# Multi-dimensional Analysis of Building Sustainability: Comparison of Reconstruction Scenarios in Singapore

## Višedimenzionalna analiza održivosti zgrada: uporedba scenarija rekonstrukcije u Singapuru


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**Abstract** Building sustainability is associated with multiple goals for sustainable global development and tackling climate change as defined by the United Nations. Sustainability goals have different interpretations across different domains; the construction industry alone incorporates multiple professional domains involved in building projects. However, assessment of sustainability without alignment of interests, regional context and a unique strategy may lead to conflicting and suboptimal building design solutions. In this paper, multiple dimensions of sustainability assessment that affect building design and construction are investigated; first, terminology and concepts are critically analysed through wider research of scientific and grey literature defining the sustainability of buildings; second, a literature review methodology is used to identify and compare multi-dimensional analyses and existing frameworks; and finally, a multiple-criteria decision analysis of a building reconstruction in the context of Singapore is performed. The results show that sustainability of buildings is not a one-way street and that a sustainability strategy must prioritise not just dimensions but also categories, criteria and indicators for each dimension of sustainability, as well as define the multiple-criteria decision analysis for the specific context. While sustainability indicators are comparable, overall sustainability performance is not and requires a case-by-case approach. The case study on reconstruction scenarios in Singapore demonstrates four scenarios incorporating ten indicators of the three most common sustainability dimensions: social, economic, and environmental. Measuring these indicators allow for a comparison and decision-making with respect to multiple criteria. This research tackles the complexity of multiple dimensions of sustainability with this case study, informing and discussing current approaches for future analyses.



**Keywords** sustainable building; Multi-Criteria Decision Analysis (MCDA); Life-Cycle Assessment (LCA); sustainability pillar.



**Sažetak** Održiva gradnja je povezana sa više ciljeva održivog globalnog razvoja i suočavanja sa klimatskim promjenama koje su definisale Ujedinjene Nacije. Ciljeve održivosti različito tumače različite struke; sama građevinska industrija obuhvata različite stručne oblasti uključene u građevinske projekte. Međutim, procjena održivosti bez usklađivanja različitih interesa, regionalnog konteksta i jedinstvene strategije može dovesti do sukobljenih i suboptimalnih projektnih rješenja. U ovom naučnom radu ispituju se višestrukost dimenzija procjene održivosti koje utiču na projektovanje i gradnju; prvo, terminologija i koncepti su kritički analizirani kroz istraživanje šire naučne i sive literature koja definiše održivost zgrada; drugo, metodologijom pregleda literature identifikovane su i poređene višedimenzionalne analize i postojeći modeli procjena održivosti; zaključno je urađena analiza višekriterijskih odluka za rekonstrukciju zgrade u kontekstu Singapura. Rezultati pokazuju da održivost zgrada nije jednosmjeran proces i da strategija održivosti mora dati prednost ne samo određenoj dimenziji, nego i kategoriji, kriterijima i indikatorima za svaku dimenziju održivosti, kao i da definiše analizu višekriterijskog odlučivanja u odnosu na specifičan kontekst. Iako su indikatori održivosti međusobno uporedivi, sveukupna održivost projektnog rješenja nije univerzalno uporediva i zahtijeva individualnu procjenu. Studija slučaja o scenarijima rekonstrukcije u Singapuru prikazuje četiri scenarija koji uključuju deset indikatora i pripadaju trima najčešće razmatranim dimenzijama održivosti: socijalnoj, ekonomskoj i ekološkoj. Mjerenje ovih indikatora omogućava uporedbu i višekriterijsko odlučivanje. Ovo istraživanje se bavi složenošću višestrukih dimenzija održivosti kroz studiju slučaja, te izvještava o postojećim procjenama i analizira ih radi budućih primjena.



**Ključne riječi** održiva gradnja; analiza višekriterijskih odluka (MCDA); procjena životnog ciklusa (LCA); stub održivosti.

## 1 Introduction

Sustainability of the ever-growing built environment is one of the critical topics of global development and climate change goals, as defined by the United Nations (UN). The UN defines 17 Sustainable Development Goals (SDGs); SDG 11, Sustainable Cities and Communities, is the most relevant one for the construction industry. However, the goals are not operating as isolated systems, and the construction industry is closely related to eight additional goals (Scherz et al., 2020). Sustainability goals are interrelated in a complex system, where different building design practices have different effects on sustainability performance. For instance, Scherz et al. (2020) investigate the synergies of design strategies on decarbonisation of the built environment. While certain design practices contribute positively to some sustainability aspects, they may at the same time have a negative impact on others. These complex interdependencies create difficulties in reaching and measuring the sustainability strivings of the construction industry.

In addition to the complexity of the system of sustainability goals, it is not straightforward which goals are relevant to the construction industry and building design. In fact, the basic concepts of sustainable buildings show terminological ambiguity and misalignments regarding their structure (Moir & Carter, 2013). We will position within this work terms like "sustainable building", "green building" and "circular building", with an aim to distinguish and structure the terminology, leading to a clearer definition of sustainability dimensions and analyses. While the main motivation to analyse the sustainability of buildings is to achieve better building performance and reduce negative impact, lack of clarity could lead to a loss of focus and not fully addressing the performance improvement.

There is no single methodology to calculate the sustainability of buildings; multiple measurement methods to analyse sustainable building designs exist, sometimes in the form of a generally applicable method and sometimes reflecting regional planning, a lifecycle phase or professional domain (Braulio-Gonzalo et al., 2022). The certification systems include diverse indicators, which are not aligned and therefore deliver different calculation results that are not comparable. Buildings are often certified with one of the internationally available certification systems, such as BREEAM, LEED or DGNB. These tools focus on different social, environmental or economic dimensions, changing over time (Andrade & Braganca, 2016). The applied sustainability analysis may not necessarily consider a desired sustainability criteria and hence not be as effective in the context where applied. The selection of criteria and the calculation of indicators need to reflect the context, bearing in mind desired outcomes.

Following the investigation of sustainability dimensions and analyses, we continue with the case study of a residential building in Singapore, where demolish and rebuild is a standard procedure in the construction industry. The objective is to clarify and understand which environmental, economic and social factors impact decisions to retain, renovate or rebuild. While renovation is better in terms of embodied carbon, there are many other aspects that impact decision making, including the ability to reduce operational energy use, impact on the inhabitants, economic factors, etc. The current certification used in Singapore is called "Green Mark" (Building and Construction Authority, 2025). It is developed by the government and focuses on environmental sustainability dimension, especially considering embodied and operational emissions. We investigate ten criteria across three generally accepted dimensions of sustainability. This case study serves as an exemplary sustainability analysis for the specific context of renovation of public housing in Singapore. It demonstrates a strategic selection of indicators that could be considered in a similar way for future calculations; however, the entirety of indicators could differ for a different context.

