SP 1.4 Deliverable 1

Report on Initial LCSA- Framework and comprehensive list of Sustainability Indicators

Authors:
Matteo Spada[1], matteo.spada@zhaw.ch
Evelyn Lobsiger-Kägi[1], evelyn.lobsiger-kaegi@zhaw.ch
Corinna Baumgartner[1], corinna.baumgartner@zhaw.ch

[1]Zurich University of Applied Sciences, Institute for Sustainable Development, Technoparkstr. 2, 8401 Winterthur

Table of Contents

List of Figures

List of Tables

Glossary

ADP	Abiotic depletion potential
AHP	Analytic Hierarchy Process
AP	Acidification potential
B-READY	Building Resilient, Adaptive and Disaster-Ready Communities
BREEAM	Building Research Establishment Environmental Assessment Method
BRLA	Building Resilience Los Angeles
CED	Cumulative energy demand
CI	Composite Indicator
DGNB	Deutsche Gesellschaft für Nachhaltiges Bauen
DMs	Decision-Makers
eLCA	Environmental Life-Cycle Assessment
ELECTRE	ÉLimination Et Choix Traduisant la Réalité
EP	Eutrophication potential
EPT	Energy payback time
ESE	Ecological Scarcity endpoint
EU	European Commission
FU	Functional Unit
GWP	Global warming potential
ISO	International Organization for Standardization
HSLU	Lucerne University of Applied Sciences and Arts
JRC	Joint Research Centre
LCC	Life Cycle Cost
LCSA-F	Life-Cycle Sustainability Assessment-Framework
LEED	Leadership in Energy and Environmental Design
MAVT	Multi-Attribute Value Theory
MAUT	Multi-Attribute Utility Theory
MCDA	Multi-Criteria Decision Analysis
MCDA-MSS	Multi-Criteria Decision Analysis – Methods Selection Software
Mio.	Million
NIST	National Institute of Standards and Technology
NYC	New York City
NYSERDA	New York State Energy Research and Development Authority
ODP	Ozone depletion potential
ORIENTING	Operational Life Cycle Sustainability Assessment Methodology Supporting Decisions Towards a Circular Economy
PEER	Performance Excellence in Electricity Renewal
POCP	Photochemical oxidation creation potential
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluations
RA	Resilience Assessment
REDi	Resilient Design for the Next Generation of Buildings
RELi	Resilience Action List and Credit Catalog
SDG	Sustainable Development Goals
SGNI	Swiss Sustainable Building Council
sLCA	Social Life Cycle Assessment
SP	Sub-Project
t	tonnes
UNEP	United Nations Environment Programme
UniGe	University of Geneva
USGBC	United States Green Building Council
VOC	Volatile organic compound
ZHAW IFM	Zurich University of Applied Sciences - Institute of Facility Management

Executive Summary

In Switzerland, buildings are one of the major sources of CO_2 emissions accounting for ~24% of the total. Therefore, to achieve the requests posed by the Paris agreement, these emissions need to be reduced [1]. In this context, this can be achieved either by efficient envelopes (reduction of energy demand) and/or by switching from fossil fuels to renewable energies (decarbonization). While such measures are straightforward in the case of new buildings, retrofit of the existing building stock is more complex [2], [3].

The RENOWAVE project aims at boosting the retrofit of the Swiss building stock, both in terms of quantity (renovation rate) and quality (performance), as to help achieve the objectives formulated for the building sector in the Swiss long-term climate strategy [4]. To accomplish this goal a holistic, value-chain oriented approach is adopted in RENOWAVE to contribute achieving several Sustainable Development Goals, including socio-economic as well as environmental ones (SDGs 7,8,12,13). The holistic approach aims at solving several multifaceted, interrelated, and transdisciplinary challenges that rise from the massive and efficient retrofit of the existing Swiss building stock. These challenges have been allocated to several individual sub-projects (SPs) clustered in different thematic pillars in RENOWAVE.

In SP1.4 a comprehensive sustainability framework specifically tailored to the sustainability, resilience and decarbonization targets and policies of the Swiss government and consider the needs and perspectives of the diverse stakeholders in the building sector is derived. The final aim of SP1.4 is to realize a tool that allows stakeholders to compare different potential renovation measures with respect to the current state of the building under interest by means of providing ranking and scores of each alternative.

This report presents the initial development of such a tool, called Life-Cycle Sustainability Assessment-Framework (LCSA-F), for multi-family houses renovation measures. The LCSA-Framework combined the Environmental Life Cycle Assessment (eLCA), Life Cycle Cost (LCC), Social Life Cycle Assessment (sLCA) and Resilience Assessment (RA) domains within the overarching Multi-Criteria Decision Analysis (MCDA) method. Therefore, the tool makes use of one of the main family of Multi-Criteria Decision Analysis (MCDA) methods, which is represented by composite indicators (CIs), or indices [5], since it leads to a score of the alternatives that can then be easily ranked.

The initial development of the proposed framework was achieved in close collaboration with a group of 8 experts from academia, construction enterprises, consulting, etc., to grasp the heterogeneous knowledges and interests from these different domains. Particularly, the experts participated to 2 Workshops to help defining the proposed framework.

In the 1st Workshop the experts were asked to define the system boundaries of the framework and their level of details. In this context, the group uniformly voted for covering the whole life cycle including the product stage, the construction process stage, the use stage, and the end-of-life stage as well as presenting all results at the process stage level. Furthermore, the experts voted the functional unit (FU) for the LCSA framework, which results to be “heated area per year of building lifetime” due to its wide application in the Swiss building context expressing the building’s energy demand.

Moreover, during the 1st Workshop, the group of experts selected the criteria to be included in the framework, since CIs are based on an aggregation of criteria that measure different domains. In this context, the framework presented here is based on a hierarchical structure of the criteria, which is composed by 3 layers. In the first layer the four abovementioned domains, i.e., eLCA, LCC, sLCA, RA,

are present. The second layer is composed by a set of 16 criteria, subdivided into 5 for eLCA and sLCA, 4 for RA and 2 for LCC, which were defined based on a comprehensive literature review and the expert selection during the 1st Workshop. The 3rd layer of the hierarchical structure of the framework contains a set of 56 subcriteria, subdivided into 10 for eLCA and sLCA, 9 for LCC and 27 for RA, which were selected based on a comprehensive literature review and in accordance with the group of experts.

Once the criteria hierarchical structure of the LCSA-Framework was defined, during the 2nd Workshop, the experts were asked to weight the 2nd and 3rd level of the hierarchy to build a default preference profile, different to the equal weight one, to be included in the tool under development. Finally, based on the problem type, the criteria and subcriteria nature, the preference elicitation, and the features of aggregation under interest, the most reasonable MCDA method for the tool under development was selected. In this context, the Multi-Attribute Value Theory (MAVT) was found to be the best methodological solution based on the MCDA-MSS tool.

1. Introduction

At Swiss level, with a share of 24% (11.2 Mio. t/year), buildings are one of the major sources of CO_2 emissions [1]. Therefore, to achieve the requests posed by the Paris agreement, these emissions need to be reduced. In this context, this can be achieved either by efficient envelopes (reduction of energy demand) and/or by switching from fossil fuels to renewable energies (decarbonization). While such measures are straightforward in the case of new buildings, retrofit of the existing building stock is more complex. In fact, challenges to massive and efficient retrofit are numerous, multifaceted, interrelated, and transdisciplinary, from a scientific as well as an operational point of view [2], [3].

Based on these premises, the RENOWAVE project is a collaborative effort over the entire concerned value-chain, to promote massive decarbonization of the existing building stock. The main goal of RENOWAVE is to boost retrofit of the Swiss building stock, both in terms of quantity (renovation rate) and quality (performance), as to help achieve the objectives formulated for the building sector in the Swiss long-term climate strategy [4]. To accomplish this goal a holistic, value-chain oriented approach is adopted in RENOWAVE to contribute achieving several Sustainable Development Goals, including socio-economic as well as environmental ones (SDGs 7,8,12,13). The holistic approach aims at solving several multifaceted, interrelated, and transdisciplinary challenges that rise from the massive and efficient retrofit of the existing Swiss building stock. These challenges have been allocated to several individual sub-projects (SPs) clustered in different thematic pillars in RENOWAVE.

The thematic pillar number 1 focus on the social innovation aspects within RENOWAVE. It relates to the participation of different stakeholders and policy analysis (SP 1.1), as well as to issues of motivation and decision-making of building owners (SP 1.2). From this, conclusions are derived for advising and supporting owners in the planning and implementation of energy renovations, and support tools are developed for this purpose (SP 1.3). These support tools will be complemented by a comprehensive life-cycle sustainability assessment-framework (LCSA-F) to support an informed and holistic decision making for a sustainable decarbonization of the Swiss building stock (SP 1.4).

The proposed framework in SP1.4 integrates four methodologies, which are Environmental Life Cycle Assessment (eLCA), Social Life Cycle Assessment (sLCA), Life Cycle Costing (LCC) and Resilience Assessment (RA) under the overarching Multi-Criteria Decision Analysis (MCDA) method. Since the 1990s, different standards and certifications have been developed and used to ensure improved sustainability in buildings, such as Leadership in Energy and Environmental Design (LEED) [6] in the United States, Building Research Establishment Environmental Assessment Method (BREEAM) [7] in the United Kingdom, or the Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB) [8] in Germany or the Swiss standard, which is derived from DGNB and led by the Swiss Sustainable Building Council (SGNI) [9]. Currently, the emergence of resilience thinking due to increasing intensity and frequency of natural catastrophes, requires buildings to be not only sustainable but also resilient [10]. In this context, efforts have been done in the last decade to integrate sustainability and resilience concepts in the context of buildings [11]. However, all cases referred to new buildings, such as for example in the LEED framework [12], rather than the renovation of already present ones. Based on these premises, this study presents a first-of-its-type framework, which combine the sustainability and resilience domains in the context of decarbonization through renovation of existing buildings, for apartment houses. The framework is going to be later tested for case studies in Switzerland.

The LCSA-F proposed here is based on a MCDA approach, which allows to (i) consider a multitude of sector-specific indicators relevant for the different abovementioned methodologies, (ii) combine the three pillars of sustainability (environment, economy, social) with resilience aspects, (iii) adapt the framework to the needs of the stakeholders (flexibility). Therefore, SP 1.4 derives a comprehensive sustainability framework specifically tailored to the sustainability, resilience and decarbonization targets and policies of the Swiss government and consider the needs and perspectives of the diverse stakeholders in the building sector. The final aim of SP1.4 is to realize a tool that allows stakeholders to compare different potential renovation measures with respect to the current state of the building under interest by means of providing ranking and scores of each alternative and their sensitivity to the weighting profile. Therefore, the tool makes use of one of the main family of MCDA methods, which is represented by composite indicators (CIs), or indices [5], since it leads to a score of the alternatives that can then be easily ranked (section 3).

This report presents the steps followed in the definition of the LCSA framework and selection of the relevant criteria and subcriteria for each considered methodology to be further used within the MCDA Framework (sections 4 and 5). Furthermore, it shows the weighting process of each criteria/subcriteria provided by selected stakeholders (section 6). Finally, based on the different scales (ordinal/cardinal/etc.) of the subcriteria and the hierarchical structure of the problem, the most reasonable MCDA method to be implemented in the tool under development is selected (section 7).

2. General LCSA framework conditions

To align the general LCSA framework conditions for each subsequent methodology, i.e., eLCA, LCC, sLCA and RA, in a first stakeholder workshop several framework conditions have been voted on and selected. The stakeholder group exists of experts from the RENOWAVE consortium and were selected to cover a variety of sectors, e.g., academia, construction enterprises, consulting, and disciplines, e.g., economy, engineering, architecture (see section 4.5).

The framework conditions in focus were the system boundaries specifically and their level of detail to display in the LCSA tool. Furthermore, the functional unit for eLCA and LCC was selected based on several applied FU from literature [13], [14]. A range of system boundaries and functional units (FU) of LCSAs in the building sector were collected from literature and existing standards [13], [15]. Following, they have been pre-selected by the authors based on their relevance and practicability for the specific application in the assessment of the retrofit of buildings.

The system boundary presented to the expert group was taken from EN 15978:2011 and presents a cradle-to-grave approach including the life cycle stages and process stages from A1-C4 (see Figure 1) [16].

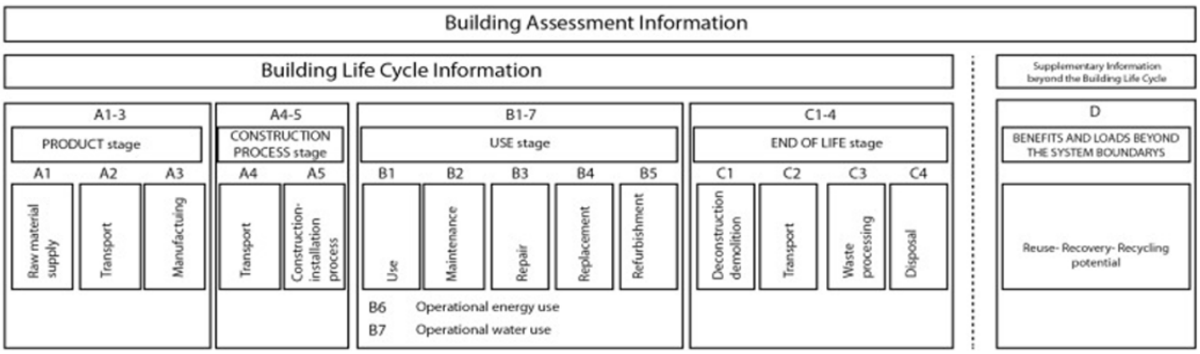

Figure 1 System boundary for building assessment information presented to expert group from A1-C4 for selecting the relevant life cycle stages and the level of detail to integrate in the LCSA tool [16].

The options to vote on the system boundaries have been assigned to (i) the life-cycle phases to be included and (ii) the presentation of the final results in the tool to be developed, i.e., the level of detail shown whether on process level (e.g., A1, A2, A3 separately) or life-cycle phase level (e.g., A1-A3 as product stage) (see Figure 1).

