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A METHODOLOGICAL APPROACH FOR LIFE CYCLE ASSESSMENT OF REFURBISHMENT MEASURES – FROM BUILDING TO NEIGHBOURHOOD AND MUNICIPAL LEVEL

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Abstract. Life cycle assessment (LCA) in the building sector has become a widely used method for quantifying environmental impacts of a building over its entire life cycle. Currently, however, no standardized procedure exists for considering refurbishment measures. In addition, the LCA, according to the European standard EN 15978, is limited to building level only. This paper shows how a methodological LCA framework of refurbishment methods can be applied at three levels: single building, neighbourhood, and municipality. Initially, the proposed methodological approaches are introduced while the framework rules are defined for each of the three levels. The system boundaries of the LCA differ regarding the assessment levels within the given methodology and are adapted accordingly. In addition, the three levels of assessment are defined by the accuracy of measurement results, and data requirements, as well as by the specific value of the calculations and the ownership of the building stock. The assessment levels provide a specific quality and quantity of environmental indicator results. Thus, the complex interrelationships of the assessment levels are shown. The developed framework for the environmental assessment of refurbishment measures provides comparability at the building level. At the neighbourhood level, emissions from refurbishment measures are compared with the reductions of emissions through heating energy demand. Ultimately, the potential of refurbishment measures at the municipal level can be identified on a large scale and used as a decision-making tool.

Keywords: Life cycle assessment, LCA framework, refurbishment, neighbourhood level, municipal level.

1. Introduction

The German federal government has declared its commitment to achieving greenhouse gas (GHG) neutrality by the year 2045. A gradual reduction of GHG emissions of 65 % by 2030 and 88 % by 2040, compared to the reference year 1990, is mandatory. A corresponding amendment to the National Climate Protection Act has been made. For the building sector, the reduction targets for the next years have been adapted.

Around 80 % of the buildings that will constitute the building stock in Europe in 2050 already exist today [1]. The energetic standard of the buildings varies considerably. About one-third of the final energy demand is assigned to the building sector [2]. Decarbonizing the energy stock has become the focus of policy efforts – not only at the national level. In Germany, the annual energetic refurbishment rate is around 1 %, although individual measures dominate [3]. However, to achieve the federal government's goals, it will be essential to increase this quota in the next years. Considering the large discrepancy within the energy demand values and the currently increasing renovation activity, energetic refurbishment measures in the building sector will make a significant contribution to climate-relevant effects.

Given the circumstances, a holistic approach is required to implement sustainable refurbishment measures. LCA offers an appropriate instrument; however, there is a current lack of uniform standards and parameters for the assessment of refurbishment measures.

1.1. Life Cycle Assessment of Buildings

LCA quantifies potential environmental impacts of products or services. In a holistic analysis, the input and output flows are evaluated over the entire life cycle. The general assessment regulations for LCA are specified in EN ISO 14040:2020 [4] and EN ISO 14044:2020 [5]. For buildings specifically, EN 15978:2011 [6] sets out additional requirements. One of the main focuses of the LCA of buildings is to cover the entire life cycle. Starting with production and construction (module A) and continuing through the use phase (module B) to disposal (module C), all life cycle phases according to EN 15804:2019 [7] are considered. Outside the system boundary, benefits from recycling or reuse are considered in Module D. Figure 1 shows the life cycle stages and further subdivisions for building LCAs.

1.2. Life Cycle Assessment of Refurbishment Measures

In the literature, no consensus exists on the specific application of LCAs of refurbishment measures. Cabeza

