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Holistic assessment of carbon abatement strategies in building refurbishment literature — A scoping review

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ABSTRACT

The refurbishment of building stocks constitutes a significant role in reducing carbon emissions from the built environment. However, refurbishment rates remain low despite tools and methods for addressing this issue has been prevalent for a long time. This article aims to perform a holistic review of scientific literature that aims to reduce carbon emissions by refurbishing buildings. A scoping review and snowball sampling of 106 articles analyzed the advantages and disadvantages of the methods used, scales applied, and carbon emission sources investigated in the literature. The study's central finding is the aspect of induced-mobility emissions due to the location of buildings, which are essential to consider avoiding sub-optimization in refurbishment studies. No standardized methods exist for assessing several buildings on a larger scale with a broader scope. The methods applied vary, and the advantages and inaccuracies exist due to trade-offs between quantity and data quality. Most studies are aware of the issue, and techniques to overcome the problems exist, but more research is needed to overcome the discussed boundaries. This article provides an overview previously not available in literature while illuminating the gaps in the current. The work will aid future studies in finding refurbishment strategies that increase the carbon emission abetment and help them avoid future pitfalls.

1. Introduction

The people operating in the built environment are responsible for as much as 70% of global greenhouse gas (GHG) emissions and predictions state that the majority of the world population will live in cities by 2050 [1]. The international energy agency (IEA) estimates that 40% of global carbon emissions derive from buildings and construction activities [2] and a reduction is necessary to ensure a sustainable future [3,4]. In Europe, buildings are responsible for approximately 40% of total energy use and 36% of greenhouse gas emissions [5] thus revealing significant mitigation potential. The European Union (EU) implemented the ambitious goal in 2019 to become carbon natural in 2050 with the partial goal of lowering GHG emissions by 55% compared to 1990 levels in the year 2030 [4,6–8]. Moreover, from 31 December 2020, all new private and public buildings should be nearly zero-energy buildings (nZEB) according to regulations from the European Union (EU). The European European Comission [9, p. 5] defines nZEB as 'a building that has a very high energy performance, as determined in accordance with Annex I. The nearly zero or very low amount of energy required should be covered to a very significant extent from renewable sources, including sources produced on-site or nearby'. