Alternative 1 for all $x > 1$.

The discount rate is a recommended interest to determine the present value of future costs and benefits. Investors may have a higher demand for swift returns on investment, warranting the use of a higher discount rate. Yet, efforts to promote DfSA cannot change the used discount rate or building owners' need for rapid financial returns. Reducing the size of the investment, on the other hand, may enable the profitability of DfSA even for higher discount rates. The results of the OFAT analysis

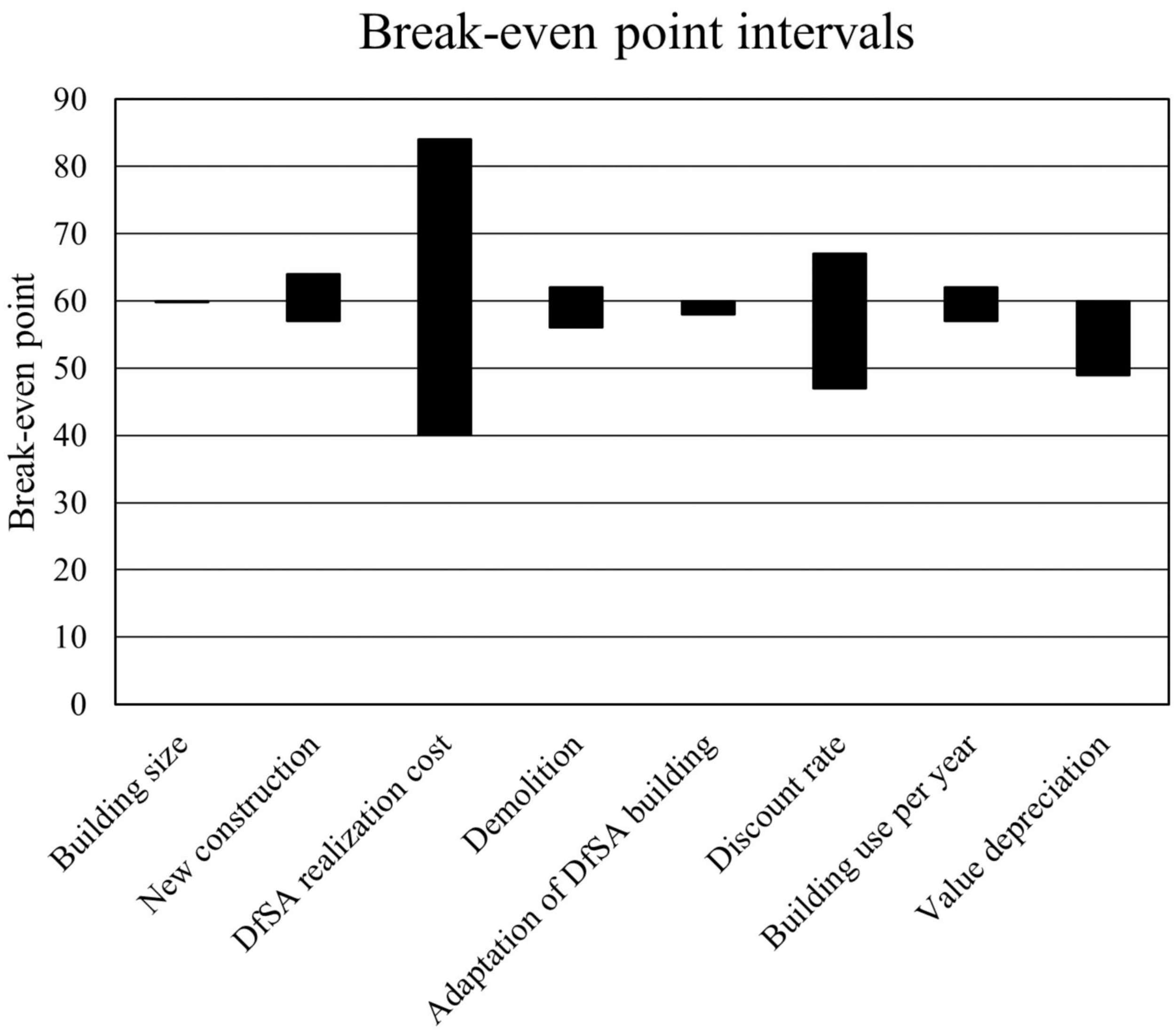

Figure 7. Compiled results of the OFAT analysis, showing the break-even point interval for each factor.

confirm this, as the realization cost is shown to be the most crucial factor in determining the economic feasibility of DfSA. This cost also only appears once in the timeline of Alternative 1, but at $t = 0$. Hence, it is not discounted like the demolition cost. The uncertainty of this variable also affects the results, as it ranges from 2% to 40% of the construction cost. Nonetheless, as Alternative 0 has no range in this scenario, a smaller variation of the DfSA realization cost would still have a significant impact on the break-even points for x.