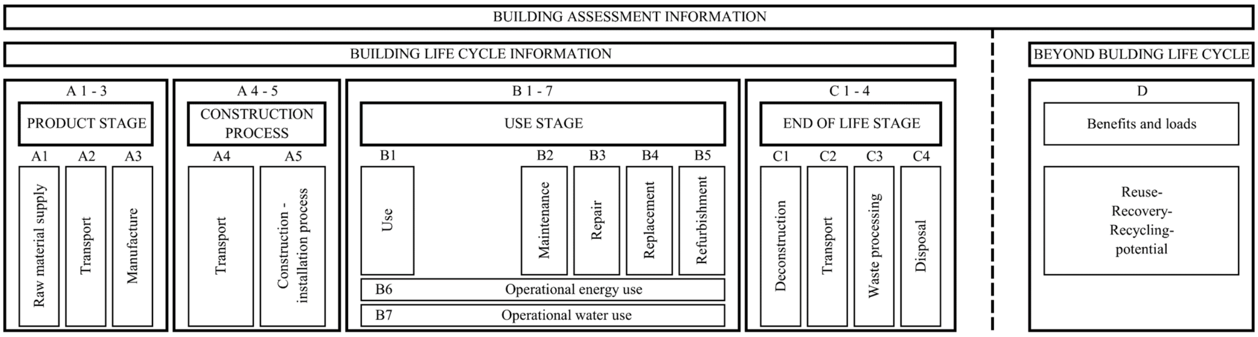

Figure 1. Life cycle stages for buildings [7].

et al. [8] reported that only few studies have evaluated actual building refurbishments in terms of LCA. According to a literature review by Vilches et al. [9], the interpretation of the system boundaries is the main difference between existing studies. The inconsistent system boundaries prevent comparative assessments from being made. The updated version DIN prEN 15978:2021 [10], currently still in the draft phase, sets out calculation rules for refurbishment at building level in a normative framework, and which are similar to the rules described by Hafner and Storck [11]. Hence, in this paper, we propose a consistent approach to LCA of refurbishment measures and extend the assessment framework from the building to the neighbourhood and to the municipal level.

When examining the LCA of refurbishment measures, an initial definition is crucial. By refurbishment measures we consider the structural substance of the building envelope, as well as the buildings' technical installations, to have been modified. Thus, structural and material changes are required to be carried out on the facade, the windows or doors, the roof or the top ceiling of the building or the basement ceiling. Moreover, replacing the building's cooling or heating systems is also considered an energetic refurbishment. In accordance with EN 15978:2011 [6], the production and transport of all new components, as well as all required construction measures and waste management of the removed components, are also included.

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2. Methodological Approach for LCA Frameworks

With consideration of the research gaps and the presented relevance of refurbishment measures, this chapter provides essential boundary conditions and concrete instructions for the implementation of LCAs of refurbishment measures. Figure 2 shows the overall LCA framework approach for all three levels. The following sections will refer to the corresponding illustration in this figure.

Refurbishment measures are the subject of the investigation, thus the production of all newly introduced building materials (modules A1–3) and the deconstruction (modules C1–4) required is considered. Thereby, the implementation point is within the study period, but not necessarily at the beginning. As seen in Figure 2, replacement cycles are accounted for the existing building components (modules B2–4 stock) over the assessment period and for the newly installed structures (modules B2–4 new components) after the refurbishment event. The operational use of energy (module B6) is covered similarly.

2.1. Building Level

The refurbishment of buildings is a useful way of saving heating energy as well as extending the life cycle of a building. LCAs of refurbishments calculate the potential environmental impact savings through heating energy reduction, as well as the environmental impact of material choice. The system boundaries for LCA of refurbishments are similar to the case of a new building. The functional unit is defined as 1 m^2 gross external area (GEA) of the entire building. Within the methodology, it is assumed that the life cycle is extended by 50 years through an energetic refurbishment.

To calculate environmental impacts, all components used in the building are determined and connected with Environmental Product Declarations. The refurbishment of a building causes that different building components from different construction periods exist in the building, such as components being removed, new components and remaining components. During the refurbishment, components are removed from the building (e.g. old windows) and are taken into