This work argues the heterogeneity of sustainability measurement methods, aligns and categorises the underlying conceptual structures, and identifies gaps in the literature. The main result reveals a lack of strategic or regional systems for sustainability assessment that reflect the local context. Existing concepts are often stretched throughout multiple dimensions, but the justification of selected indicators is not derived from local planning goals. The future recommendations suggest more emphasis on the filtering processes from the entirety of sustainability rather than generic one-size-fits-all solutions. In other words, the analysis criteria should be based on the context: place and time for choosing the best design. In the case study of a reconstruction project in Singapore, a multi-dimensional approach addresses four possible scenarios. This case study represents a novel approach to decision making for multiple involved parties, with varying interests and perceptions of sustainability. The final sustainability analysis is not a one-way street, but a compromise of all involved parties with varying priorities, who need to be aware of the effects of various criteria before reaching a final decision.

The subsequent section presents the methodology of this research, including the three parts of the research: clarification of terminological ambiguity, analysis of research works investigating sustainability dimensions, and the case study performing a sustainability analysis of the reconstruction of a residential building in Singapore. The results presented in the third section follow the same structure as the methodology section, presenting the results for each methodological step individually. The discussion in the fourth section reflects on the findings, especially on the need to move away from standard generic sustainability certification and focus on the local context. The conclusion in the fifth section recaps the study and describes its limitations and next steps.

## 2 Methodology

The research design includes three methodological steps which serve the main objective — clarifying the multi-dimensional sustainability assessment (Figure 1).

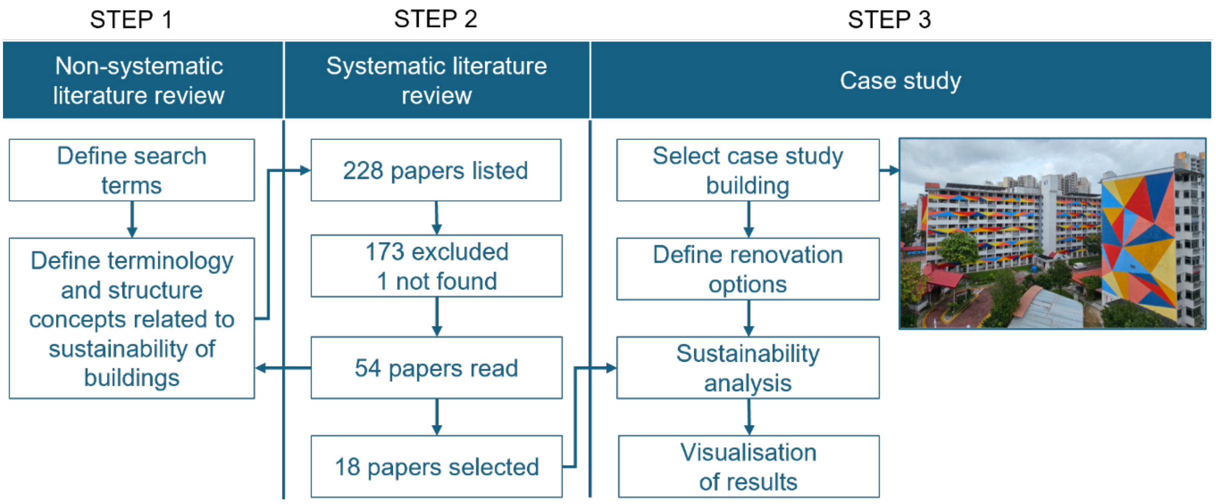


**Figure 1** Research design consists of three steps, including non-systematic and systematic literature review and a case study.
Source: Authors, 2025.

### 2.1 Clarification of Terminological Ambiguity

The terminology is explored by non-systematically investigating the literature; by searching through databases such as Google Scholar and Scopus and sorting the results by relevance. It was performed with the keywords "sustainable building" and "sustainable construction", further expanded with additional related keywords. This search delivered a list of topics and terminology for a subsequent systematic literature review, and provided a base terminology, which was further extended and improved following the systematic literature review. The databases were visited and searched on multiple occasions, last in September 2025.

### 2.2 Systematic Literature Review on Multi-Dimensional Sustainability Analysis

The systematic literature review included the following search ("sustainability direction" OR "sustainability pillar" OR "sustainability dimension") and ("building" OR "construction"). The objective was not to conduct exhaustive research on the dimensions of sustainability, but rather to investigate the existing approaches, compare them and identify the research gaps and directions.

The main exclusion criterion for the research papers was if they did not deal with buildings' sustainability. The first screening eliminated sustainability analysis for other industries, such as agriculture, urban planning, or manufacturing, as well as the sustainability of construction materials, supply chains and organisational sustainability. Research dealing with the sustainability of infrastructure was also excluded, but all types of buildings were included. Energy related sustainability was considered if it was directly related to buildings. The first screening eliminated 173 papers out of 228 by title or abstract. Review papers were considered for step one and for discussion, but they were excluded from the overview as they did not elaborate on any particular sustainability analysis. Step two resulted in 18 papers, which were analysed in detail and their characteristics are presented below.

### 2.3 Case Study on Multi-Dimensional Sustainability Analysis

The case study component of this paper was conducted as a master's thesis by one of the authors (Dai, 2025), supervised and consulted by the remaining authors. Some results have been presented as a poster presentation and not published so far. The analysis is based on an investigation of sustainability concepts and consultations with researchers from multiple research projects, concluding that multiple sustainability dimensions need to be considered and indicators must be specific for Singapore. The work proceeded with four viable scenarios that could be considered for renovation, and the calculations of the selected indicators. The sustainability assessment included a multiple-criteria decision analysis (MCDA) of the chosen sustainability indicators, the results of which can be compared and used as decision-making support.

The case study involved a building in Singapore developed by the Housing & Development Board (HDB), the largest real estate company in Singapore and publicly owned. A particular feature of HDB buildings is that they are developed with a 99-year lease; therefore, they have a limited planned use. Once the lease expires, the buildings are returned to HDB, which can then reconsider their future. The oldest HDB estates in Singapore are around 60 years old. The case study building was constructed in 1964.