The effect of each factor's variation on the break-even point for x is compiled in Figure 7. Again, it is clear that the DfSA realization cost is key in determining the economic feasibility of DfSA. The figure also shows the break-even point range for an increasing value depreciation rate. The result of the OFAT analysis for the value depreciation rate is also represented in the baseline graph of Figure 8(b).

Best- and worst-case scenario

The best- and worst-case scenarios, illustrated in Figure 8, demonstrate the substantial differences between a scenario that favours DfSA and one that favours the BaU. In the least favourable scenario for DfSA, structural obsolescence would need to occur every 14 years to economically justify its implementation. In contrast, the favourable scenario results in a break-even point at $x = 99$ years when the depreciation rate is 0%. It should be noted that the stagnation at 99 years is due to the calculation model's time horizon, which is 100 years. A break-even point of 100 years would entail that no adaptations are carried out within the timeline,

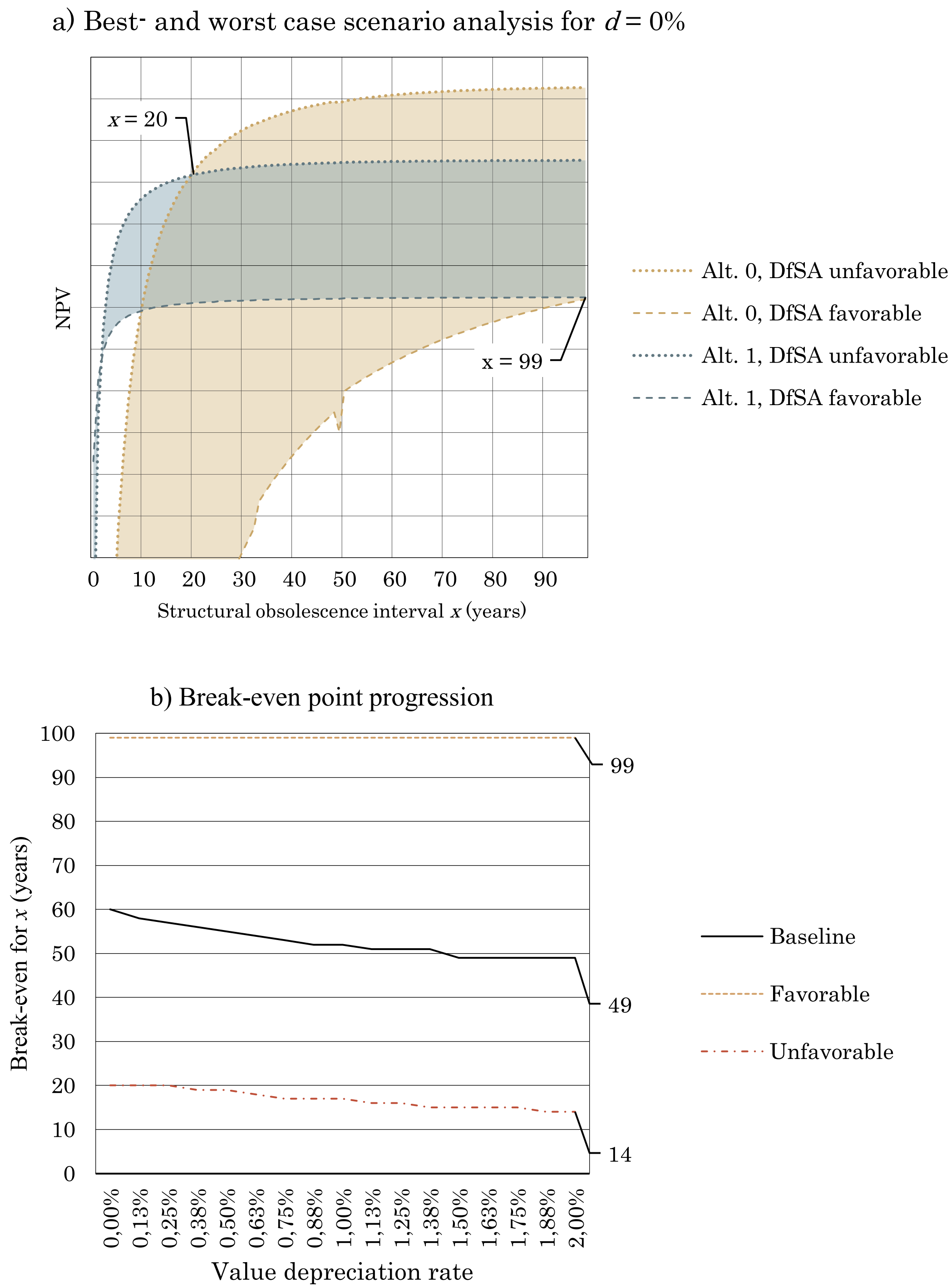

Figure 8. Results from the best- and worst-case scenario analysis, showing the least and most favourable scenarios for Alternative 1 for (a) $d = 0\%$ and (b) $0\% \leq d \leq 2\%$.

thus making it impossible for DfSA to be the more profitable option.

Conclusion

The results of this study show that the DfSA realization cost has the most significant effect on the break-even point, followed by the discount rate. The other variables investigated in the sensitivity study had a trivial effect on the break-even point.

The realization cost of DfSA included a relatively large range in the sensitivity study, although not the largest one. The range was chosen to consider the uncertainty of costs related to the implementation of DfSA. As the concept is developed, these costs can be more clearly defined. For instance, the cost of implementing digital solutions for traceability or adaptable connections can be assessed in order to estimate the total realization cost of DfSA. This cost can consequently be compared to the results of this study to assess the economic feasibility of the chosen DfSA strategy.

The discount rate, having the second most significant effect on the results, cannot be influenced by the development of the concept. It is nonetheless an important factor to consider, as it can be connected to the stakeholders' expected return on investment. The discount rate is typically recommended by regional or national governments, which suggests that an application of this study's CBA model to another country may result in a significantly changed break-even point. The 3.5% used as a baseline value in this study can be considered relatively low in an international context. Conversely, some countries recommend a lower discount rate for long-term investment, which would favour the DfSA alternative of this CBA model.