The expert group voted uniformly for covering the whole life cycle including the product stage (A1-3), the construction process stage (A4-5), the use stage (B1-7) and the end-of-life stage (C1-4) as well as presenting all results on process stage level.

Furthermore, the stakeholders had to vote on the functional unit (FU) for the LCSA. Different FUs, which build the common basis for the several methodologies under the LCSA-framework, have been taken from a review study by Toosi et al. [14]. Following FUs, which are widely used for assessing life-cycle sustainability in the context of building energy retrofitting, have been presented to the stakeholders:

- Internal space volume of building
- Total building
- Total living area
- Heated area for building lifetime
- Heated area per year of building lifetime
- Footprint Building
- Net internal area per year

The voting of the expert group resulted in a parity between “total building” and “heated area per year of building lifetime” from which the latter was finally selected due to its wide application in the Swiss building context expressing the building’s energy demand [17].

3. Multi-Criteria Decision Analysis (MCDA) Background

Sustainability assessments require the management of a wide variety of information types belonging to different domains (environmental, economic, and social). In this context, multi-criteria decision analysis (MCDA) has been regarded as a suitable set of methods to perform sustainability evaluations because of its flexibility and the possibility of facilitating the dialogue between stakeholders, analysts, and scientists [18].

MCDA is a formal process to support decision-makers (DMs) in structuring their decision problems and to offer them tools and methods leading to recommendations about the decisions at stake [19]. The recommendations are based on a comprehensive identification of the considered alternatives and the selection of criteria/subcriteria/etc. evaluating them, which are aggregated considering the preferences of the DMs [20]. There is a wide availability of MCDA methods that can be used to integrate information and either classify alternatives into preference-ordered classes or rank them from the best to the worst. Generally, three main MCDA methods families can be identified [21]:

1. Utility-based theory, which includes methods synthesizing the information in a unique parameter that are also called performance aggregation-based approaches or scoring-based approaches. This approach is the theory behind the construction of CIs, which are widely used synthetic measures for ranking and benchmarking alternatives across complex concepts [5]. Examples of such methods are the multi-attribute utility/value theory (MAUT/MAVT) aggregation models [22], the analytical hierarchy process [23] and the fuzzy sets techniques [24].
2. Outranking-based approaches, also known as preference aggregation-based approaches, which involve methods based on comparisons between pairs of options to verify whether “alternative *a* is at least as good as alternative *b*” [25]. Examples of such methods are ELECTRE [26] and PROMETHEE [27].

3. Rule-based systems, which originates from the artificial intelligence domain, allow deriving a preference model using classification or comparison of decision examples [28]. Example of such methods are the decision rule [29], and verbal decision analysis [30].

According to the decision problem in hand, i.e., the comparison and ranking of different renovation measures, the framework under development lies under point 1 above. In fact, a scoring/ranking problem belong to the utility-based theory, which allows building CIs by means of aggregating the considered criteria. CIs construction required several steps as described in the Handbook on Constructing Composite Indicators published by the Joint Research Centre (JRC) of the European Commission (EC) [31]. In general, for a comprehensive MCDA application the following steps should be achieved:

1. Literature review to obtain a broad understanding of sustainability and resilience assessment in the context of building renovation.
2. Development of a theoretical framework aimed at defining the research topic, which is the comparison of different renovation measures.
3. Selection of an initial set of criteria/subcriteria.
4. Selection of the final criteria/subcriteria dataset, which is based in this study on expert judgment.
5. Selection of the alternatives.
6. Collection of the criteria/subcriteria data for each alternative.
7. Selection of the normalization method, which is strongly based on the DMs interests and the scales of the criteria under analysis.
8. Collection of criteria weighting schemes, which are based in this study on expert judgment (section 6).
9. Selection of the aggregation method.
10. Analysis and interpretation of the results.

This report focuses on steps 1-4 and 7-8 in a direct or indirect way. In particular, (i) section 4 presents the literature review for the initial criteria dataset and the selection of the final set of criteria; (ii) section 5 presents the literature review and the selection of the final set of subcriteria; (iii) section 6 presents the criteria weighting scheme; and (iv) section 7 presents the selected MCDA method to be implemented in the LSCA-F tool.

4. Criteria Selection

One of the first steps in the construction of the LSCA framework proposed in this study is the selection of criteria to be measured by subsequent sub-criteria (section 5). For each of the domains considered in this study, a set of criteria is defined based on a comprehensive literature review followed by the selection, by a group of 8 experts from different domains, of the most important criteria in the context of building renovation to be included in the tool. A total of 16 criteria are finally selected. In this section, the selection of the criteria for each domain is described (sections 4.1, 4.2, 4.3, 4.4), followed by the results from the Stakeholder Workshop (section 4.5).

4.1. Environmental Life Cycle Assessment (eLCA)

Environmental LCA is a wide-spread and acknowledged methodology for products and services, which is also represented by the ISO standards 14040 and 14044 [32], [33]. The eLCA framework to be integrated in the LCSA should enable stakeholders from the building sector to compare and consider relevant environmental impacts from renovation measures for multi-family buildings. As one of the main goals of RENOWAVE is to decarbonize the Swiss building stock. CO_2-equivalent emissions (CO_2-eq.) is one key performance indicator to be measured among others, which have been selected.

In a first step, the eLCA's scope was defined according to the system boundaries selected by the expert group and the categorization A1-C4 including circular economy related processes [34]. Inputs and outputs have been defined and distinguished in processes/materials- and energy-related (see Table 1).

Secondly, indicators have been preselected based on literature review and according to the DGNB standards, which are relevant for the building sector and even more specifically to the retrofit of buildings [8], [15], [35], [36]. Following, the most relevant indicators and comprehensive life cycle impact assessment (LCIA) methodologies, such as Ecological scarcity [37] have been presented to the expert group for voting and selection:

- Global warming potential (GWP)
- Cumulative energy demand (CED)
- Ozone depletion potential (ODP)
- Acidification potential (AP)
- Eutrophication potential (EP)
- Photochemical oxidation creation potential (POCP)
- Abiotic depletion potential (ADP)
- Energy payback time (EPT)
- Ecological Scarcity endpoint (ESE)

The indicators resp. methodologies are intended to cover a wide variety of relevant environmental aspects to account for and reflect several aspects and impacts regarding environmental sustainability from the building sector. Therefore, the selection is intentionally going beyond the focus of RENOWAVE, which is mainly decarbonization by reducing greenhouse gases and energy.

4.2. Life Cycle Costing (LCC)

LCC is the oldest of the three life-cycle based assessment methodologies for this LCSA-framework, originally based on financial aspects only [38]. Nevertheless, the development of the methodology until now brought different types of LCC up, which differ in the scope resp. the system boundaries as well as the relevant cost and revenue factors to be included. The three types of LCC are depicted in Figure 2 [38]:

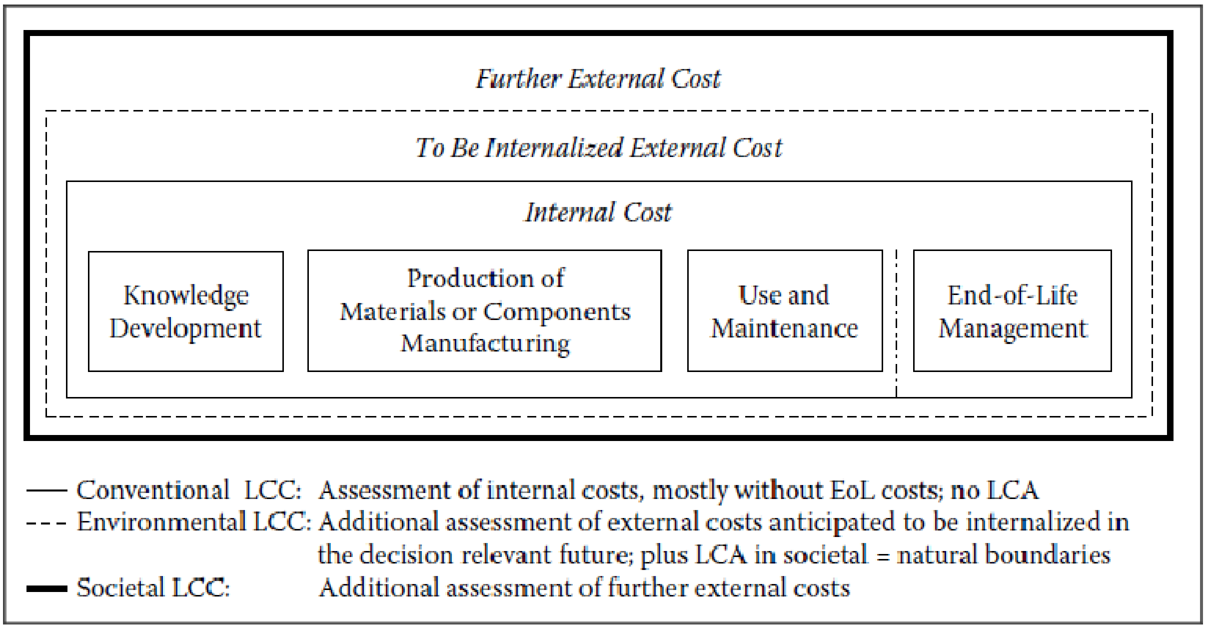

Figure 2: The three types of Life Cycle Costing and their related scopes [38].

Due to the fact, that environmental and social/societal externalities are already accounted for in eLCA and sLCA included in this LCSA-framework by including the environmental and social impacts in the MCDA, the conventional LCC is the appropriate choice for this LCSA-framework to avoid double-counting on any sustainability-related aspect.

Furthermore, other specific and relevant guidelines for conducting LCC in the building sector have been taken into account, such as the ISO 15686-5:2017 the recommendations for LCC by DGNB in order to define the cost and revenue factors, which are in the scope of this LCC (see Table 2) [8], [39]. The cost and revenue factors also have been assigned to different main categories, which are the following ones:

- Market costs: Economic and financial costs, related to life-cycle processes, such as construction and disposal costs, electricity costs.
- Non- market costs: Fees and taxes
- Market revenues: Economic and financial revenues, such as the revenue from selling electricity or recycled materials.
- Non-market revenues: Subsidies, such as a subsidy for a specific renovation measure

Additionally, the cost and revenue factors have also be assigned to the categorization A1-C4 including circular economy related processes to align the system boundaries to the ones of eLCA and to the selection of the detail level of the stakeholder group like applied on other studies [34] [40], [15].

The LCC criteria to be presented to the stakeholders for selection have been mainly taken from literature, which is focusing specifically on LCC for the building sector, in some cases for retrofit and renovation [14], [36], [40]–[42].

The most widely used criteria have been given to the stakeholder group for selection, which are following:

- Operational expenditure (OPEX)
- Capital expenditure (CAPEX)
- Net Present Value (NPV)
- Resale benefit
- Net Present Costs
- Net savings
- Saving to investment ratio
- Internal Rate of Return
- Energy Costs
- Payback Period Time

As it is fundamental to avoid double-counting also within one life-cycle methodology, not all criteria can be used in parallel in the MCDA. Nevertheless, the mainly applied criteria have been proposed for selection to derive the main interest of the diverse stakeholder group.

Table 1 Scope of eLCA regarding inputs and outputs along life-cycle stages and categorized in process/materials and energy.

Life Cycle Stage	Product stage	Construction process stage	Use stage	End-of-Life stage	Circular economy aspects
Process stages	A1-3	A4-5	B1-5	C1-4	Beyond System boundaries
Processes and Materials	**Input**				
	Raw materials: primary, secondary	Transportation	Maintenance: Material, transportation, energy	Deconstruction efforts	Recycling efforts A1-C4
	Transportation	Construction/installation process	Repairing efforts: materials energy, disposal, CE	Transportation	Recovery efforts A1-C4
	Manufacturing		Replacements: Materials, energy, disposal, CE	Sorting efforts	Reuse efforts A1-C4
			Refurbishment: Materials, energy, disposal, CE	Disposal: MSWI, landfill	
	Output				
					Recycled materials A1-C4
					Recovered materials A1-C4
					Reused materials A1-C4
Energy	**Input**				
	Process energy	Process energy	Electricity	Process energy	Process energy
			Gas		
			Oil		
	Output				
	Energy from MSWI	Energy from MSWI	Electricity	Energy from MSWI	
			Heat		
			Energy from MSWI		

Table 2 Scope of LCC regarding life cycle costs and revenues along life-cycle stages and categorized in market and non-market costs & revenues (MC = Market costs, NMC = Non-market costs, MR = Market revenues, NMR = Non-market revenues).

Life Cycle Stage	Product stage	Construction process stage	Use stage	End-of-Life stage	Circular economy aspects
Process stages	A1-3	A4-5	B1-5	C1-4	Beyond System boundaries
Total Life cycle costs (cost factors)					
MC	**Production costs**	**Construction process costs**	**O&M costs**	**EOL costs**	**Circular economy costs**
	Raw material costs	Transportation costs	Use costs: energy (fuel, electricity, etc.)	Deconstruction/Demolition costs	Recycling costs A1-C4
	Transportation costs	Construction/Installation costs	Maintenance costs	Transportation costs	Recovery costs A1-C4
	Manufacturing costs		Repair costs	Waste processing costs	Reuse costs A1-C4
			Replacement costs	Disposal costs (without fee)	
			Refurbishment costs		
NMC	**Fees**				
	Disposal fee	Disposal fee	Use costs: CO_2 fee fuels	Disposal fee	
			Disposal fee		
	Taxes				
			Income tax of imputed rental value		
			Property tax		
			Wealth tax		
Total Life Cycle Revenues (revenue factors)					
MR			**O&M revenues**		**Circular Economy revenues**
			Sale of energy: feed-in-tariff		Sale of recycled material A1-C4
			Added value of building		Sale of recovered material A1-C4
			Rental income / addedd value of building		Sale of reused material A1-C4
NMR	Federal, cantonal, communal subsides				

4.3. Social Life Cycle Assessment (sLCA)

The sLCA approach is used to evaluate the social impacts of a product [43] and has not been standardized yet. First proposals of a common framework were published in 2009 [44]. Until now different methodologies of sLCA were developed [45], [46], but none of them has reached broad application in practice. Also, specific criteria to assess the social impacts of building constructions were developed [47], [48].