Currently, the majority of existing buildings are expected to be demolished; however, HDB is considering more sustainable options for future redevelopment. Various programs are being considered in Singapore, such as the Home Improvement Programme (HIP), which includes both mandatory and optional improvements. The government is also planning to launch the Voluntary Early Redevelopment Scheme (VERS) in the early 2030s for buildings that reach 70 years of age (Housing & Development Board, 2025). This scheme would involve a voluntary buyout of the flats by the government for redevelopment, provided that the majority of residents agree.

Based on this context, we address the sustainability aspects of different lifecycle scenarios that could be applied to the HDB building once it reaches 70 years of age (Figure 2):

Scenario A is the reference case and serves as a baseline for comparison with the other scenarios. The building could theoretically remain in use for another 29 years until the 99-year lease expires, assuming no major structural deficiencies are found during mandatory inspections. However, the value of the units is expected to decline rapidly after 70 years. In this scenario, no significant renovation works are performed. Therefore, a 1% demolition rate is assumed for losses during construction works. The building's total lifespan is assumed to be 70 years due to the degradation of the concrete structure in Singapore's climatic condition. Window-type AC units are observed during the site visit, which represent the major HVAC system of 1960s HDB flats. This scenario has minimal impact on residents because most of the maintenance will be conducted in the public area, except that residents' units will eventually become unusable and lose their value at the end of life.

Scenario B involves mandatory refurbishment works after 70 years. It is estimated that with proper renovation works offered by HDB — such as upgrading elevators, lighting, structural reinforcement, repainting, and improvements to the facade to reduce operational carbon emissions — the building's lifespan can be extended by 50 years. To reduce operational carbon emissions, a high energy efficient HVAC system is implemented. This Variable Refrigerant Flow (VRF) system is like a smart refrigerant faucet providing exactly the right amount of cooling. Interior works within the units are limited and minimized to reduce disruption to residents, while facade improvements are designed to fit the existing unit layout. This scenario aims to minimize the residents' impact and maximize the building lifespan and life quality.

Scenario C involves mandatory and optional refurbishment, including upgrades to installations within apartment units and more extensive interior renovations. The renovated building is expected to last an additional 60 years. The HVAC system is upgraded to a Dedicated Outdoor Air System (DOAS) with VRF, enhancing residents' thermal comfort. The DOAS installation causes a temporary disturbance to the residents because of necessary construction works within the units, but provides them with long-term benefits like improving air quality and thermal comfort. In addition, unit layouts will be redesigned to align with the newest HDB layout design and multi-functional spaces will be provided for residents. In this scenario, construction works require residents' temporary relocation and result in higher embodied carbon emissions but will significantly increase building quality and reduce operational carbon emissions.

Scenario D involves the complete demolition of the existing building and the construction of a new one. The new building is estimated to have an 80-year lifespan due to improved construction materials and maintenance processes. It assumes a prefabricated reinforced concrete structure for the new structure and examines the potential use of recycled materials. This scenario also targets reduced embodied carbon values as a result of the use of recycled materials in the new construction, assuming that the resources recovered from the existing building can serve up to the allowed percentages of the new construction materials, considering that the new building has more than double the gross floor area (GFA) of the old building. The HVAC system includes a DOAS with district cooling system integrated with VRF. In this scenario, the HVAC system installed will be the same as in the previous scenario so as to compare the same HVAC system decarbonization potential within different building settings. The large-scale demolition required in this scenario, which causes significant disruption to the residents and generates substantial embodied carbon emissions, fundamentally distinguishes it from the other scenarios.

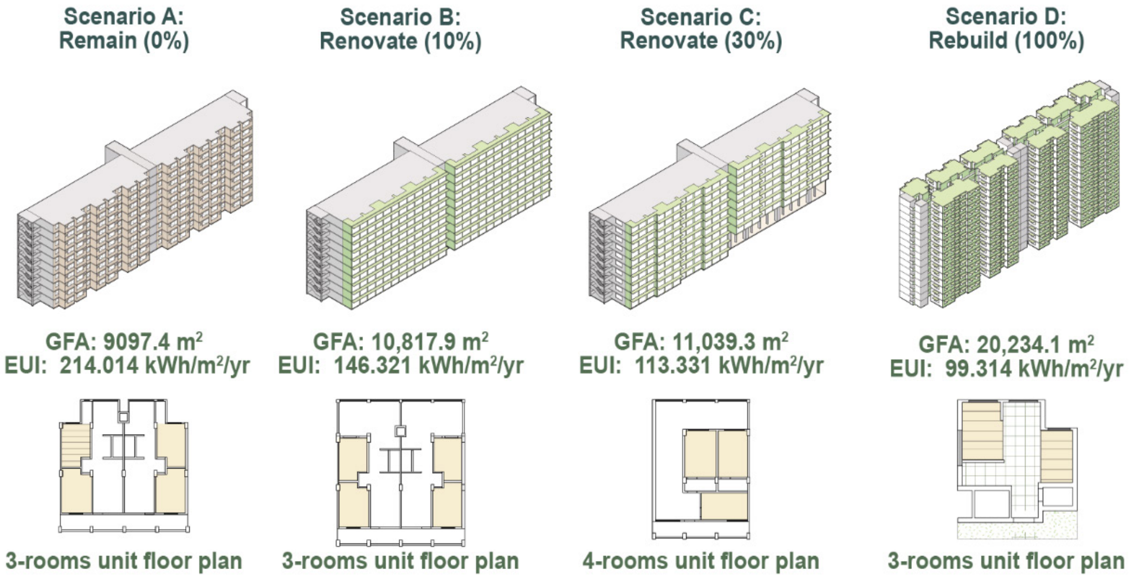


**Figure 2** Overview of different scenarios, 3D building representation and a typical apartment unit (EUI - Energy Use Intensity). Source: Authors, 2025.

The building models were created in the Rhinoceros environment, with additional calculations and simulations performed using Grasshopper and the Ladybug, Honeybee, and Butterfly plugins. The One Click LCA tool was used to calculate $CO_2$ values for embodied carbon across the different scenarios. The results of the case study analysis were visualized using Microsoft Excel diagram tools. Data was collected from multiple databases, including internal databases of the used software tools, the HDB website, the GHG app (Alva et al., 2024), Singapore statistics data (e.g. Energy Market Authority of Singapore (2025)), and complemented with additional sources if required (e.g. environmental product declarations of specific products). LCA data was checked and adapted for the Singapore context with the values from governmental agencies such as "Green Mark" or the Singapore Building Carbon (Building and Construction Authority, 2025; JTC Corporation & Katto Studios, 2025), and research data (Zhang et al., 2024).