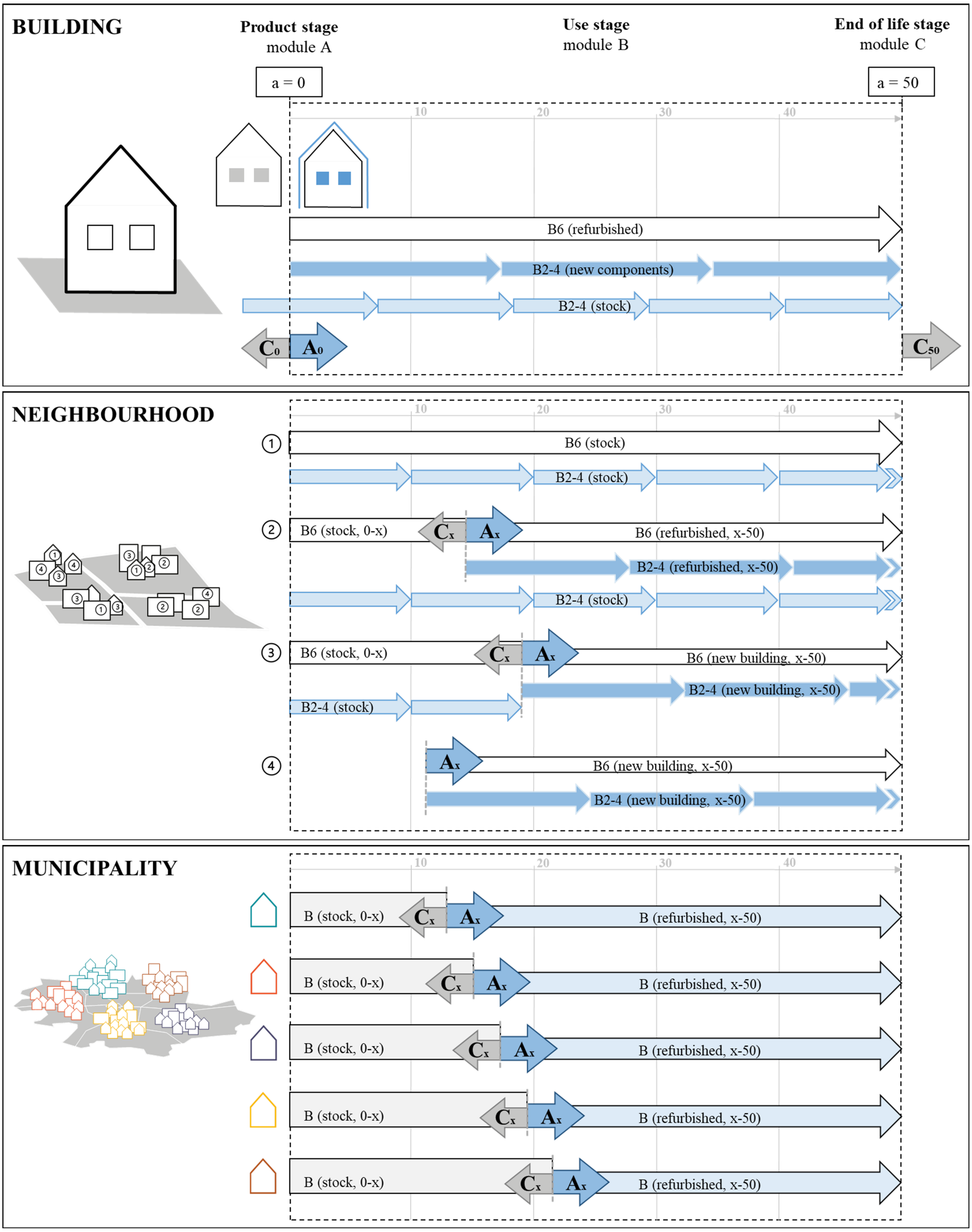

Figure 2. LCA Framework for the different level approaches.

account in module C1–$4_{(0)}$ at time zero, shown in Figure 2 (grey arrow C_0). An exception for this is the carbon content of materials, which is released from the materials in module C. This content should not be accounted for the global warming potential result module of C1–$4_{(0)}$, as it leads to a skewing of the results. All new components added to the building, such as insulation materials or new heating systems, are calculated in module A1–$3_{(0)}$ (blue arrow A_0), as in the case of a new building. In addition, there are building components that are not replaced during the refurbishment. The use stage of the building is described by the operational energy use (module B6) as well as the replacement of building components according to their service life (module B2–4), and these are shown as longer arrows in Figure 2. For building components that exist in the building and are not replaced during the measure, the replacement cycles are assumed to be based on regular replacement and the year of construction is chosen as the reference value. The newly installed parts are replaced according to regular maintenance cycles, as in the case of new buildings in module B2–4. The reduced operational energy use resulting from the refurbishment measure is calculated further over the life cycle (module B6). At the end of the extended life cycle, it is assumed that all components, from existing components and components installed during the refurbishment, are dismantled, and calculated in module C1–$4_{(50)}$ (grey arrow C_{50}).