To define the most important and suitable criteria to assess different renovation alternatives in the building sector we first screened the literature for existing indicator(s) evaluating the social aspects in the building sector. Besides the above-mentioned sustainability standards in the building sector, scientific papers were screened to collect possible social sustainability criteria. For the definition of the first set of criteria (review) studies on sustainability assessments as well and specific studies on social aspects in the construction area were considered:

- Application of Life Cycle Sustainability Assessment in the Construction Sector: A Systematic Literature Review. [49]
- Development of social sustainability assessment method and a comparative case study on assessing recycled construction materials. [50]
- Green building research – current status and future agenda: A review. [51]
- AHP based life cycle sustainability assessment (LCSA) framework: a case study of six storey wood frame and concrete frame buildings in Vancouver. [52]
- Applying multi-criteria decision-making on alternatives for earth-retaining walls: eLCA, LCC, and sLCA. [53]
- Sustainability choice of different hybrid timber structure for low medium cost single-story residential building: Environmental, economic and social assessment. [54]
- Modeling socioeconomic pathways to assess sustainability: a tailored development for housing retrofit. [55]

Furthermore, the criteria and principles from the international Guidelines for Social LCA from the UNEP [44] were considered, as well as the established guidelines from the German Sustainable Building Council [8] and the LEED Guidelines from the U.S. Green Building Council [6]. Also, the recently published report from the ORIENTING project (EU Horizon 2020) on the “Critical evaluation of social aspects” [56] in the sustainability assessment of products social served as an important source for defining the criteria and their scales. Out of this body of literature the most established and most frequently applied criteria and sub-criteria were identified considering that all five stakeholder categories defined by the UNEP guidelines are represented: Workers, Value Chain Actors, Consumers/Users, Society, Local Community. Where possible the criteria and scales were defined in line with the DGNB guidelines, as those are already in use in Switzerland and are suitable for the Swiss context. These criteria were then checked for their appropriateness for the renovation of buildings and the ones not applicable were eliminated. The following set of criteria was selected:

- Safe and healthy living conditions for users, e.g., thermal, acoustic comfort.
- Freedom of association and collective bargaining e.g., employment is not conditioned by any restrictions on the right to collective bargaining.
- Health and Safety for workers, e.g., occupational accident rate.
- Living non poverty wages for workers, e.g., minimum wage/Non poverty wage by country.
- Local employment, e.g., share of local employers, share of seasonal workers.
- Local economic development, e.g., local added value, local business opportunities.

- Accessibility for all kind of users.
- Gentrification, e.g., increase in rents.
- Cultural heritage of building/district.
- Social responsibility, e.g., fair wages along the value chain, environmental standards, no conflict minerals.

4.4. Resilience Assessment

In the past decade, due to the increase in frequency and severity of some extreme events, such as drought, heatwaves, etc., resilience in buildings has become a growing topic in the current global discussion on climate change adaptation [11]. This calls for the consideration of the resilience concept in addition to the sustainability one in the context of buildings development or renovation. In fact, whereas the core idea of sustainability is to reduce negative impacts on the environment to avoid changes, resiliency is about adaptation to change [57]. Although greening practices and lowering pollutants are the primary concerns of sustainability, the emergence of resilience thinking due to increasing intensity and frequency of natural catastrophes, requires buildings to be not only sustainable but also resilient [10].

Generally, resilience can be defined as the ability to "anticipate, absorb, adapt to, and/or rapidly recover from a potential disruptive event" [58]. Furthermore, the resilience in the building sector focuses on the ability of the building under interest at maintaining a good quality of life when affected by a particular event (e.g., floods, heatwaves, blackout, etc.). In this context, resilience is assessed either by modelling a response of the building under interest against a specific event (e.g., electricity shortages [58], heatwaves [59], etc.) or by making use of specific frameworks. The latter could be categorized, on the one hand, as guidance documents (e.g., Strategies for Multifamily Building Resilience (ENTERPRISE) [60], etc.), in which guidance on identifying a building's exposure to hazards, assessing risks, and determining resilience strategies are provided, and on the other hand, as resiliency rating systems (e.g., Resilience Action List and Credit Catalog (RELi) [61], etc.), in which specific strategies are implemented to achieve a defined level of resiliency. Furthermore, while most of the frameworks in the literature are generalized to all building typologies (e.g., Resiliency Design Pilot Credits (LEED) [6], etc.), other are specific to, for example, commercial buildings (e.g., FORTIFIED Commercial [62]), single family residential buildings (e.g., FORTIFIED Home [62]), multifamily homes (e.g., B-READY [63], FORTIFIED Multifamily [64]).

To define a set of resilience criteria to be further analyzed during the Stakeholder Workshop, information about the most common hazards considered in different frameworks are collected. A total of 19 frameworks are analyzed, which shows that the frameworks range from being hazard-specific to have an all-hazard approach as summarized in Table 2.

Table 3 Frameworks for building construction/renovation considering resilience collected in this study. For each framework the analyzed hazards and the applied approach to analyzed them are presented

Framework	Description	Hazard	Approach
LEED	The LEED rating system is one of the most popular green building rating systems in the world. From 2015 pilot credits on resilience were adopted [6].	These tools considered a long list of hazards, such as: air and water quality, flooding, heatwaves, hurricanes,	All-Hazards
PEER	The PEER standards evaluate the performance of power systems in seven categories, including reliability and resilience [65].		

RELi	RELi is a resilient rating system providing certification for buildings, neighborhoods, homes, and infrastructure [61].	storms, hail, radon, blackout, noise, landslides, etc. Therefore, these frameworks make use of an all-hazard approach. For the full list of the considered hazard in these frameworks, please refers to the references.	
ENVISION	The ENVISION rating system is a framework of sustainability criteria for infrastructure projects. The objective of ENVISION is to improve the performance and resiliency of physical infrastructure [66].		
DGNB	The DGNB has developed a certification system which, as a planning and optimization tool, helps all those involved in construction to implement holistic sustainability quality. To be able to evaluate a sustainable construction method, various certification criteria, including resilience related criteria, are applied individually to different building types [8].		
B-READY	The B-READY building resilience assessment tool incorporates an assessment of local climatic hazards and a building's vulnerability and resilience to provide a resiliency index [63].		
BRLA	The BRLA primer for facilities in the Los Angeles area offers guidance for organizations and buildings to become more resilient [67].	Earthquakes, Drought, Wildfires, Flooding, Hurricanes, Storms, Heatwaves	Multiple Hazards
ENTERPRISE	ENTERPRISE provides guidance for existing multifamily buildings through several retrofit and mitigation strategies [60].	Flooding, Storms, Heatwaves	
USGBC	This guidance report highlights research on the projected impacts of climate change by region, and explores design, construction, and operation strategies that improve a building's resilience [68].	Drought, Wildfires, Flooding, Hurricanes, Storms, Heatwaves	
NIST	The NIST guide is subdivided in two volumes: volume 1 illustrates a process for planning resilience; volume 2 provides tools to characterize the social and built community and identify dependencies, and highlights examples of community resilience metrics [69], [70].	Earthquakes, Flooding, Storms	
NYSERDA	The NYSERDA document provides guidance to owners and operators, policymakers and planners, and architects and engineers on how to prepare buildings for the expected impacts of climate change in New York State [71].	Water quality, Air quality, Pest Infestation, Rising Sea Level, Flooding, Hurricanes,	

		Storms, Heatwaves	
BOSTON	This guide for large buildings and institutions examined the resilience of commercial buildings in Boston [72].	Pest Infestation, Rising Sea Level, Storms, Heatwaves	
NYC	Guidelines to incorporate forward-looking climate data in the design of infrastructure and buildings in New York City [73].	Pest Infestation, Rising Sea Level, Storms, Heatwaves	
REDi	A three-level earthquake related resilience rating system for buildings [74].	Earthquakes	Hazard Specific
FORTIFIED Residential (Hurricanes)	Recommendations for reducing damage caused by specific natural hazards for existing and new buildings, either residential or commercial [62], [64], [75].	Hurricanes	
FORTIFIED Residential (High Wind)		High Wind	
FORTIFIED Residential (High Wind & Hail)		High Wind & Hail	
FORTIFIED Multifamily (Hurricanes)		Hurricanes	
FORTIFIED Multifamily (High Wind)		High Wind	
FORTIFIED Multifamily (High Wind & Hail)		High Wind & Hail	
FORTIFIED Commercial (Hurricanes)		Hurricanes	
FORTIFIED Commercial (High Wind & Hail)		High Wind & Hail	

From the frameworks in Table 2, a set of resilience criteria is collected. Furthermore, the set is defined by considering the Swiss case scenario only, since RENOWAVE is applied to the decarbonization of the Swiss building sector. Therefore, hazards like, for example, Hurricanes, were not selected in the development phase of the criteria set. Based on these premises, the final list of the selected criteria for resilience are the followings:

- Power Outage / Blackout
- Heatwave
- Coldwave
- Earthquake
- Avalanche
- Storm
- Flood

- Heavy Rain
- Hail
- Landslide/Subsidence
- Wildfire
- Air quality
- Water quality
- Outdoor noise
- Radon

The list considered (i) common hazards, e.g., Earthquakes; (ii) climate change related hazards, e.g., heatwaves; (iii) quality level related hazards, e.g., Air quality; (iv) specific Swiss hazards, e.g., Radon. Therefore, the list can be considered complete and comprehensive for the Swiss case scenario, like, for example, the DGNB list of hazards for Germany [8].

4.5. Selected Criteria for the Tool

The extensive literature review described in sections 4.1-4.4 produced a set of several criteria for each of the considered domains. Since many criteria, including their sub-criteria, on a MCDA can have a negative effect on the understanding the problem as well as the final ranking of the alternatives due to the large ramification of the domain structure [76], a stakeholder workshop has been setup. The aim of the workshop was to allow experts to select a reasonable number of criteria (3-5) for each considered domain to be included in the renovation tool. During the workshop the experts selected the most reasonable criteria, which could of interest during the renovation of a building. The experts participating at the workshop were a mix of academic project partners (e.g., UniGe, ZHAW IFM, HSLU), implementation partners (e.g., City of Winterthur), associations (e.g., SGNI) and industry (e.g., Intep GmbH, Implenia AG) for a total of 8 experts. The heterogeneous knowledge of the selected experts allowed to get a broader view on the potential criteria of interest to be included in the tool. After the workshop, the long list of criteria for each domain is reduced to a total of 16 criteria subdivided as shown in Table 3.

Table 4 Domains and related criteria for the renovation tool

Domains	Criteria
eLCA	Global Warming Potential
	Cumulative Energy Demand
	Land and water (ecosystem) impacts
	Atmospheric impacts (ozone)
	Abiotic Depletion Potential
LCC	Total Life Cycle Cost
	Total Life Cycle Revenues
sLCA	Save and healthy living conditions for users
	Accessibility for all kind of users
	Contribution to local economic development
	Cultural heritage of building/district
	Promoting social responsibility
RA	Floods
	Heavy Rain/Hail
	Heat- & Cold-waves
	Blackout / Energy Shortages

The criteria in Table 3 are going to be implemented in the renovation tool under construction. Furthermore, for each selected criteria (5 for eLCA and sLCA, 4 for RA and 2 for LCC) a set of subcriteria have been defined to be able to measure them. The selection of the subcriteria is presented in section 5.

5. Subcriteria selection

The first step in the construction of the LSCA framework continued with the selection of the subcriteria, which measured the criteria selected by the experts (Table 3). For each of the domains and criteria considered in this study, a set of subcriteria are defined based on an extensive literature review and a refining process (i.e., only subcriteria meaningful to the building renovation process are considered). A total of 56 subcriteria are finally selected in accordance with the group of 8 experts invited for the 1st Stakeholder Workshop (section 4.5) to a 2nd Workshop in which they have been invited to weight the criteria and subcriteria for the tool under development (section 6). In this section, the process for the selection of the set of subcriteria for each criteria is presented for each of the considered domains, i.e., eLCA (section 5.1), LCC (section 5.2), sLCA (section 5.3) and RA (section 5.4).

5.1. Environmental Life Cycle Assessment (eLCA)

As shown in Table 4, eLCA is described by 5 criteria each of which are measured by 1-3 indicators. The respective subcriteria are presented and explained in detail in sections 5.1.1 - 5.1.5.

Most of the criteria for eLCA will be taken from Life Cycle Impact Assessment (LCIA) methodologies *CML-IA baseline* and *CML-IA non-baseline* for further calculation of the selected renovation measures [77]–[79]. As reference system for both *CML-IA* methodologies *EU25 +3* has been selected, which represents the 25 countries of the European Union in 2006 including Iceland, Norway and Switzerland [78]. This European system will be further referred to as EU_{25+3} Solely, the cumulative energy demand (CED) will be based on the LCIA methodology *Cumulative Energy Demand 1.11* and the Global Warming Potential (GWP) on the LCIA methodology *IPCC 2021 GWP 100a* [80], [81].

5.1.1. Global Warming Potential (GWP)

The Global Warming Potential will be calculated according to the life cycle impact assessment (LCIA) methodology *IPCC 2021 GWP 100a* [81]. The latest version of the methodology includes three subcriteria, which are focusing on different sources of the accounted CO_2-eq emissions (see Table 5).

Table 5 Subcriteria for Global Warming Potential to be included in the tool under development.

Subcriteria	Description
GWP100-fossil (CO_2-eq.)	CO_2 emissions from fossil sources, such as fossil fuels. e.g., fossil methane.
GWP100-biogenic (CO_2-eq.)	CO_2 emissions from biogenic sources such as wood, paper, grass trimmings, and other biofuels
GWP100-land transformation (CO_2-eq.)	CO_2 emissions from land transformation such as deforestation.