## 3 Sustainable, Green and Circular Buildings Have Different Purposes

There is a terminological ambiguity regarding sustainability in the construction industry (Berardi, 2013). The initial research gave an overview of building sustainability. In the literature, three terms describing the sustainability of buildings were identified. These were *sustainable*, *circular* and *green* buildings, and related terms such are circular economy and sustainable construction. All three terms have similar ideas, have grown in popularity with time, and have at the same time expanded their conceptual meaning. Due to their overlap and misconceptions, we relate these concepts with the following equation:

*sustainable (building) > green (building) > circular (building)*

This equation signifies that the green adjective is considered as a part of sustainability and specifically encompasses the environmental dimension of sustainability. A circular building means it incorporates the principles of the circular economy to improve its environmental sustainability but not necessarily other principles (e.g. reducing thermal requirements). Therefore, these terms should not be interchanged, and the assessments and strategies should follow accordingly. The equation explicitly refers to buildings; however, it could be applied to other construction assets, such as infrastructure. For instance, the environmental, social, and governance (ESG) principle of planting a tree to increase sustainability might be part of the assessment and strategy of sustainability, but it would not make a company more circular or green. The term sustainable buildings increasingly overlaps with circular and green buildings — terms which often appear as synonyms but still carry different meanings in the literature. With some further exploration, a sustainable building is identified as the widest concept, defined as a "healthy facility designed and built in a cradle-to-grave resource-efficient manner, using ecological principles, social equity, and life-cycle quality value, and which promotes a sense of sustainable community" (Berardi, 2013). A green building focuses on the environmental aspects of that concept, primarily cradle-to-grave resource efficiency and using ecological principles" (GeeksforGeeks, 2024). A circular building implements circular economy principles to recover resources and generally is focused on the end-of-use or end-of-life phase of a construction resource to improve environmental efficiency (Šibenik et al., 2025).

Sustainability is generally measured with indicators; however, there is no single system describing the relation between the indicators and dimensions of sustainability. An interesting approach is proposed by Moir & Carter (2013); not to constrain the definition of sustainable construction and not to institutionalise the analysis, they propose a "cosmonomic" view on sustainability. The "cosmonomic" framework consists of 15 hierarchically dependent modalities related to sustainability. When investigating BREEAM, they detect social, economic and aesthetic modalities as incomplete.

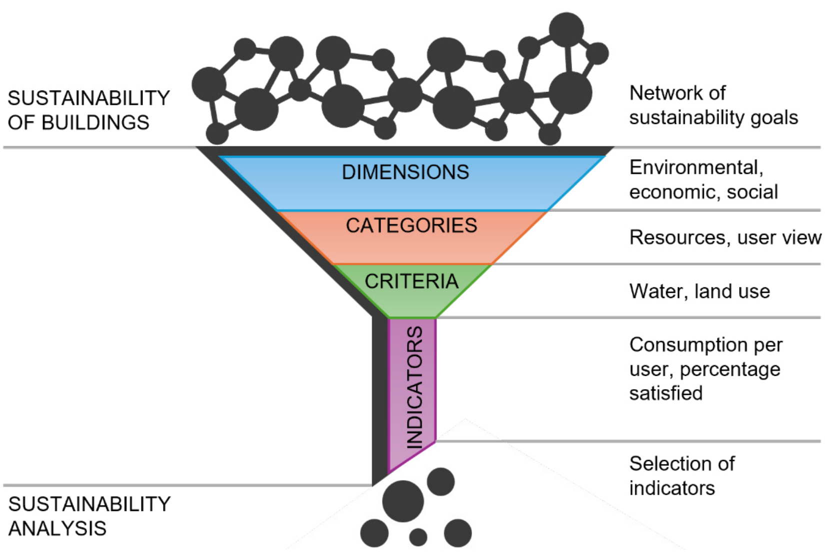


**Figure 3** Hierarchical system of sustainability concepts, connecting sustainability of buildings and sustainability indicators.
Source: Authors, 2025.

More simple structuring approaches were represented in Wen et al. (2020) and Shams & Alkhalifa (2025), assessing GBRT and SBAT tools for sustainability analysis, respectively. In our work, we combine those two hierarchical systems of concepts, identifying four hierarchical levels for the concept of sustainability: dimensions, categories, criteria and indicators (Figure 3). A sustainability analysis is performed with a specific selection of indicators that paint a picture of the sustainability of buildings. Generally, there are many indicators that influence sustainability, which are not all considered in the sustainability analysis. Concepts that are higher in the hierarchy are more standardised. However, the way in which the selection of criteria takes place is not standardised nor straightforward. Therefore, different analysis approaches have been investigated to understand the reasons behind specific selections of indicators.

**Table 1** Overview of research papers performing multi-dimensional sustainability analysis (all papers consider environmental, economic and social dimensions). Source: Authors, 2025.

| | Additional Dimensions | Subject of analysis | LC phase | Case study location |
|---|---|---|---|---|
| Abushaqra & Al Khalifa (2023) | / | residential | operation | Bahrain |
| Ahmad et al. 2016 (2016) | / | systems and techniques | post-design | Pakistan |
| Alalawi & Allani (2025) | / | healthcare | operation | Bahrain |
| Alatawneh & Germana (2016) | humanitarian | earth construction | refurbishment | Palestine |
| Bjorberg & Temeljotov Salaj (2023) | / | multiple | refurbishment | Europe |
| BuHamdan et al. (2019) | / | residential | post-design | Canada |
| Elsamni et al (2024) | / | megaproject | construction | Saudi Arabia |
| Forster et al. (2025) | gestalt | multiple | pre-design | Austria |
| Hassan & Ali (2024) | cultural and aesthetic | stadium | operation | Iraq and USA |
| Hosseini et al. (2021) | / | temporary housing | post-design | Iran |
| Issah Iddi and Padala (2024) | / | multiple | multiple | Ghana |
| Jafari & Valentin (2017) | / | ranch-style home | retrofit | USA |
| Josa et al. (2025) | / | concrete structure | post-design | Italy |
| Keena et al. (2024) | / | residential | post-design | Canada |
| Popovic et al. (2021) | / | hotel | pre-design | Serbia |
| Shams & Alkhalifa (2025) | / | educational | post-design | Bahrain |
| Wilkinson et al. (2014) | / | multiple | multiple | Australia |
| Yuan et al. (2019) | / | elderly facilities | operation | China |

# 4 Results

### 4.1 Multi-Dimensional Sustainability Analysis is Context Dependent

Table 1 represents the overview of the selected research papers from the systematic literature review of sustainability analyses of buildings. The identified studies showed different subjects of analysis, different lifecycle (LC) phases for which the analysis was made, and also different locations, sometimes having more specific urbanisation-related contexts within the location. All analyses include three sustainability dimensions: environmental, economic and social; three research works each add an additional sustainability dimension to the analysis: humanitarian, gestalt and cultural and aesthetic.