By calculating LCA results of individual buildings, the savings of environmental impacts at the building material level, as well as from an energy perspective, can be presented. Different refurbishment options can be compared regarding to the resulting savings, such as environmental or energetic for each building.

2.2. Neighbourhood Level

The neighbourhood has become a crucial perspective for urban planning and the implementation of urban transition projects. Benefits of neighbourhood-level implementation range from joint energy supply, for example through district heating systems, to linked mobility concepts and shared facilities. This paper focuses on existing neighbourhoods to assess refurbishment measures holistically using LCAs. However, no uniform approach for LCA has been established for either new or existing neighbourhoods and all approaches taken have differed considerably [12].

Initially, the neighbourhood investigated must be spatially identified and delimited as such. Three criteria are decisive for spatial coverage: geographical boundaries, land use and building and settlement structure. The LCA system boundary considers all buildings that are subject to refurbishment measures in the defined area. Moreover, the assessment period is 50 years, and the functional equivalent is defined as $1\,m^2$ GEA.

Within the methodology for neighbourhood LCA, a distinction must be made between 4 four scenarios, as shown in Figure 2. Scenario 1 represents an untouched building on which no measures are carried out. Therefore, it is not part of the assessment framework. In scenario 2, a refurbishment measure is carried out at a time x. The operational energy use before the measurement $B6_{(0-x)}$ decreases subsequently and results in $B6_{(x-50)}$. Similarly, the replacement cycles in modules B2–$4_{(0-x)}$ before the measurement and B2–$4_{(x-50)}$ afterwards, are differentiated. The replacement cycles of the building structures of the existing building stock are covered separately and extend over the entire observation period. Impacts in module A1–$3_{(x)}$ and module C1–$4_{(x)}$ are determined specific to the time x. In analogy, scenario 3 is to be considered, where demolition and subsequent new construction is implemented at a time x in the neighbourhood. Finally, scenario 4 describes a new building that is constructed as a densification at a given time x, and without demolition having to take place beforehand. The assessment period is set to a time frame of 50 years which compensates the life cycle of an individual building and does not have to necessarily end with the demolition of the buildings. Thus, modules C1–$4_{(50)}$ and $D_{(50)}$ will not be considered in the LCA framework after the 50 years at the neighbourhood level.

To model the entire building stock in the neighbourhood, the buildings are clustered based on building typology-specific criteria, such as building age, type of use or typical building constructions. Accurate planning documents are necessary for the life cycle inventory, which are frequently not available in sufficient quality, especially in existing buildings. Thus, proxy buildings of the clusters are identified with planning documents of sufficient data quality and representative character. Different scenarios can be carried out in one cluster, allowing multiple proxy buildings to be designated. A building-specific life cycle inventory (LCI) is then conducted for all proxy buildings, followed by an impact assessment combining LCI data and environmental impacts. To extrapolate the results to the entire neighbourhood, the building-specific data must first be related to the GEA of the proxy building. Afterwards, the obtained value is multiplied by the total GEA of the cluster. The sum of the clusters presents the environmentally relevant influences of the neighbourhood.