The best- and worst-case scenario analysis showed that there is a wide range of possible break-even points between the least and most favourable scenarios for DfSA. In the worst-case scenario, structural obsolescence would need to occur every 14 years to economically justify the implementation of DfSA. On the other end of the spectrum, a 99-year occurrence rate would be enough to justify DfSA if all parameters were favourable. Given that this is the highest possible value for x within the timeline of 100 years, an expansion of the time horizon may have shown an even higher break-even point. Still, as these two points are the result of extreme values for all variables, a realistic break-even point for a given project would likely be somewhere in between.

This study concludes that to overcome the economic challenges, the development of technical solutions for DfSA for timber needs to be particularly focused on finding low-cost approaches. This could, for instance, entail demountable connection systems that do not require special tools or added time for assembly. Another example is non-proprietary solutions for traceability – e.g. software for material passports or digital twins. The realization cost of DfSA has the greatest impact on the economic feasibility of implementing it. Hence, if the technical challenges of DfSA for timber are resolved with costly solutions, it could prevent DfSA from being implemented at all. When investigating adaptable connection solutions, for instance, cost should be a prioritized factor alongside structural capacity and demountability. It should also be noted that the cost of producing, designing and installing the connection is significantly more crucial than the cost of eventually demounting and replacing it.

This research has potential implications in several parts of the construction industry and research field. It provides a clear motivation for the development of DfSA for timber and indicates how costly the solutions for implementing it may be before its economic feasibility is diminished. It can further act as a motivator for governmental incentives for DfSA for timber. While private companies often have strict demands for rapid return-on-investment, indications of long-term economic feasibility may promote financial subsidies and incentives. Lastly, the CBA model developed in this study can be applied by researchers to other contexts. By adjusting the values of the included factors, the model could be used to analyze buildings in other structural materials, with other functions, or in other countries or regions.

This study contributes to the field by addressing a previously identified challenge of implementing a circular economy concept in the timber industry. By identifying key aspects to facilitate implementation of DfSA for timber, it advances the development towards resource-efficient timber construction.

CRediT authorship contribution statement

Vera Öberg: Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Robert Jockwer:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Yutaka Goto:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Mohammad al-Emrani:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Conceptualization.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the Swedish Research Council for Sustainable Development, FORMAS, under grant number 2021-02499.

Data availability statement

Data will be made available on request.

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