There are 18 research papers identified from the literature set, each displaying a distinct sustainability analysis. Distinct analysis methods are characterised by different indicators — generally, the works define different methods that they deem suitable for measuring sustainable performance in a given context. The sustainability analyses and case studies deal with various subjects, and although all three dimensions of sustainability are present in each of the works, the analyses cannot be compared. The indicators are either newly defined, extracted from existing analyses or created as an intersection of multiple indicators. Besides the selection of indicators, their weighting (if performed to provide a single score) also differs. Following this overview, context seems to be of high relevance for any sustainability analysis. In the works of Wen et al. (2020) and Braulio-Gonzalo et al. (2022), different certification systems are compared and evaluated, further emphasising the differentiation between the sustainability analyses. Therefore, for our case study, the lessons from existing research works show that the indicators must be adapted to the context for which the sustainability analysis is performed and that a universal set of indicators does not lead to an optimal analysis.

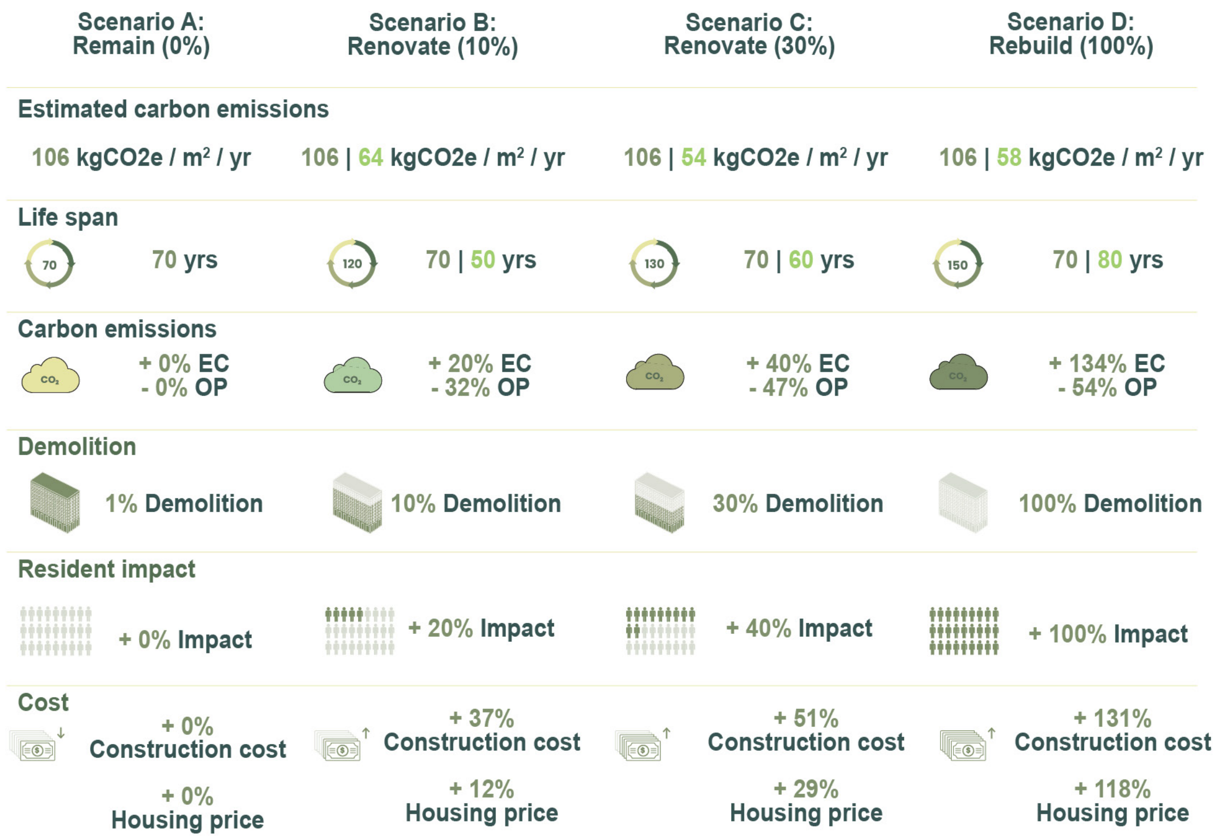


**Figure 4** Overview of the main results for all four scenarios. Source: Authors, 2025.

### 4.2 Case Study Investigating 10 Sustainability Indicators

The oldest residential buildings in Singapore are reaching 70 years, and HDB, as the relevant real estate agency, together with residents and governmental agencies, is deciding on the way forward. The indicators of interest differ among the participants; however, environmental impacts across different scenarios, impacts on residents, and economic implications remain highly relevant for the current real estate situation in Singapore. Hosseini & Kaneko (2012) describe the interconnectivity of four sustainability dimensions (in their work they consider the institutional dimension as well), showing different causalities. For instance, clean water, which indicates environmental sustainability, also affects social sustainability, affecting human health. Therefore, sustainability indicators are all connected to the final result; in our case study, we decided on ten indicators: three for environmental sustainability (building lifespan, carbon emissions, and percentage of demolition), five for social sustainability (relocation time, expected noise, community and daily disruptions, and relocation rate) and two for economic sustainability (construction and housing cost). The indicators were chosen due to their relevance for Singapore. Environmental sustainability considers carbon emissions, but also how long it can fulfil its function and how much waste would be produced. The case study building is characterised by a high percentage of older residents, where disruption is of high importance. The renovation would affect residents' cost of living, but also provide a possibility to sell the unit, which is why the economic indicators could influence decision making. As described in the methodology section, the case study is an HDB residential building in Singapore which is simulated for multiple future scenarios, including retaining and maintaining the building and demolition, two types of renovation before the demolition, or demolition and rebuilding. An overview of the main results is presented in Figure 4. Weighting of alternatives can be done by normalising the results for each indicator; however, the main results represent different sustainability dimensions that vary in relevance for different parties. The results are therefore presented as an overview for discussion among different interested parties, who can determine their own priorities and compare the cases accordingly. This reflects the core of sustainability analysis, responding to the involved parties and context in the best possible way, and finding a compromise between sometimes conflicting indicators.