2.3. Municipal Level

Municipal self-governance is one of the important elements of the political structure of the Federal Republic of Germany. Nowadays, municipal self-governance has a key role in the increasingly diverse interaction of processes. A municipality is authorized to a certain level of autonomy in terms of statutes, finances, planning and execution. Issues of municipal policy include, especially recently, the protection of the environment

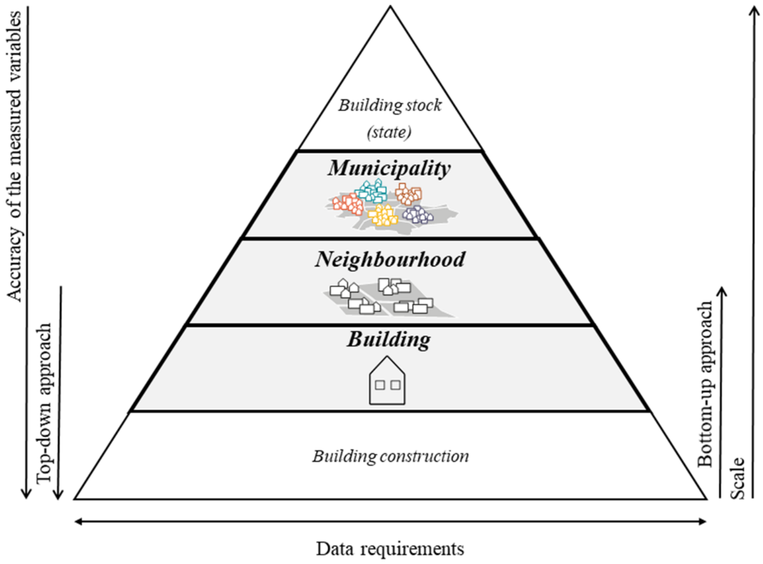

Figure 3. Context of the different level approaches.

and natural resources [13, 14].

Regarding the building sector, refurbishment can be identified as a municipal climate- and environmentally friendly approach to reduce the operational energy consumption. Additionally, in public building projects and their tendering, environmental aspects will be given greater prominence. For this, LCA of refurbishment measures can provide the data basis for municipal funding [15].

The size of the municipality does not play a role in the methodology, since the LCA of refurbishment measures is realized using extrapolations. As a bottom-up approach, LCA are carried out for an assembly of building components, which are also the objects of assessment. In this level, the LCA system boundary is limited to the exterior envelope components of a building, highlighted colourful in Figure 2. The LCA is carried out in the functional equivalent in 1 m^2 GEA. The reference study period will remain 50 years, regardless of the actual date of the refurbishment, see Figure 2. Different building types were considered, which can differ both in terms of use and year of construction, expressed in the Figure 2, by the colour subdivision of the building icons.

Starting at year 0 of the assessment period, the modules B2–$4_{(0-x)}$ and $B6_{(0-x)}$ of the exterior envelope components of a building are included in the LCA framework. As the refurbishment is realized in year x, further life cycle stages will be added: For the exterior envelope components, which will be removed within the measure, the modules C1–$4_{(x)}$ are included in the LCA. For the added new components, the modules A1–$3_{(x)}$ are calculated in an analogous manner. Independently from the refurbishment measure, the modules B2–$4_{(x-50)}$ of the existing components remained in situ will continue. Now, the modules B2–$4_{(x-50)}$ for the newly installed exterior envelope components will be additionally included. The impact of operational energy consumption ($B6_{(x-50)}$) remains part of the LCA after the refurbishment but will be reduced to take account of the consequences of the refurbishment. After the assessment period of 50 years, it is assumed that the investigated municipality will not be demolished, and the existing buildings will remain. Therefore, consideration of modules C1–$4_{(50)}$ and $D_{(50)}$ in the framework is not applied at the municipal level, analogously with the neighbourhood level.

For the data basis of the LCA framework of refurbishing the exterior envelope of the municipal buildings, a building typology can be used. It can contain data on different types of buildings and years of construction, in addition to information on the structure of the building envelope before and after refurbishment measures. Using this information, the life cycle inventory of the exterior envelope can be performed within the LCA as described. By using a geographic information system, the calculations can be extrapolated over the functional equivalent of 1 m^2 GEA for the whole municipality.

3. Comparison

The correlation of the levels for which LCA methodologies are proposed is presented in Figure 3. In our framework, the municipality is the largest level of assessment. Moreover, various neighbourhoods form an urban structure, which is why this level represents the meso level. Finally, the building level is the foundation for the proposed approaches and constitutes the smallest level.