5.1.2. Cumulative Energy Demand (CED)

The CED will be calculated according to the LCIA methodology *Cumulative Energy Demand 1.11* [80]. The two subcriteria included are *non-renewable* and *renewable CED* (presented in Table 6), which are both based on different cumulated energy sources.

Table 6 Subcriteria for Cumulative Energy Demand (CED) to be included in the tool under development.

Subcriteria	Description

Non-renewable CED (MJ)	Accumulated energy demand along whole life cycle from non-renewable sources (fossil, nuclear and non-renewable biomass)
Renewable CED (MJ)	Accumulated energy demand along whole life cycle from renewable sources (wind, solar, geothermal, water, renewable biomass)

5.1.3. Land and water (ecosystem) impacts

Land and water (ecosystem) impacts are included to pay attention to the pressure on biodiversity according to the concept of the planetary boundaries ([82]). These impacts are based on two subcriteria, which are midpoint indicators of the LCIA methodology *CML-IA baseline* [77]–[79]. Both indicators are also proposed by the DGNB to be included in LCA for buildings [83]. These subcriteria are presented in Table 7.

Table 7 Subcriteria for Land and water (ecosystem) impacts to be included in the tool under development.

Subcriteria	Description
Acidification (AP) (kg SO_2 eq)	Acidic gases such as Sulphur dioxide (SO_2) react with water in the atmosphere, leading to the formation of “acid rain”, which can cause damage to the ecosystem.
Eutrophication (EP) (kg PO_{4^-}- eq.)	Certain levels of nitrates and/or phosphates in water can eventually lead to damage of ecosystems.

5.1.4. Atmospheric impacts (ozone)

The subcriteria of the criterion atmospheric impacts describe the environmental pressures resulting from stratospheric ozone depletion and photochemical ozone creation close to ground (see Table 8), which are also midpoint indicators of the LCIA methodology *CML-IA baseline* [77]–[79].

Table 8 Subcriteria for Atmospheric impacts (ozone) to be included in the tool under development.

Subcriteria	Description
Stratospheric Ozone Depletion Potential (ODP) (kg CFC-11 eq.)	Ozone-depleting gases (e.g., CFCs, HCFCs and halons) cause damage to the ozone layer.
Photochemical Ozone Creation Potential (POCP) (kg C_2H_4-eq.)	Nitrogen oxides (NOx) and volatile organic compounds (VOCs) can form ozone and other air pollutants in low level of the atmosphere, causing smog.

5.1.5. Abiotic Depletion Potential (ADP)

The criterion ADP does not include any subcriteria (see Table 9). It is included as it is also part of the proposed criteria for LCA of the DGNB [8] and is also taken for calculation from the midpoint indicators of the LCIA methodology *CML-IA baseline* [77]–[79].

Table 9 Subcriteria for Abiotic Depletion Potential to be included in the tool under development.

Subcriteria	Description
Abiotic depletion, elements (kg Sb-eq.)	This covers the use of scarce non-renewable resources, including scarce chemical elements (ADPE).

5.1.6. Additional indicators eLCA

According to the voting of the expert group two additional indicators will be included in the LCSA tool, but not in the LCSA and the MCDA as it would lead to a double counting. Nevertheless, the stakeholders voted for them as they are of particular interest and should be represented in the LCSA tool.

1. **Energy Payback Time (a)** describes the time, which is needed to get the cumulated energy invested in a renovation measure during the production and installation back during its lifetime – be it by energy production (e.g., with photovoltaics) or energy savings. It is a measure for the amortization of energy of a renovation measure.
2. **Ecological Scarcity (UBP)** describes the overall environmental impact based on a LCIA methodology, which refers to Swiss regulatory goals and target limits regarding environmental pressures and emissions into the environment [37].

5.2. Life Cycle Cost (LCC)

As shown in Table 4, LCC is described by two criteria: *Total Life Cycle Costs* and *Total Life Cycle Revenues,* which reflect mainly the overall life-cycle costs. Both criteria are measured by 4-5 subcriteria (see Table 10 and Table 11). The stakeholder voted on two additional indicators, which are included in the LCSA tool, but not the in the LCSA itself and in the MCDA due to avoiding double-counting.

5.2.1. Total Life Cycle Cost (TLCC)

The TLCC are subdivided in market and non-market costs as shown in Table 2. Market costs are represented by the subcriteria *CAPEX* and *OPEX*, non-market costs by *CO_2 fee*, *disposal fee* and *taxes*. The detailed description of each is shown in Table 10.

Table 10 Subcriteria for Total Life Cycle Cost to be included in the tool under development.

Subcriteria	Description
CAPEX	Initial costs, including material and construction costs etc.
OPEX	Operational costs, including maintenance, energy, repair, disposal etc.
CO_2 fee	Fee on fossil fuels.
Disposal fee	Fee for disposal in incineration or landfill.
Taxes	Imputed rental value, wealth tax, property tax

5.2.2. Total Life Cycle Revenues (TLCR)

The TLCR are also subdivided in market and non-market revenues as shown in Table 2. Market revenues are represented by the subcriteria *Material sales*, *Energy sales* and *Rental Income*, non-market revenues by *Subsidies.* The detailed description of each is shown in Table 11.

Table 11 Subcriteria for Total Life Cycle Revenues to be included in the tool under development.

Subcriteria	Description
Material sales	Material sales from recycling and reuse at the end-of life or during maintenance
Energy sales	Feed-in-tariff from e.g., PV
Rental income	Income from renting the property and/or apartments
Subsidies	Communal, cantonal or federal subsidies for renovation measures.

5.2.3. Additional Indicators LCC

Similar to eLCA the expert group voted on two additional indicators, which will be included in the LCSA tool, but not in the LCSA and the MCDA as it would lead to a double counting. Nevertheless, the stakeholders voted for them as they are of particular interest for example for investors and should be represented in the LCSA tool.

1. **Net Present Value (NPV)** is a financial metric used to evaluate the profitability of an investment or project such as future renovation measures. It calculates the difference between the present value of cash inflows and the present value of cash outflows over a period of time. NPV takes into account the time value of money by discounting future cash flows to their present value

using a specified rate of return. A positive NPV indicates that the investment is expected to be profitable, while a negative NPV suggests it may result in a loss. NPV is widely used in capital budgeting and investment analysis to compare different investment opportunities and make informed financial decisions.

2. **Internal Rate of Return (IRR)** is a financial metric used to estimate the profitability of potential investments. It is the discount rate that makes the net present value (NPV) of all cash flows from a particular project equal to zero. In other words, IRR is the rate at which an investment breaks even. Investors use IRR to compare different projects or investments, typically favoring those with higher IRRs. It's particularly useful in capital budgeting and energy efficiency projects, where it can help determine if an investment will yield a positive return. However, IRR should be used alongside other metrics like NPV for a comprehensive investment analysis, as it has limitations in certain scenarios.

2.1. Social-Life Cycle Assessment (sLCA)

As shown in Table 4, sLCA is described by 5 criteria each of which are measured by different indicators.

2.1.1. Save and healthy living conditions for users

This criterion is dealing with the users and thus in the operations phase of the building. There are of course many other subcriteria for measuring save and healthy living conditions, but those are the ones (Table 12), that are important factors for human health as well as potentially affected by refurbishment measures. The possibility for users is measured with a semi-quantitative scale describing the subcriteria on different extents. The first two sub-criteria are defined as well on a scale from 0- 3 but describing the extent based on quantitative levels.

Table 12 Subcriteria for Save and healthy living conditions for users to be included in the tool under development.

Subcriteria	Description
Acoustic/thermal comfort	Thermal comfort regarding indoor temperature: stable and convenient temperature
Indoor air quality: VOC concentration	Through the correct choice of materials, harmful emissions (e.g., VOC) from installed materials can be avoided.
Possibility for users to exert influence	Possibility to set temperature on its own and room-by-room (important for living condition satisfaction)

2.1.2. Accessibility of all kinds of users

This criterion is measured by only one sub-criteria (Table 12). To foster the inclusion of all possible users we consciously don't want to measure the criteria based on different kinds of users. The sub-criterion is measured with a semi-quantitative scale describing the extent of an accessibility concept.

Table 13 Subcriteria for Accessibility of all kinds of users to be included in the tool under development.

Subcriteria	Description
Accessibility of the building for all user groups	Accessibility of the building for all user groups (people with motor, sensory and cognitive impairments, language barriers) regarding physical infrastructures, but also concerning signaling in/around the building

2.1.3. Contribution to local economic development

This criterion is measured by two sub-criteria: the commercial use of the ground is measuring the impact in the operational phase and the contribution to local value creation is addressing the construction phase (Table 13). Both criteria are measured with a semi-quantitative scale describing the subcriteria on different extents.

Table 14 Subcriteria for Contribution to local economic development to be included in the tool under development.

Subcriteria	Description
Commercial use of the ground	Economic use of the ground floor to induce local value creation as well as a lively neighborhood
Contribution to local value creation	Induced contribution to local development by considering local companies for the renovation process

2.1.4. Cultural heritage of building/district

To include the cultural value and the contribution to community building in the neighborhood, two subcriteria are defined (Table 14). Both criteria refer to the operation phase and are measured with a semi-quantitative scale describing the subcriteria on different extents. Especially the external appearance is also a very important criteria for the social acceptance in the local community of a refurbished building or district.

Table 15 Subcriteria for Cultural heritage of building/district to be included in the tool under development.

Subcriteria	Description
External appearance and image/spreading effect in the neighborhood	Appearance of building is fitting into the characteristic of the neighborhood and has an identity-forming effect
Possibilities for traditional, social activities (e.g., neighborhood festivals) in the buildings/ settlements	Flexible, common spaces need to be available to allow for community building activities in the neighborhood (common indoor and outdoor spaces, infrastructure for cooking and festivities)

2.1.5. Promoting social responsibility

To account for the resource extraction and construction phase also on a global scale the criteria promotion of social responsibility along the value chain is included. As it would be too much of an effort at the decision-making stage to analyze several possible impacts on the potentially long value chain in foreign countries of the different materials needed in the renovation process, two process subcriteria were defined, one about fair wages, the other about environmental standards in the value chain (Table 15). Respecting environmental standards are crucial for the health and the economic opportunities in the producing countries, that's why this is addressed in the social aspects. The environmental impacts of the renovation measures are of course assessed comprehensively in the eLCA part of the tool, but those measurements often rely on generic data and cannot account for specific situations in the respective companies. That is why this process criterion is important to incorporate at some point. Both are measured with a semi-quantitative scale describing the subcriteria on different extents.

Table 16 Subcriteria for Promoting Social Responsibility to be included in the tool under development.

Subcriteria	Description
Fair wages in the value chain	Defining criteria for faire wages (corresponding to national/international recommendations), child labor and forced labor in tender documents for all products

	and services used along the lifecycle of the renovation process
Environmental standards in the value chain	Defining environmental standards in the tender documents as for example regarding reduction of harmful emissions and odors of building components, compliance with local environmental laws

2.2. Resilience Assessment (RA)

As shown in Table 3, RA has 4 criteria each of which are measured by different subcriteria. In the resilience context, the subcriteria belongs to different phases of the system performance under interest (e.g., internal building temperature). These phases are generally known as resilience dimensions, functions, abilities, capacities, etc. and are used to capture the resilience curve (Figure 2) full complexity and transform resilience into a measurable concept. Where the resilience curve described the performance (e.g., internal building temperature) of the system under interest (e.g., a multifamily house) during and after a particular event (e.g., heatwave) [59]. In general, these dimensions are not fixed, therefore, different scholars defined them depending on the final aim of their study [10], [11], [57], [84], [85]. Based on an extensive literature review, a set of most common dimensions used in the building context can be defined as shown in Figure 2.

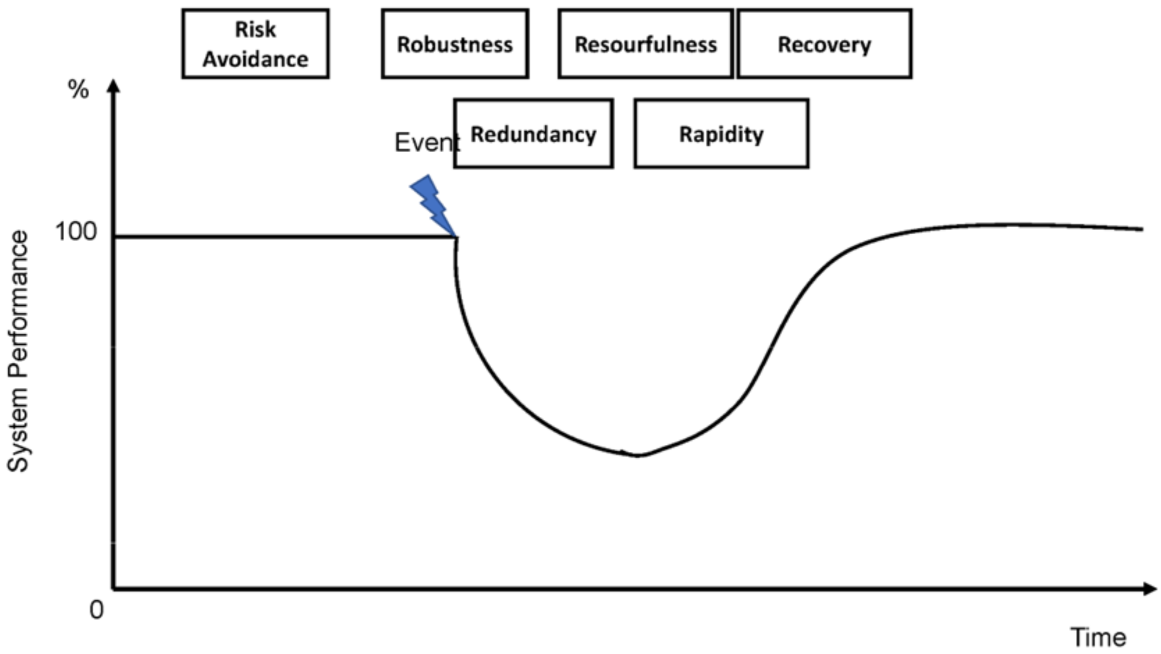

Figure 3 Most common resilience dimensions describing the behavior of the system performance along the resilience curve used in the building context.