#### 4.2.1 Environmental Sustainability

As part of the environmental sustainability dimension, we investigated three indicators which are building lifespan (Figure 5a), demolition efforts (Figure 5b), and carbon emissions including embodied and operational carbon (Figure 5c). Considering the whole building LC is a critical concept for sustainable renovation, we frame the maximisation of a building's use against its carbon emissions over time. In contrast to new construction, renovation strategies extend a structure's service life, thereby mitigating the effects of embodied carbon, which presents an important factor to the environmental sustainability. To quantify environmental impact, embodied carbon and operational carbon emissions serve as the primary assessment indicators. The substantial carbon emissions generated from demolition activities (Figure 5b) constitute a major consideration in planning for building renewal, a decisive factor in comprehensive building redevelopment evaluations. Consequently, embodied carbon, operational carbon, and demolition-related emissions form a tripartite framework for assessing environmental sustainability.

This framework is employed to evaluate and compare the environmental implications of the proposed scenarios. This analysis examines four distinct renovation scenarios, evaluating the trade-offs between intervention types. A key comparison is drawn between demolition and new building (Scenario D), which incurs higher initial carbon emissions to significantly prolong the life cycle, and more moderate retrofits (Scenarios B and C).

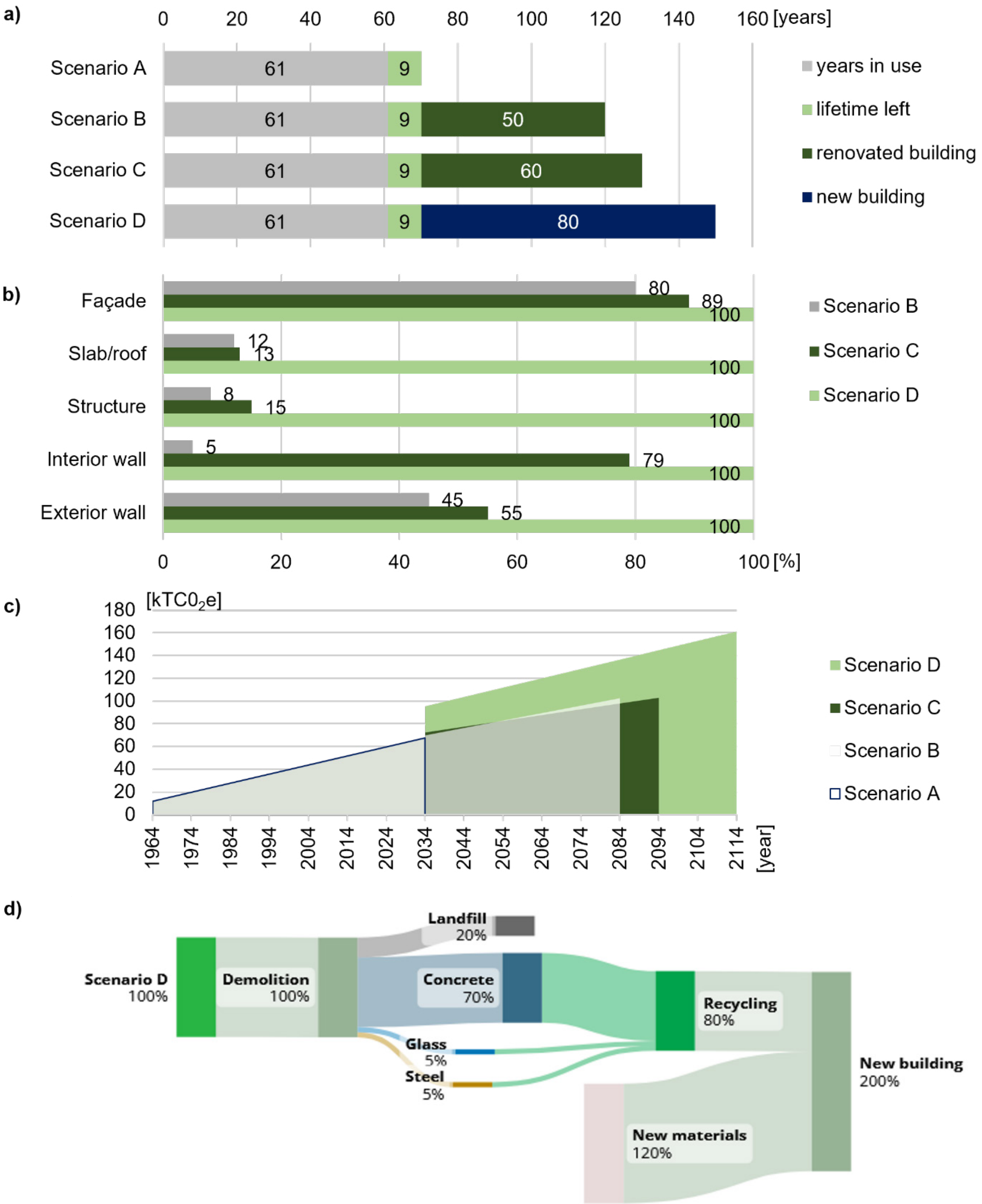


**Figure 5** Diagrams showing the results of calculations of environmental indicators. **5a** Expected lifespan; **5b** Percentage of deconstructed components per scenario; **5c** Expected embodied and operational carbon over the years; **5d** Example of a potential material reuse for Scenario D. Source: Authors, 2025.

An additional option to reduce material use for the construction is seen in the circular economy, also to reduce the cost of waste treatment. From a circular economy perspective, building material recycling presents a significant opportunity for waste reduction, but also cost and carbon emission savings. We focus in this work on its environmental influence, although it could significantly influence the economic impact. Reconstruction projects are particularly well-suited to utilizing recycled construction waste, thereby directly reducing the embodied carbon emissions associated with new material production. New construction, however, demands a greater volume of materials, which recycled waste alone cannot fulfil (Figure 5d). An exemplary Sankey diagram is provided which shows a potential saving on material by implementing principles of circular economy (Figure 5d). Reducing the use of virgin materials has the highest potential in Scenario D, where the building is demolished and a new building is constructed.

The analysis indicates that retrofitting effectively prolongs building service life, thereby reducing the environmental impact of the initial embodied emissions per year. The carbon emission intensity, however, varies significantly with the degree of intervention. A comparative assessment reveals that a mild retrofit (Scenario B) is superior to a full retrofit (Scenario C) in minimizing both demolition-related and embodied carbon emissions. The full retrofit demonstrates an advantage in reducing operational carbon emissions over the long term. Although a complete rebuild (Scenario D) incurs substantial initial carbon emissions from demolition and new construction, it offers the most significant reduction in operational carbon emissions throughout its extended lifespan. Consequently, each scenario presents a distinct trade-off between short-term embodied carbon and long-term operational carbon. The best choice depends on how the decision-makers prioritise these competing factors.