As the scale decreases, the level of consideration becomes smaller, and the data requirement increases. Assumptions must be made for the municipal analysis, as certain data is no longer available at this level, or it would not be practical to collect missing data for the

Framework	Building	Neighbourhood	Municipality
Object of assessment	Building	Proxy building	Assembly of building components
Functional equivalent	$1\,m^2$ GEA	$1\,m^2$ GEA	$1\,m^2$ GEA
Assessment period	50 years	50 years	50 years
System boundaries	Building	Building	Exterior building components
Approximation	Building specific	Extrapolation via proxy buildings in clusters	Extrapolation via building typology
Life-cycle stages			
$B2–4_{(0-x)}$	-	Components in situ	Components in situ
$B6_{(0-x)}$	-	Operational energy use before measurement	Operational energy use before measurement
$A1–3_{(x)}{}^{*}$	Components newly installed	Components newly installed	Components newly installed
$C1–4_{(x)}{}^{*}$	Components demolished in situ	Components demolished in situ	Components demolished in situ
$B2–4_{(x-50)}{}^{*}$	Components newly installed + retained components in situ	Components newly installed + retained components in situ	Components newly installed + retained components in situ
$B6_{(x-50)}{}^{*}$	Operational energy use	Operational energy use	Operational energy use
$C1–4_{(50)}$	All building components	-	-
$D_{(x)}$	Informative	Optional	Optional

* For building level: x = 0 years.

TABLE 1. Comparative overview of the different LCA approaches.

entire municipality. In the neighbourhood, building-specific data can be collected. Collaboration with stakeholders or companies is particularly conducive to data acquisition. Highest quality data is required at the building level.

Due to the different data requirements, the accuracy of the measured variables is affected. For the evaluation of potentials offering refurbishment measures, the municipal level requires less precise data quality. At the neighbourhood and building level, the accuracy of the results increases in line with the increasing availability of data. However, the bottom-up approach ensures that losses in calculation accuracy are limited.

The functional equivalent for all approaches is $1\,m^2$ GEA and the assessment period is 50 years. Both the object of assessment and the system boundaries vary. Specific buildings are assessed at the building and neighbourhood level. At the municipal level, in contrast, components of the exterior building envelope are examined. Based on these evaluations, and with consideration of special building types, approximations are possible for the neighbourhood and the municipality. Upward extrapolation is a central element of the methodologies.

At neighbourhood and municipality level, several measurements can be implemented at the same time or with a time lag, which is why the considered life cycle stages must be differentiated from the building specific LCA. At the building level, a measurement takes place at the beginning of the assessment period. Thus, there is no calculation of the modules B2–4 and B6 before the refurbishment. At neighbourhood and municipality level, however, the operational phases before and after the measurement must be examined differently. Moreover, only at the building level, the demolition of the entire building is included in module $C1–4_{(50)}$ after the end of the period of study. Table 1 shows the key differences in the frameworks and life cycle stages of the approaches presented.

4. Conclusion

The proposed methodologies are to contribute holistically to the sustainable transformation of the building stock. Through the different levels of assessment, decision-making tools are provided for different stakeholders and authorities, which enables the evaluation of the environmental quality of refurbishment measures. Therefore, it is essential that energetic refurbishment measures are implemented on a large scale to achieve the climate protection goals set. Increasing the refurbishment rate is equally important. The three levels allow for broad applicability based on a coherent methodology.

At this stage, the individual methodologies require evaluation through practical application on sample objects. Subsequently, data can be determined that will serve for the creation of benchmarks and likewise as a comparison for further studies. In addition, the influence of different materials used during refurbishment measures must be further investigated. As Hafner et al. [16] have already shown, renewable materials appear beneficial. Particularly at a larger scale in the built environment, carbon storage through enabling technologies in and around the building must be considered. To meet climate protection targets, it is necessary to use existing technologies besides refurbishment measures to reduce GHG emissions and, simultaneously, to store and sequester carbon [17].

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