The resilience performance of a system due to an event can be generally measured by assessing each of the 6 dimensions shown in Figure 2:

- *Risk Avoidance*, which refers to the risk identification and mitigation strategies to be applied to new buildings [86].
- *Robustness*, which is the ability to withstand an impact that effects the overall severity of an event [70].

- *Redundancy*, which refers to having backup or failsafe technologies/strategies in place as an alternative means of maintaining functionality and/or accessing critical resources [85].
- *Resourfulness*, which refers to have resources readily available in times of need, and the ability to prepare for and anticipate an event by reorganizing and implementing resources as needed [85].
- *Rapidity*, which is the speed with which disruption can be overcome and safety, services, and financial stability restored [70].
- *Recovery*, which is the ability to bounce-back (i.e., return to normalcy) or forward (i.e., improve beyond normalcy) following a sudden shock/stress that alters typical performance, and the rate at which this process occurs [85].

However, by focusing on the different dimensions, it resulted clear that most of those could be merged to reduce the number and, therefore, to avoid the spread of information along too many branches of the hierarchical structure of the framework under development. Based on these premises, in this study, 3 dimensions are defined based on the combination of the different abovementioned dimensions for the description of resilience (Figure 3):

- pre-event measures, which are generally based on risk management against disruptions (e.g., floods). This dimension is based on the solely *Risk Avoidance* above.
- a phase named "absorb", where the building has measures in place (e.g., electricity backup) to reduce the effect of a disruption (e.g., blackout). This dimension is defined by subcriteria that belongs to the Robustness and Redundancy dimensions above.
- the recovery phase from the disruption. This dimension is defined by subcriteria that belongs to the Resourfulness, Rapidity and Recovery dimensions above.

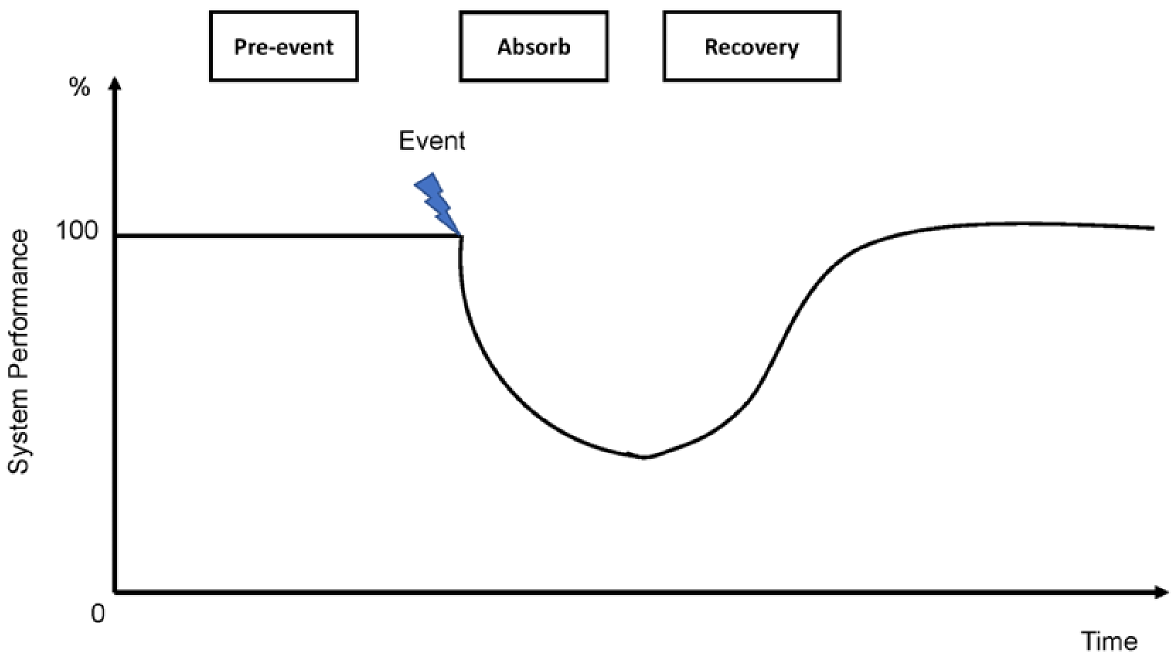

Figure 4 Resilience dimensions defined in this study.

Furthermore, since the tool under development aims at assessing the most reasonable renovation measures for a multifamily house, the pre-event measures are not considered in the RENOWAVE context. In fact, these measures do not depend upon the renovation or not of the building under interest since the building is already in place. Therefore, only subcriteria meaningful for the renovation process and measuring the “Absorb” and the “*Recovery*” phases are collected for each of the resilience criteria (Table 3).

2.2.1. Floods

For Floods, a preliminary set of 13 subcriteria subdivided between pre-event (2 subcriteria), absorb (6 subcriteria) and recovery (5 subcriteria) resilience domains are identified and collected from an extensive literature review [87]–[90]. According to section 5.4, only the subcriteria meaningful for the renovation process are considered in this study. Therefore, based on this premise and the acceptance of the subcriteria by the experts during the 2nd Stakeholder Workshop, the final set of subcriteria for Floods to be included in the tool are summarized in Table 16.

Table 17 Subcriteria for Floods to be included in the tool under development.

Resilience Domain	Subcriteria	Description
Absorb	Plinth Level	The plinth level is the height of the house with respect to the adjacent road. A high plinth level reduces the flood depth and, therefore, the water pressure.
	Drainage	Adequate drainage availability with appropriate slope force water to drain out, which cause less damage to the infrastructure and reduced the depth of the flood water
	Floor Covering	Depending on the type of material covering the floor, it can increase resistance to floods. For example, cork is a non-water-resistant material, while natural stone (e.g., granite, dolomite) is
	Wall Material	Depending on the type of material composing the wall, it can increase resistance to the floodwater. For example, wood is a non-water-resistant material, while concrete is
	Wall Thickness	The thickness of the wall indicates the resistance of the wall to the flood water pressure. For example, a thicker wall can resist more floodwater pressure as compared to a thinner wall
Recovery	Resource Availability	The availability of the construction material will affect the recovery of the structure
	Personal in Place	The availability of construction personal will affect the recovery of the structure

2.2.2. Heavy Rain/Hail

For Heavy Rain/Hail, a preliminary set of 11 subcriteria subdivided between pre-event (2 subcriteria), absorb (5 subcriteria) and recovery (4 subcriteria) resilience domains are identified and collected from an extensive literature review [91]–[93]. According to section 5.4, only the subcriteria meaningful for the renovation process are considered in this study. Therefore, based on this premise and the acceptance of the subcriteria by the experts during the 2nd Stakeholder Workshop, the final set of subcriteria for Heavy Rain/Hail to be included in the tool are summarized in Table 17.

Table 18 Subcriteria for Heavy Rain/Hail to be included in the tool under development.

Resilience Domain	Subcriteria	Description
Absorb	Doors Material	Depending on the type of material composing the doors, it can increase resistance to rain and hail. For example, wood is a non-water-resistant material, while galvanized steel is

	Wall Material	Depending on the type of material composing the wall, it can increase resistance to rain and hail. For example, wood is a non-water-resistant material, while concrete is
	Floor Covering	Depending on the type of material covering the floor, it can increase resistance to rain and hail. For example, cork is a non-water-resistant material, while natural stone (e.g., granite, dolomite) is
	Windows Type	Depending on the type of windows, they can have a different level of resistance to heavy rain and hail. For example, a window which has the outer glass tempered or covered with an additional film will have a higher resistance to hail compared to a window without one of them
Recovery	Resource Availability	The availability of the construction material will affect the recovery of the structure
	Personal in Place	The availability of construction personal will affect the recovery of the structure

2.2.3. Heat- & Coldwaves

For Heat- & Coldwaves, a preliminary set of 8 subcriteria subdivided between pre-event (1 subcriteria), absorb (5 subcriteria) and recovery (2 subcriteria) resilience domains are identified and collected from an extensive literature review [59], [94]–[98]. According to section 5.4, only the subcriteria meaningful for the renovation process are considered in this study. Therefore, based on this premise and the acceptance of the subcriteria by the experts during the 2nd Stakeholder Workshop, the final set of subcriteria for Heat- & Coldwaves to be included in the tool are summarized in Table 18.

Table 19 Subcriteria for Heat- & Coldwaves to be included in the tool under development.

Resilience Domain	Subcriteria	Description
Absorb	Thermally Active Building System	A thermally activated building system will influence how both heat- & coldwaves could affect the temperature inside the building
	Thermally Loadable Air Supply Systems	The presence of a thermally loadable air supply system will influence both heat- and coldwaves that affect the building. For example, during a heatwave/coldwave and in presence of a loadable air supply system, the internal temperature of the building could be kept within a livable temperature
	Wall Thickness	The thickness of the wall will influence how both heat- & coldwaves could affect the temperature inside the building. A thicker wall can resist more to both heat- & coldwaves compared to a thinner wall
	Wall Material	Depending on the material composing the walls, this will influence how both heat- & coldwaves could affect the temperature inside a building.
	Insulation and Lightsurface (Albedo)	The presence of a good insulation and/or a light surface will influence how both heat- & coldwaves could affect the temperature inside a building. A good insulation will help the building to keep the temperature within a livable range
Recovery	Expected Adverse Thermal Conditions	The expected number of days under adverse thermal conditions will inform about the potential recovery time of the building

2.2.4. Blackout / Energy Shortages

For Blackout/Energy Shortages, a preliminary set of 10 subcriteria subdivided between pre-event (2 subcriteria), absorb (6 subcriteria) and recovery (2 subcriteria) resilience domains are identified and collected from an extensive literature review [99]–[102]. According to section 5.4, only the subcriteria meaningful for the renovation process are considered in this study. Therefore, based on this premise and the acceptance of the subcriteria by the experts during the 2nd Stakeholder Workshop, the final set of subcriteria for Blackout/Energy Shortages to be included in the tool are summarized in Table 19.

Table 20 Subcriteria for Blackout/Energy Shortages to be included in the tool under development.

Resilience Domain	Subcriteria	Description
Absorb	Electricity Autarchy level	A high electricity autarchy level will reduce the effect of a blackout/energy shortage. For example, a building with an 80% autarchy level reached using a combination of PV and battery systems will be less affected by a blackout compared to a building fully dependent to the electricity distribution network
	Backup for electricity	The presence of an electricity backup (e.g., a diesel engine or a combination PV + battery) will reduce the effect of a blackout/energy shortage
	Backup for water	The presence of a water backup (e.g., a water tank) will reduce the effect of a blackout/energy shortage on the water supply
	Backup for heating	The presence of a heat backup (e.g., wood or pellet stove) will reduce the effect of a blackout/energy shortage on the heating supply
	Wall Thickness	The thickness of the wall will influence the temperature inside the building during a blackout. A thicker wall can keep the temperature within a livable range for a longer time compared to a thinner wall
	Wall Material	Depending on the material composing the walls, this will influence the temperature inside a building during blackout/energy shortage
	Insulation and Lightsurface (Albedo)	The presence of a good insulation and/or a light surface will influence the temperature inside a building. A good insulation will help the building to keep the temperature within a livable range during a blackout/energy shortage
Recovery	Expected Blackout Shortage	The expected number of days for a blackout will inform about the potential recovery time of the building

3. Criteria and Subcriteria Weighting

In sections 4 and 5, the criteria and subcriteria considered in this study are presented. Based on these inputs, the structure of the framework can be defined as shown in Figure 4.

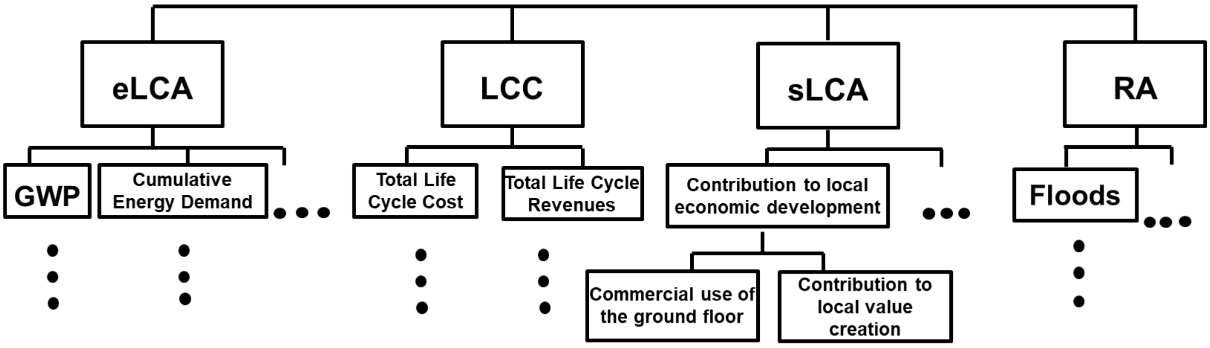

Figure 5 Hierarchical structure of the proposed framework.

As expected, the framework is represented by a hierarchical structure with at the 1st level the domains under interest (eLCA, LCC, sLCA, RA), at the second level the selected criteria (section 4.5) and at the third level the subcriteria (indicators), which are going to quantify the criteria and, therefore, the domains. Important to note that for RA the resilience domains (Absorb and Recovery) are not considered in the structure of the tool to avoid an asymmetrical hierarchical structure with respect to the other domains (eLCA, LCC, sLCA), which is not allowed in MCDA [103].

As described in section 3 point 8 the defined domains, criteria and sub-criteria need to be weighted. The weighting is an important aspect in MCDA since it allows the stakeholders to give their preferences to the criteria under interest. Furthermore, it allows, considering different stakeholder weighting profiles, to assess the sensitivity of the MCDA results, which shows how MCDA does not provide a unique result, but rather a set of results that need to be discuss in a participative process [104]. In the tool under development two weighting profile options are expected:

1) Equal weights, i.e., all the criteria and sub-criteria have an equal weight. However, in this case the user will be allowed to modify the weights at the domains, criteria and sub-criteria levels based on their interests.
2) Expert weights, i.e., the user is allowed to weight only the 1st level of the hierarchy, which is the domains level, while the criteria and sub-criteria levels are provided by experts.