4.2.2 Social Sustainability

Our social impact assessment identifies five key indicators affecting resident well-being: the necessity of temporary relocation, exposure to construction noise, the rate of permanent displacement, overall community disruption, and disturbances to daily life (Figure 6a). These factors are most likely to appear during renovation or new construction work. The analysis in Figure 6a evaluates the comparative performance of each scenario across these social parameters.

Scenarios B and C exert a comparatively minor direct impact on current residents. Specifically, minor reconstruction significantly reduces the probability of resident displacement. This approach not only enhances residents' quality of life by allowing them to remain in situ but also avoids the substantial disruptions typically associated with relocation. In contrast, demolition and rebuilding necessitate the complete vacating of the property, making continued occupancy impossible. Consequently, this scenario imposes a significantly greater effect on social sustainability, primarily through the dissolution of existing community structures and the forced relocation of inhabitants.

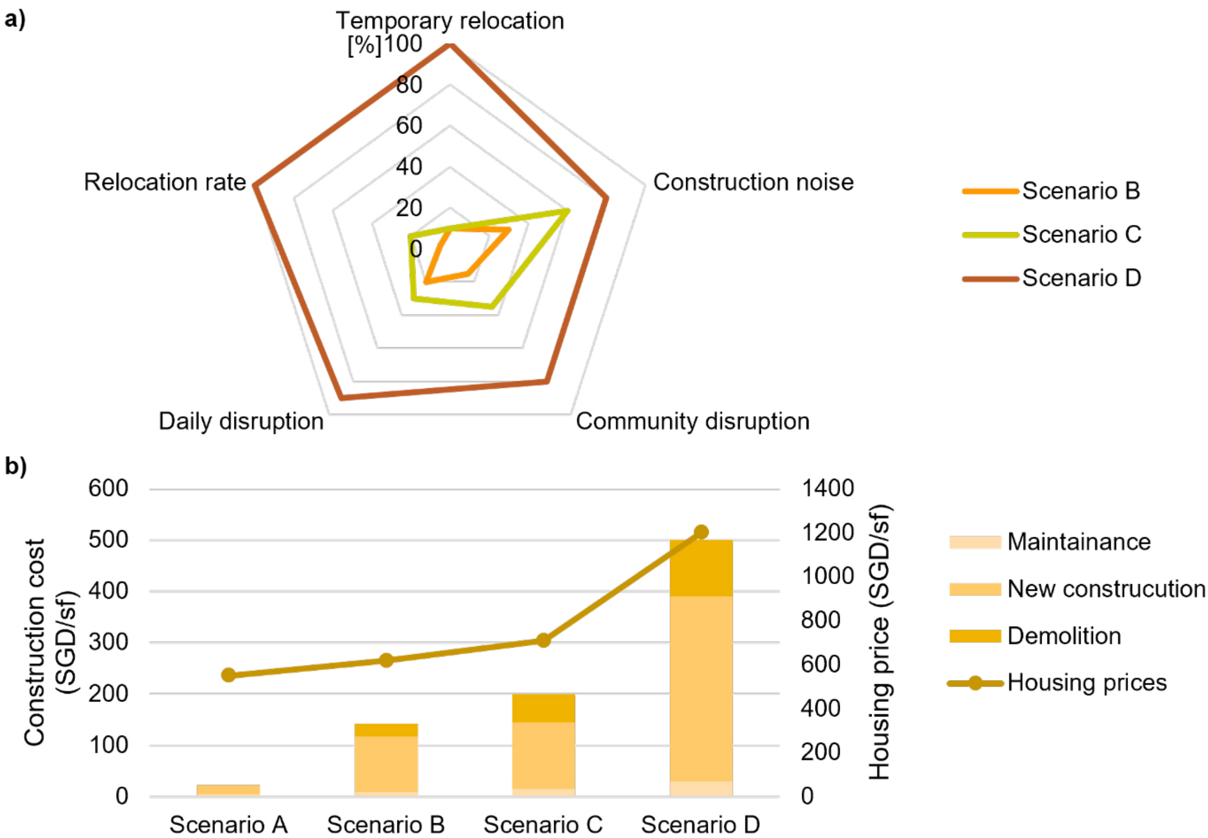


**Figure 6a** Radar chart showing social impacts on the residents. Source: Authors, 2025.; **6b** Comparison of economic indicators: construction and deconstruction costs with the development of housing prices. Source: Authors, 2025.

4.2.3. Economic Sustainability

Economic considerations constitute one of the fundamental dimensions of sustainable renovation. Within the residential sector, key economic metrics typically include construction costs and fluctuations in property value. Utilizing data sourced from the Singapore Department of Statistics and prominent real estate platforms, we have quantified the construction expenditures and projected changes in housing prices for each scenario. Furthermore, the costs of renovation works have also been considered. An aspect which was not considered is the potential for reusing and repurposing construction waste generated from demolition activities. The combined impact of these two factors, construction costs and housing price changes, across the different scenarios is illustrated in Figure 6b.

Our analysis of economic indicators reveals a critical trade-off between renovation and new construction. While renovation strategies effectively control initial construction costs, their influence on enhancing property values is comparatively limited. Newly constructed residences (Scenario D), by contrast, command a premium due to modernised living facilities and comprehensive community amenities, ultimately resulting in a higher overall property value.

## 5 Discussion

### 5.1 Sustainability Assessment Effectiveness Depends on Priorities

Creating a more sustainable built environment is a widely present motivation in the construction industry. Multiple building designs can be compared for their sustainable performance. However, there is no single formula for sustainability. Sustainability involves numerous, sometimes hierarchical concepts (Scherz et al., 2020). Building certification systems, which tend to provide a generally applicable evaluation of sustainability, are constantly changing (Wen et al., 2020), further proving that there is no single sustainability formula. One way to align these heterogeneous understandings is to structure the sustainability into smaller, partial concepts. However, these structures can also differ due to terminological ambiguities.