Based on these premises, a second stakeholder workshop involving the 8 experts presented in section 4.5 has been set up. The aim of the workshop was to assess the preferences for the criteria and sub-criteria described in sections 4 and 5, since the domains level is considered equally weighted (see 2)) as a default, but this could be modified later by the users based on their specific interests.

In the workshop each expert is requested to give their preferences (on a scale from 0 to 10) to each criterion and sub-criteria. During this process, the experts could give also equal preferences to some of the criteria if they considered some of them as equally important. Furthermore, the preferences were given following a step-by-step approach. For each domain, first the experts gave their preferences to the criteria as shown, for example, in Figure 5.

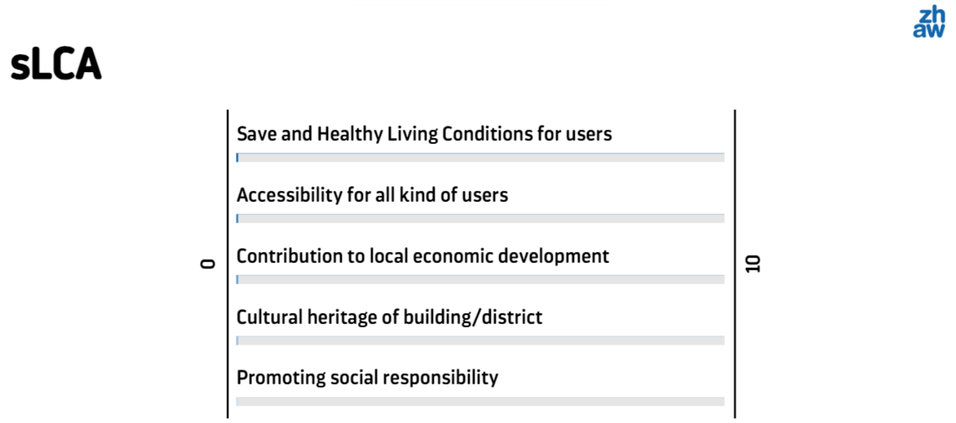

Figure 6 Example page where the experts gave their preferences to each criterion of the sLCA domain.

Once the preferences were given by all experts at the criteria level, the preference selection could move forward. In the latter, for each criterion, the experts assess their preferences for the subcriteria under interests as shown, for example, in Figure 6.

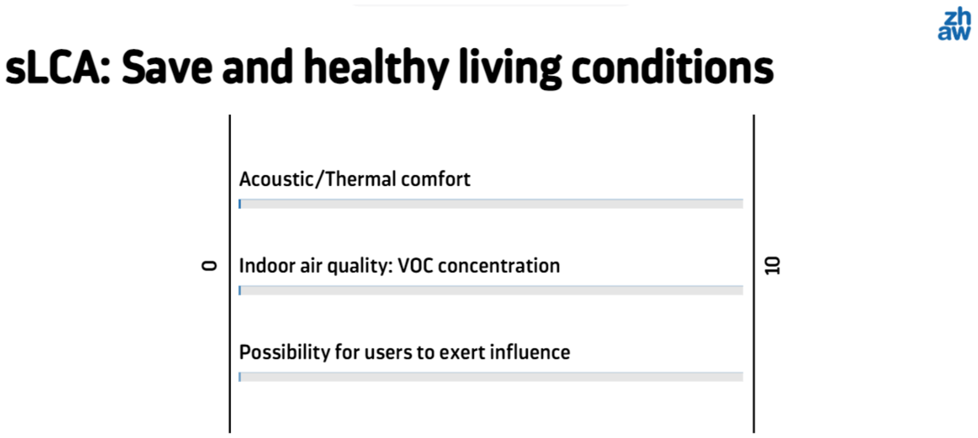

Figure 7 Example page where the experts gave their preferences to each subcriteria of the *Save and healthy living conditions* criteria of the sLCA domain.

Once the preferences were given by each expert to each criterion and subcriteria of the hierarchical structure in Figure 6, the weights could be estimated. Since only a common expert weighting profile should be generated for the tool as default preference profile, to assess it from the preferences, the following steps are considered:

1) Each expert could have his own vision in giving preferences. In fact, while some made use of the full scale from 0 - 10, some others were more positive limiting worst preferences, i.e., ranging their preferences from 3 - 10, or more demanding limiting good preferences, i.e., ranging their preferences from 0 - 8. Therefore, to assess the weights, first the preference scales of all experts should be comparable to be able to aggregate them. To do this, the minimum and maximum preference for each expert along all criteria and sub-criteria are estimated. Afterwards, for each expert, a min-max normalization of each criteria/subcriteria preference (x) is assessed [105]:

$$\frac{x - \min(x)}{\max(x) - \min(x)} \quad (1)$$

Furthermore, during the normalization process, the resulting preferences are estimated in % since the new considered common scale among all experts is from 0 – 100%. In fact, by using the min-max normalization the scales of all criteria/subcriteria for each expert are 0 - 100% rather than 0 - 10, 3 - 10, 0 - 8, etc. letting the preferences be comparable.

2) Once the preferences of all criteria/subcriteria for each expert has been assessed, the unique expert's preference profile can be built. To do this, for each criteria/subcriteria the trimmed average among each expert preference is estimated. In fact, the trimmed (5 - 95% percentile) average is used to avoid effects related to extreme preferences (either positive or negative) on the mean value.

Based on these premises, the final expert weighting profile is presented in Table 20. In the eLCA case, the most weighted criteria are, as expected, the *Global Warming Potential* (with the *GWP100-fossil* subcriteria being the most weighted) followed by the *Cumulative Energy Demand* (with the *Non-Renewable CED* subcriteria being the most weighted), while the *Abiotic Depletion Potential*, which is described by a unique subcriteria and therefore, not being considered in the preference selection by the experts, results the worst. For LCC the *Total Costs* have a larger preference with respect to the *Total Revenues*, with *CAPEX/OPEX* and *Rental Income/Energy sales* being the most preferred subcriteria, respectively. For sLCA the *Save and healthy living conditions for users'* criteria has higher weight, while the *Contribution to local economic development* having the lowest. In these cases, the most prominent subcriteria are the *Acoustic/thermal comfort* and the *Contribution to local value creatio*n for the *Save and healthy living conditions for users* and the *Contribution to local economic development criteria*, respectively. Finally, for RA the most weighted criteria is the *Heat- & Coldwaves*, which is somehow expected due to the potential increase of such extreme events in the future [59]. On the other hand, the lowest weight criterion is found for Blackouts. At the subcriteria level, the highest weights are given to *Thermally Active Building System* and *Electricity Autarchy level* for the *Heat- & Coldwaves* and *Blackouts criteria*, respectively.

As shown in Table 20, the complex hierarchical structure and the number of expertise needed, explain the necessity for different options in the tool. Depending on the user and its expertise, the tool will allow to make use of the weighted profile given by the experts, with the possibility to modify the weights at the domains level; an equal weight profile, where the user is allowed to modify the weights at all levels of the hierarchy. This will allow the tool to be fully transparent and the user to understand the results based on his/her preferences and their comparison to experts and to a base case (equal weights) weighting profiles.

Table 21 Hierarchical Structure of the LSCA-F and relative expert related weight profile defined in this study.

1st Level	**2nd Level**		**3rd Level**	
Domain	**Criteria**	**Weight [%]**	**Sub-criteria**	**Weight [%]**
eLCA	Global Warming Potential	24%	GWP100-fossil (CO_2-eq.)	39%
			GWP100-biogenic (CO_2-eq.)	32%
			GWP100-land transformation (CO_2-eq.)	29%
	Cumulative Energy Demand	22%	Non-renewable CED (MJ)	54%
			Renewable CED (MJ)	46%

	Land and water (ecosystem) impacts	20%	Acidification (AP) (kg SO2 eq)	54%
			Eutrophication (EP) (kg PO4-- eq.)	46%
	Atmospheric impacts (ozone)	18%	Stratospheric Ozone Depletion Potential (ODP) (kg CFC-11 eq)	51%
			Photochemical Ozone Creation Potential (POCP) (kg NMVOC)	49%
	Abiotic Depletion Potential	16%	Abiotic depletion, elements (kg Sb-eq.)	100%
LCC	Total Life Cycle Cost	57%	CAPEX	24%
			OPEX	24%
			CO_2 fee	20%
			Disposal fee	18%
			Taxes	15%
	Total Life Cycle Revenues	43%	Material sales	23%
			Energy sales	25%
			Rental income	30%
			Subsidies	22%
sLCA	Save and healthy living conditions for users	29%	Acoustic/thermal comfort	36%
			Indoor air quality: VOC concentration	36%
			Possibility for users to exert influence	28%
	Accessibility for all kind of users	20%	Accessibility of the building for all user groups	100%
	Contribution to local economic development	15%	Commercial use of the ground floor	46%
			Contribution to local value creation	54%
	Cultural heritage of building/district	17%	External appearance and image/spreading effect in the neighborhood	45%
			Possibilities for traditional, social activities (e.g., neighborhood festivals) in the buildings / settlements	55%
	Promoting social responsibility	19%	Fair wages in the value chain	49%
			Environmental standards in the value chain	51%
RA	Floods	23%	Plinth Level	19%
			Drainage	18%
			Floor Covering	16%
			Wall Material	15%

			Wall Thickness	11%
			Resource Availability	10%
			Personal in Place	11%
	Heavy Rain / Hail	25%	Doors Material	10%
			Wall Material	19%
			Floor Covering	13%
			Windows Type	17%
			Resource Availability	17%
			Personal in Place	12%
	Heat- & Coldwaves	29%	Thermally Active Building System	20%
			Thermally Loadable Air Supply Systems	15%
			Wall Thickness	19%
			Wall Material	18%
			Insulation and Lightsurface (Albedo)	17%
			Expected Adverse Thermal Conditions (days)	11%
	Blackout / Energy Shortages	22%	Electricity Autarchy level	17%
			Backup for electricity	16%
			Backup for water	14%
			Backup for heating	11%
			Wall Thickness	8%
			Wall Material	7%
			Insulation and Lightsurface (Albedo)	7%
			Expected Blackout Shortage (Days)	10%

4. MCDA method selection

In the last decade a plethora of MCDA methods have been proposed [21]. However, with the proliferation of methods, it can be challenging for an analyst to select the appropriate method for the problem under consideration. The consequences of choosing an inappropriate approach among the plethora of available methods are significant, leading to the neglect of some critical aspects of the problem, unwanted trade-offs, and ultimately a recommendation that does not match the actual characteristics of the problem and the preferences of the stakeholders involved. Furthermore, it has been shown that in previous studies, scholars may not have been selected and used the correct method for their analysis, leading to potentially incorrect recommendation [104].

In this context, in recent years, scholars have started to help MCDA users to select the most appropriate set of methods for their problem [76]. The proposed taxonomy included a series of steps that users could follow to find the most appropriate MCDA method for their decision problem. These steps are as follows:

1) Problem type, which refers to the type of recommendation the users is expecting from the decision-making problem. As defined in section 3, three problem types referred to the three types of methodologies can be defined. The first problem type refers to the ranking/scoring of the alternatives; the second problem type refers to the classification of the alternatives, which are subdivided in classes from the best to the worst according to the pair-wise comparison of their criteria; the third problem type refers to the selection of the best (s) alternatives making used of the decision-rules methods.
2) Criteria, which refers to the criteria characteristic themselves. In particular to their structure (i.e., flat or hierarchical structure), their type of measurement scale (i.e., ordinal and/or cardinal scales), and the type of performance used as input data (i.e., deterministic or uncertain).
3) Preference elicitation, where the preference of the stakeholders can be used to shape the structure of the model, and they can be provided with direct (as done in this study with the criteria selection in section 4.5 and the weighting scheme presented in section 6) and indirect methods.
4) Features of aggregation, which refers to the key considerations about the implication of the choice of the MCDA method with respect to:
    a. the level of compensation, which refers to the admissible trade-offs between criteria performance and can range from a full to a null level, with a wide spectrum of possibility in between.
    b. the capacity of the MCDA methods to deal with inconsistent preferences, which appears when the preferences are not compatible with the assumed model, e.g., due to the underlying strict axioms (e.g., additivity, monotonicity, or preferential independence) or the DM's judgments are conflicting (e.g., when the DM assigns two alternatives with identical performances on all criteria to different decision classes, or when the DM prefers a pairwise comparison for an alternative that is dominated by the other alternative with respect to all considered criteria).
    c. the dependency of the recommendation on the decision context, where the addition or deletion of alternatives can lead to a change in the problem structure, which can have implications on the decision recommendation. A common example is the rank reversal, where considering 3 alternatives where $a > b > c$, when the user removes the alternative *a* then c > b.

Following the taxonomy implemented in the free (upon registration) MCDA-MSS tool [106], which includes 205 MCDA methods and 156 key decision-making features, the MCDA method to be implemented in the proposed LSCA-F tool is found. Based on the fact that the proposed tool should deal with a scoring/ranking problem, with a hierarchical structure of the criteria, the mixed measurement scales of the criteria (sLCA are all ordinal scales, while eLCA, LCC are cardinal and RA is a mixed of the two), the elicitation preference was direct and the aggregation should consider a full or partial compensation, the MCDA-MSS tool suggested the Multi-Attribute Value Theory (MAVT) as best methodological option.

The MAVT is a ranking method that develops a single score for each alternative by aggregating, with the additive and multiplicative aggregations being the most widely applied, the normalized criteria and their weights. The normalized criteria values are obtained by means of value functions [107].

5. Conclusions

This report presents the initial development of the LCSA-Framework for multi-family houses renovation measures, which is proposed within the SP1.4. The LCSA-Framework combined the Environmental Life Cycle Assessment (eLCA), Life Cycle Cost (LCC), Social Life Cycle Assessment (sLCA) and Resilience Assessment (RA) domains within the overarching Multi-Criteria Decision Analysis (MCDA) method. In fact, the final aim of the SP1.4 is to provide a tool to compare different renovation measures (alternatives) by using Composite Indexes (CIs), also known as indices.

The initial development of the proposed framework was achieved in close collaboration with a group of 8 experts from academia, construction enterprises, consulting, etc., to grasp the heterogeneous knowledges and interests from these different domains. Particularly, the experts participated to 2 Workshops to help defining the proposed framework.

In the 1st Workshop the experts were asked to define the system boundaries of the framework and their level of details. In this context, the group uniformly voted for covering the whole life cycle including the product stage, the construction process stage, the use stage, and the end-of-life stage as well as presenting all results at the process stage level. Furthermore, the experts voted the functional unit (FU) for the LCSA framework, which results to be “heated area per year of building lifetime” due to its wide application in the Swiss building context expressing the building’s energy demand.

Moreover, during the 1st Workshop, the group of experts selected the criteria to be included in the framework, since CIs are based on an aggregation of criteria that measure different domains. In this context, the framework presented here is based on a hierarchical structure of the criteria, which is composed by 3 layers. In the first layer the four abovementioned domains, i.e., eLCA, LCC, sLCA, RA, are present. The second layer is composed by a set of 16 criteria, subdivided into 5 for eLCA and sLCA, 4 for RA and 2 for LCC, which were defined based on a comprehensive literature review and the expert selection during the 1st Workshop. The 3rd layer of the hierarchical structure of the framework contains a set of 56 subcriteria, subdivided into 10 for eLCA and sLCA, 9 for LCC and 27 for RA, which were selected based on a comprehensive literature review and in accordance with the group of experts.

Once the criteria hierarchical structure of the LCSA-Framework was defined, during the 2nd Workshop, the experts were asked to weight the 2nd and 3rd level of the hierarchy to build a default preference profile, different to the equal weight one, to be included in the tool under development. Finally, based on the problem type, the criteria and subcriteria nature, the preference elicitation, and the features of aggregation under interest, the most reasonable MCDA method for the tool under development was selected. In this context, the Multi-Attribute Value Theory (MAVT) was found to be the best methodological solution based on the MCDA-MSS tool [106].

References

[1] BAFU, “Emissionen von Treibhausgasen nach CO2-Gesetz und Kyoto-Protokoll, 2. Verpflichtungsperiode (2013-2020).,” Bundesamt für Umwelt, Bern, Switerland, 2021.

[2] P. H. Shaikh, F. Shaikh, A. A. Sahito, M. A. Uqaili, and Z. Umrani, “An Overview of the Challenges for Cost-Effective and Energy-Efficient Retrofits of the Existing Building Stock,” in *Cost-Effective Energy Efficient Building Retrofitting*, Elsevier, 2017, pp. 257–278. doi: 10.1016/B978-0-08-101128-7.00009-5.

[3] BAFU, “Indikator Klima – Treibhausgasemissionen.,” Bundesamt für Umwelt, Bern, Switerland, 2021.

[4] BAFU, “Langfristige Klimastrategie der Schweiz,” Schweizer Bundesrat, Bern, Switerland, 2021.

[5] S. Greco, A. Ishizaka, M. Tasiou, and G. Torrisi, “On the Methodological Framework of Composite Indices: A Review of the Issues of Weighting, Aggregation, and Robustness,” *Soc. Indic. Res.*, vol. 141, no. 1, pp. 61–94, Jan. 2019, doi: 10.1007/s11205-017-1832-9.

[6] USGBC, 2021, “LEED v4 for BUILDING DESIGN AND CONSTRUCTION.” 2019. [Online]. Available: https://www.usgbc.org/guide/bdc

[7] BREEAM, “BREEAM International New Construction 2016 - Technical Manual,” Watford, UK, 2016.

[8] DGNB, “DGNB System Kriterienkatalog Gebäude Sanierung.” DGNB, 2021.

[9] SGNI, “Nachhaltig planen, bauen, nutzen und betreiben. Zertifi zierte Gebäude der SGNI weisen den Weg.,” Bern, Switerland, 2018.

[10] S. Roostaie, N. Nawari, and C. J. Kibert, “Sustainability and resilience: A review of definitions, relationships, and their integration into a combined building assessment framework,” *Build. Environ.*, vol. 154, pp. 132–144, May 2019, doi: 10.1016/j.buildenv.2019.02.042.

[11] L. Felicioni, A. Lupíšek, and J. Gaspari, “Exploring the Common Ground of Sustainability and Resilience in the Building Sector: A Systematic Literature Review and Analysis of Building Rating Systems,” *Sustainability*, vol. 15, no. 1, p. 884, Jan. 2023, doi: 10.3390/su15010884.

[12] C. L. Champagne and C. B. Aktas, “Assessing the Resilience of LEED Certified Green Buildings,” *Procedia Eng.*, vol. 145, pp. 380–387, 2016, doi: 10.1016/j.proeng.2016.04.095.

[13] A. Vilches, A. Garcia-Martinez, and B. Sanchez-Montañes, “Life cycle assessment (LCA) of building refurbishment: A literature review,” *Energy Build.*, vol. 135, pp. 286–301, Jan. 2017, doi: 10.1016/j.enbuild.2016.11.042.

[14] H. Amini Toosi, M. Lavagna, F. Leonforte, C. Del Pero, and N. Aste, “Life Cycle Sustainability Assessment in Building Energy Retrofitting; A Review,” *Sustain. Cities Soc.*, vol. 60, p. 102248, Sep. 2020, doi: 10.1016/j.scs.2020.102248.

[15] X. Oregi, P. Hernandez, and R. Hernandez, “Analysis of life-cycle boundaries for environmental and economic assessment of building energy refurbishment projects,” *Energy Build.*, vol. 136, pp. 12–25, Feb. 2017, doi: 10.1016/j.enbuild.2016.11.057.

[16] Europäisches Komitee für Normung, “EN 15978:2011 - Nachhaltigkeit von Bauwerken - Bewertung der umeltbezogenen Qualität von Gebäuden - Berechnungsmethode.” Nov. 2011.

[17] Energie Schweiz, Bundesamt für Energie, “Gebäude erneuern Energieverbrauch halbieren.” Bundespublikationen, 2022.

[18] M. Cinelli, S. R. Coles, and K. Kirwan, “Analysis of the potentials of multi criteria decision analysis methods to conduct sustainability assessment,” *Ecol. Indic.*, vol. 46, pp. 138–148, 2014, doi: 10.1016/j.ecolind.2014.06.011.

[19] B. Roy, “Decision Aiding: Major Actors and the Role of Models,” in *Multicriteria Methodology for Decision Aiding*, B. Roy, Ed., Boston, MA: Springer US, 1996, pp. 7–17. doi: 10.1007/978-1-4757-2500-1_2.

[20] D. Bouyssou, T. Marchant, M. Pirlot, A. Tsoukiàs, and P. Vincke, Eds., “Problem Formulation and Structuring: The Decision Aiding Process,” in *Evaluation and Decision Models with Multiple Criteria: Stepping stones for the analyst*, Boston, MA: Springer US, 2006, pp. 19–65. doi: 10.1007/0-387-31099-1_2.

[21] S. Greco, M. Ehrgott, and J. R. Figueira, Eds., *Multiple Criteria Decision Analysis: State of the Art Surveys*, vol. 233. in International Series in Operations Research & Management Science, vol. 233. New York, NY: Springer New York, 2016. doi: 10.1007/978-1-4939-3094-4.
[22] J. S. Dyer, "Multiattribute Utility Theory (MAUT)," in *Multiple Criteria Decision Analysis: State of the Art Surveys*, S. Greco, M. Ehrgott, and J. R. Figueira, Eds., New York, NY: Springer New York, 2016, pp. 285–314. doi: 10.1007/978-1-4939-3094-4_8.
[23] T. L. Saaty, "The Analytic Hierarchy and Analytic Network Processes for the Measurement of Intangible Criteria and for Decision-Making," in *Multiple Criteria Decision Analysis: State of the Art Surveys*, S. Greco, M. Ehrgott, and J. R. Figueira, Eds., New York, NY: Springer New York, 2016, pp. 363–419. doi: 10.1007/978-1-4939-3094-4_10.
[24] D. Dubois and P. Perny, "A Review of Fuzzy Sets in Decision Sciences: Achievements, Limitations and Perspectives," in *Multiple Criteria Decision Analysis: State of the Art Surveys*, S. Greco, M. Ehrgott, and J. R. Figueira, Eds., New York, NY: Springer New York, 2016, pp. 637–691. doi: 10.1007/978-1-4939-3094-4_16.
[25] B. Roy, "The outranking approach and the foundations of electre methods," *Theory Decis.*, vol. 34, pp. 49–73, 1991, doi: 10.1007/BF00134132.
[26] J. R. Figueira, V. Mousseau, and B. Roy, "ELECTRE Methods," in *Multiple Criteria Decision Analysis: State of the Art Surveys*, S. Greco, M. Ehrgott, and J. R. Figueira, Eds., New York, NY: Springer New York, 2016, pp. 155–185. doi: 10.1007/978-1-4939-3094-4_5.
[27] J.-P. Brans and Y. De Smet, "PROMETHEE Methods," in *Multiple Criteria Decision Analysis: State of the Art Surveys*, S. Greco, M. Ehrgott, and J. R. Figueira, Eds., New York, NY: Springer New York, 2016, pp. 187–219. doi: 10.1007/978-1-4939-3094-4_6.
[28] S. Greco, B. Matarazzo, and R. Slowinski, "Rough sets theory for multicriteria decision analysis," *Eur. J. Oper. Res.*, vol. 129, no. 1, pp. 1–47, Feb. 2001, doi: 10.1016/S0377-2217(00)00167-3.
[29] S. Greco, B. Matarazzo, and R. Słowinński, "Decision Rule Approach," in *Multiple Criteria Decision Analysis: State of the Art Surveys*, J. Figueira, S. Greco, and M. Ehrogott, Eds., New York, NY: Springer New York, 2016, pp. 507–555. doi: 10.1007/0-387-23081-5_13.
[30] H. Moshkovich, A. Mechitov, and D. Olson, "Verbal Decision Analysis," in *Multiple Criteria Decision Analysis: State of the Art Surveys*, J. Figueira, S. Greco, and M. Ehrogott, Eds., New York, NY: Springer New York, 2016, pp. 609–633. doi: 10.1007/0-387-23081-5_15.
[31] Organisation for Economic Co-operation and Development (OECD), *Handbook on Constructing Composite Indicators: Methodology and User Guide*. Organisation for Economic Co-operation and Development (OECD) Joint Research Center (JRC) European Commission, 2008.
[32] EUROPEAN COMMITTEE FOR STANDARDIZATION, Ed., "Environmental management - Life cycle assessment - Principles and framework (ISO 14040:2006)." Jun. 2006.
[33] EUROPEAN COMMITTEE FOR STANDARDIZATION, Ed., "Environmental management Life cycle assessment Requirements and guidelines (ISO 14044:2006)." Jul. 2006.
[34] International Organisation of Standardization (ISO), Ed., "ISO/FDIS 21931-1 Sustainability in buildings and civil engineering works — Framework for methods of assessment of the environmental, social and economic performance of construction works as a basis for sustainability assessment — Part 1: Buildings." 2022.
[35] A. Shirazi and B. Ashuri, "Embodied Life Cycle Assessment (LCA) comparison of residential building retrofit measures in Atlanta," *Build. Environ.*, vol. 171, p. 106644, Mar. 2020, doi: 10.1016/j.buildenv.2020.106644.
[36] A. Hajare and E. Elwakil, "Integration of life cycle cost analysis and energy simulation for building energy-efficient strategies assessment," *Sustain. Cities Soc.*, vol. 61, p. 102293, Oct. 2020, doi: 10.1016/j.scs.2020.102293.
[37] R. Frischknecht *et al.*, "Swiss Eco-Factors 2021 according to the Ecological Scarcity Method." Federal Office for the Environment (FOEN), 2021.
[38] D. H. Rebitzer Kerstin Lichtenvort, Gerald, *Environmental Life Cycle Costing*. Boca Raton: CRC Press, 2008. doi: 10.1201/9781420054736.