Environmental, economic and social dimensions are commonly regarded as the three main aspects of sustainability, although other structuring concepts exist as well (e.g. Moir & Carter, 2013). Dimensions are further divided into narrower concepts, and sustainability is calculated with prioritized indicators. One-size-fits-all assessments that are most common in the industry still rely on a specific set of indicators, which is never exhaustive. Using a limited set of indicators automatically prioritises certain solutions and designs compared to other analyses. It is not possible to respond to all sustainability indicators in the same way with a single solution and without compromising other ones. A single holistic sustainability realm on each of the hierarchical levels is lacking (Figure 3); such a network of indicators would be useful to more strategically serve various purposes and perspectives. Priorities of the analysis are then selected by narrowing down the focus and filtering relevant indicators. Our case study demonstrated a possible application of MCDA calculating ten exemplary indicators related to three sustainability dimensions.

### 5.2 Tailor-Made Assessments Can Help Make Crucial Sustainability Decisions

Currently, research works such as those listed in Table 1 individually select priorities so they could address the specifics of a context. Methods and tools closer to practical applications, such as different certification systems, also consider only a subset of indicators, which are not necessarily relevant for each case study. Therefore, future research should prioritise context-based filters, which could be useful for policymakers and yield a stronger effect on a practical application. Therefore, to have an effective sustainability assessment, it is necessary to focus on the important criteria within the specific context. Analyses in practice are increasingly context-based and implemented in the form of local policies,

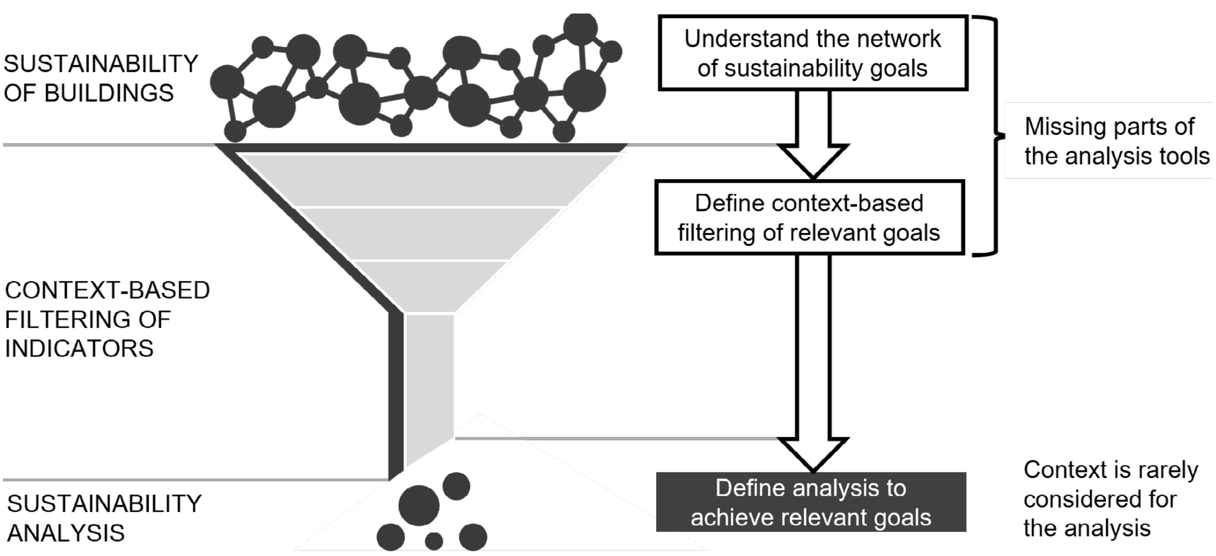


**Figure 7** The gaps identified in the analysis and proposed next steps for the analysis methods. Source: Authors, 2025.

e.g., through a masterplan. Actually, existing masterplans already consider multiple sustainability indicators. An underlying system that suggests relevant and comparable indicators could have global application. In literature, especially in the research papers presented in Section 3, it is evident that the different analysis contexts require different indicators. These indicators are not always straightforward to identify, and it is necessary to focus on providing a pipeline between sustainability in the physical world and its indicators (Figure 7).

Instead of following a generally applicable sustainability measurement tool, the sustainability of a building should be defined in coordination with the master planning authority and should perform well on indicators relevant to the specific context. Based on the prioritized indicators, the project should be further evaluated to determine in which scope certain indicators are working well or not. Our context-based filtering considering conditions relevant for Singapore covers perspectives of relevance for different parties involved in the process. In our case study, which calculates and describes ten indicators of multiple dimensions of sustainability, the next step would be to weigh and compare the indicators in order to find the overall optimal solution. We don't focus on one weighting or a single solution; instead, we plan to assess the results after multiple parties have prioritized the indicators and once we've provided insight into different scenarios. A similar concept can be implemented for any sustainability analysis. Understanding the complexity of the pipelines that connect real-world sustainability performance with indicators could significantly contribute to achieving the desired context-based outcomes.

## 6 Conclusion

This research paper investigates how to analyse multiple dimensions of sustainability of buildings. Widely accepted dimensions of sustainability are environmental, economic and social; however, the indicators which are used for analysis are highly diverse. This research follows three methodological steps (reflected in Sections 2 and 3): first, it investigates existing terminology related to sustainable, green, and circular buildings, as well as the dimensions, categories, criteria, and indicators of building sustainability; second, it investigates and structures approaches to measuring multiple dimensions of sustainability; and finally, we perform a multi-criteria decision analysis for a case study in Singapore. The analysis of terminology indicates that the higher the hierarchical concept, the smaller the ambiguity, and vice versa. The review of multi-dimensional analyses shows that it is neither feasible nor necessary to consider all indicators for each sustainability analysis. The reviews lead to a case study multi-criteria decision analysis, resulting in an overview of unweighted indicators. The case study serves as a discussion and provides insights for future decision-makers, ranging from users and real estate companies to governmental agencies, which can assign individual and differing weighting systems and decide on subsequent actions.

A limitation of this study is that the relevant indicators were chosen by the authors. The existing scenarios are limited to hypothetical cases that do not necessarily reflect all possible (or potentially better) solutions. The simulations do not consider changes in parameters, such as past or future emission values. The terminology definition does not exhaustively review the literature to prove its wide applicability, especially beyond the construction industry. For the next steps, it is necessary to focus on the pipelines relating the indicators with the holistic system or set of systems that would be applicable more globally. It is planned to define the building sustainability knowledge domain and especially the filtering processes to connect top-down and bottom-up approaches, relating building sustainability and its indicators. Existing generic solutions (e.g., sustainability certifications) support only a very limited set of cases; however, by increasing their context sensitivity and variability, they could become more effective for global application. The interrelation of indicators also requires further research, as they could affect the overall quantification.

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