[39] International Organisation of Standardization (ISO), Ed., “ISO 15686-5: 2017 Buildings and constructed assets — Service life planning — Part 5: Life-cycle costing.” ISO, 2017.
[40] F. Fantozzi, C. Gargari, M. Rovai, and G. Salvadori, “Energy Upgrading of Residential Building Stock: Use of Life Cycle Cost Analysis to Assess Interventions on Social Housing in Italy,” *Sustainability*, vol. 11, no. 5, Art. no. 5, Jan. 2019, doi: 10.3390/su11051452.
[41] M. S. Gustafsson, J. A. Myhren, E. Dotzauer, and M. Gustafsson, “Life Cycle Cost of Building Energy Renovation Measures, Considering Future Energy Production Scenarios,” *Energies*, vol. 12, no. 14, Art. no. 14, Jan. 2019, doi: 10.3390/en12142719.
[42] A. M. Y. Ho, J. H. K. Lai, and B. W. Y. Chiu, “Key performance indicators for holistic evaluation of building retrofits: Systematic literature review and focus group study,” *J. Build. Eng.*, vol. 43, p. 102926, Nov. 2021, doi: 10.1016/j.jobe.2021.102926.
[43] S. Neugebauer, M. Traverso, R. Scheumann, Y.-J. Chang, K. Wolf, and M. Finkbeiner, “Impact Pathways to Address Social Well-Being and Social Justice in SLCA—Fair Wage and Level of Education,” *Sustainability*, vol. 6, no. 8, Art. no. 8, Aug. 2014, doi: 10.3390/su6084839.
[44] UNEP, *Guidelines for social life cycle assessment of products: Lignes directrices pour l’analyse sociale du cycle de vie des produits*. Canadian Electronic Library, 2009.
[45] R. Wu, D. Yang, and J. Chen, “Social Life Cycle Assessment Revisited,” *Sustainability*, vol. 6, no. 7, pp. 4200–4226, Jul. 2014, doi: 10.3390/su6074200.
[46] M. Kühnen and R. Hahn, “Indicators in Social Life Cycle Assessment: A Review of Frameworks, Theories, and Empirical Experience,” *J. Ind. Ecol.*, vol. 21, no. 6, pp. 1547–1565, 2017, doi: 10.1111/jiec.12663.
[47] Y. H. Dong and S. T. Ng, “A social life cycle assessment model for building construction in Hong Kong,” *Int. J. Life Cycle Assess.*, vol. 20, no. 8, pp. 1166–1180, Aug. 2015, doi: 10.1007/s11367-015-0908-5.
[48] S. Y. Janjua, P. K. Sarker, and W. K. Biswas, “A Review of Residential Buildings’ Sustainability Performance Using a Life Cycle Assessment Approach,” *J. Sustain. Res.*, vol. 1, no. 1, Jun. 2019, doi: 10.20900/jsr20190006.
[49] J. G. Backes and M. Traverso, “Application of Life Cycle Sustainability Assessment in the Construction Sector: A Systematic Literature Review,” *Processes*, vol. 9, no. 7, Art. no. 7, Jul. 2021, doi: 10.3390/pr9071248.
[50] Md. U. Hossain, C. S. Poon, Y. H. Dong, I. M. C. Lo, and J. C. P. Cheng, “Development of social sustainability assessment method and a comparative case study on assessing recycled construction materials,” *Int. J. Life Cycle Assess.*, vol. 23, no. 8, pp. 1654–1674, Aug. 2018, doi: 10.1007/s11367-017-1373-0.
[51] J. Zuo and Z.-Y. Zhao, “Green building research–current status and future agenda: A review,” *Renew. Sustain. Energy Rev.*, vol. 30, pp. 271–281, Feb. 2014, doi: 10.1016/j.rser.2013.10.021.
[52] N. Hossaini, B. Reza, S. Akhtar, R. Sadiq, and K. Hewage, “AHP based life cycle sustainability assessment (LCSA) framework: a case study of six storey wood frame and concrete frame buildings in Vancouver,” *J. Environ. Plan. Manag.*, vol. 58, no. 7, pp. 1217–1241, Jul. 2015, doi: 10.1080/09640568.2014.920704.
[53] A. T. Balasbaneh and A. K. B. Marsono, “Applying multi-criteria decision-making on alternatives for earth-retaining walls: LCA, LCC, and S-LCA,” *Int. J. Life Cycle Assess.*, vol. 25, no. 11, pp. 2140–2153, Nov. 2020, doi: 10.1007/s11367-020-01825-6.
[54] A. T. Balasbaneh, A. K. B. Marsono, and S. J. Khaleghi, “Sustainability choice of different hybrid timber structure for low medium cost single-story residential building: Environmental, economic and social assessment,” *J. Build. Eng.*, vol. 20, pp. 235–247, Nov. 2018, doi: 10.1016/j.jobe.2018.07.006.
[55] M. I. Touceda, F. J. Neila, and M. Degrez, “Modeling socioeconomic pathways to assess sustainability: a tailored development for housing retrofit,” *Int. J. Life Cycle Assess.*, vol. 23, no. 3, pp. 710–725, Mar. 2018, doi: 10.1007/s11367-016-1194-6.
[56] R. Harmens *et al.*, “Critical evaluation of social approaches,” EU Horizon 2020, 2021.

[57] N. B. Rajkovich and Y. Okour, "Climate Change Resilience Strategies for the Building Sector: Examining Existing Domains of Resilience Utilized by Design Professionals," *Sustainability*, vol. 11, no. 10, p. 2888, May 2019, doi: 10.3390/su11102888.
[58] M.-W. Tian and P. Talebizadehsardari, "Energy cost and efficiency analysis of building resilience against power outage by shared parking station for electric vehicles and demand response program," *Energy*, vol. 215, p. 119058, Jan. 2021, doi: 10.1016/j.energy.2020.119058.
[59] S. Homaei and M. Hamdy, "Thermal resilient buildings: How to be quantified? A novel benchmarking framework and labelling metric," *Build. Environ.*, vol. 201, p. 108022, Aug. 2021, doi: 10.1016/j.buildenv.2021.108022.
[60] RDI, "Strategies for Multifamily Building Resilience - Enterprise Community Partners, New York City," Resilience Design Institute, New York, NY, USA, 2015.
[61] D. Pierce, "Resilience Action List & Credit Catalog." 2017.
[62] IBHS, "FORTIFIED Home." USA, 2023.
[63] L. Taymor and J. Leahy, "The Case for Resilience." DNV-GL, Oakland, CA, USA.
[64] IBHS, "Fortified Multifamily." USA, 2023.
[65] PEER, "Rating System," 2022.
[66] ISI, "ENVISION Rating System." The Institute for Sustainable Infrastructure, USA, 2020.
[67] USGBC-LA, "Building Resilience Los Angeles," US Green Building Council Chapter Los Angeles, Los Angeles, 2016.
[68] L. Larsen *et al.*, "Green Building and Climate Resilience: Understanding and Preparing for Changing Conditions.," University of Michigan; US Green Building Council, 2011.
[69] NIST, "Community Resilience Planning Guide for Buildings and Infrastructure Systems - Volume I," National Institute of Standards and Technology, USA, 2016.
[70] NIST, "Community Resilience Planning Guide for Buildings and Infrastructure Systems - Volume II," National Institute of Standards and Technology, USA, 2016.
[71] NYSERDA, "Climate Resilience Initiative." New York, NY, USA.
[72] RDI, "Building Resilience in Boston," Resilience Design Institute, Boston, MA, USA, 2013.
[73] NYC Mayor's Office of Resiliency, "Climate Resiliency Design Guidelines," New York, NY, USA, 2020.
[74] I. Almufti and M. Willford, "REDi Rating System: Resilience-based Earthquake Design Initiative for the Next Generation of Buildings," Arup, 2013.
[75] IBHS, "FORTIFIED Commercial." USA, 2023.
[76] M. Cinelli, M. Kadzinski, M. Gonzalez, and R. Slowinski, "How to support the application of multiple criteria decision analysis? Let us start with a comprehensive taxonomy," *Omega*, vol. 96, 2020, doi: 10.1016/j.omega.2020.102261.
[77] J. de Bruijn *et al.*, *Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards*. Dordrecht: Kluwer Academic Publishers, 2002.
[78] A. W. Sleeswijk, L. F. C. M. Van Oers, J. B. Guinée, J. Struijs, and M. A. J. Huijbregts, "Normalisation in product life cycle assessment: An LCA of the global and European economic systems in the year 2000," *Sci. Total Environ.*, vol. 390, no. 1, pp. 227–240, Feb. 2008, doi: 10.1016/j.scitotenv.2007.09.040.
[79] "CML-IA Characterisation Factors," Leiden University. Accessed: Jan. 04, 2024. [Online]. Available: https://www.universiteitleiden.nl/en/research/research-output/science/cml-ia-characterisation-factors
[80] R. Hischier *et al.*, "Implementation of Life Cycle Impact Assessment Methods".
[81] Intergovernmental Panel On Climate Change, *Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, 1st ed. Cambridge University Press, 2023. doi: 10.1017/9781009157896.
[82] K. Richardson *et al.*, "Earth beyond six of nine planetary boundaries," *Sci. Adv.*, vol. 9, no. 37, p. eadh2458, Sep. 2023, doi: 10.1126/sciadv.adh2458.
[83] D. A. Braune, C. R. Durán, and J. Gantner, "Leitfaden zum Einsatz der Ökobilanzierung".

[84] S. Jia and D.-J. Zhan, "Resilience and sustainability assessment of individual buildings under hazards: A review," *Structures*, vol. 53, pp. 924–936, Jul. 2023, doi: 10.1016/j.istruc.2023.04.095.
[85] O. Ladipo, G. Reichard, A. McCoy, A. Pearce, P. Knox, and M. Flint, "Attributes and metrics for comparative quantification of disaster resilience across diverse performance mandates and standards of building," *J. Build. Eng.*, vol. 21, pp. 446–454, Jan. 2019, doi: 10.1016/j.jobe.2018.11.007.
[86] S. Burroughs, "Development of a Tool for Assessing Commercial Building Resilience," *Procedia Eng.*, vol. 180, pp. 1034–1043, 2017, doi: 10.1016/j.proeng.2017.04.263.
[87] K. M. De Bruijn, "Resilience indicators for flood risk management systems of lowland rivers," *Int. J. River Basin Manag.*, vol. 2, no. 3, pp. 199–210, Sep. 2004, doi: 10.1080/15715124.2004.9635232.
[88] D. Proverbs and J. Lamond, "Flood Resilient Construction and Adaptation of Buildings," in *Oxford Research Encyclopedia of Natural Hazard Science*, Oxford University Press, 2017. doi: 10.1093/acrefore/9780199389407.013.111.
[89] M. K. Sen, S. Dutta, and G. Kabir, "Modelling and quantification of time-varying flood resilience for housing infrastructure using dynamic Bayesian Network," *J. Clean. Prod.*, vol. 361, p. 132266, Aug. 2022, doi: 10.1016/j.jclepro.2022.132266.
[90] Y. Yang, H. Guo, L. Chen, X. Liu, M. Gu, and W. Pan, "Multiattribute decision making for the assessment of disaster resilience in the Three Gorges Reservoir Area," *Ecol. Soc.*, vol. 25, no. 2, p. art5, 2020, doi: 10.5751/ES-11464-250205.
[91] S. Arns, M. Hellmig, A. Schlenkhoff, S. Vöcklinghaus, and N. Appler, "Effects of heavy rainfall on construction-related infrastructure," Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR), Bonn, Germany, 2018.
[92] S. Golz, T. Naumann, M. Neubert, and B. Günther, "Heavy rainfall: An underestimated environmental risk for buildings?," *E3S Web Conf.*, vol. 7, p. 08001, 2016, doi: 10.1051/e3sconf/20160708001.
[93] E. Long, "Building Design Principles for Excess Rainfall," *Building Enclosure (BE)*, 2021.
[94] R. Dylewski and J. Adamczyk, "Economic and ecological indicators for thermal insulating building investments," *Energy Build.*, vol. 54, pp. 88–95, Nov. 2012, doi: 10.1016/j.enbuild.2012.07.021.
[95] S. Flores-Larsen, F. Bre, and M. Hongn, "A performance-based method to detect and characterize heatwaves for building resilience analysis," *Renew. Sustain. Energy Rev.*, vol. 167, p. 112795, Oct. 2022, doi: 10.1016/j.rser.2022.112795.
[96] G. Hatvani-Kovacs, M. Belusko, N. Skinner, J. Pockett, and J. Boland, "Heat stress risk and resilience in the urban environment," *Sustain. Cities Soc.*, vol. 26, pp. 278–288, Oct. 2016, doi: 10.1016/j.scs.2016.06.019.
[97] I. A. Rana *et al.*, "A localized index-based approach to assess heatwave vulnerability and climate change adaptation strategies: A case study of formal and informal settlements of Lahore, Pakistan," *Environ. Impact Assess. Rev.*, vol. 96, p. 106820, Sep. 2022, doi: 10.1016/j.eiar.2022.106820.
[98] C. Zhang *et al.*, "Resilient cooling strategies – A critical review and qualitative assessment," *Energy Build.*, vol. 251, p. 111312, Nov. 2021, doi: 10.1016/j.enbuild.2021.111312.
[99] S. Attia *et al.*, "Resilient cooling of buildings to protect against heat waves and power outages: Key concepts and definition," *Energy Build.*, vol. 239, p. 110869, May 2021, doi: 10.1016/j.enbuild.2021.110869.
[100] CCES, "Resilience Strategies for Power Outages," Center for Climate and Energy Solutions, Arlington, VA, USA, 2018.
[101] H. Gong and D. M. Ionel, "Improving the Power Outage Resilience of Buildings with Solar PV through the Use of Battery Systems and EV Energy Storage," *Energies*, vol. 14, no. 18, p. 5749, Sep. 2021, doi: 10.3390/en14185749.

[102] K. Singh and C. Hachem-Vermette, “Techniques of Improving Infrastructure and Energy Resilience in Urban Setting,” *Energies*, vol. 15, no. 17, p. 6253, Aug. 2022, doi: 10.3390/en15176253.
[103] S. Corrente, S. Greco, and R. Słowiński, “Multiple Criteria Hierarchy Process for ELECTRE Tri methods,” *Eur. J. Oper. Res.*, vol. 252, no. 1, pp. 191–203, Jul. 2016, doi: 10.1016/j.ejor.2015.12.053.
[104] M. Cinelli, P. Burgherr, M. Kadziński, and R. Słowiński, “Proper and improper uses of MCDA methods in energy systems analysis,” *Decis. Support Syst.*, vol. 163, p. 113848, Dec. 2022, doi: 10.1016/j.dss.2022.113848.
[105] H. Jiawei, K. Micheline, and P. Jian, “Data Transformation and Data Discretization,” in *Data Mining: Concepts and Techniques.*, Waltham, MA, USA: Elsevier, 2012.
[106] M. Cinelli, M. Kadzinski, G. Miebs, R. Stowinski, M. Gonzalez, and Burgherr Peter, “MCDA Methods Selection Software (MCDA-MSS),” MCDA Methods Selection Software (MCDA-MSS). [Online]. Available: https://mcda.cs.put.poznan.pl/
[107] M. Bottero, V. Ferretti, and G. Mondini, “Constructing Multi-attribute Value Functions for Sustainability Assessment of Urban Projects,” in *Computational Science and Its Applications – ICCSA 2014*, vol. 8581, B. Murgante, S. Misra, A. M. A. C. Rocha, C. Torre, J. G. Rocha, M. I. Falcão, D. Taniar, B. O. Apduhan, and O. Gervasi, Eds., in Lecture Notes in Computer Science, vol. 8581. , Cham: Springer International Publishing, 2014, pp. 51–64. doi: 10.1007/978-3-319-09150-1_5.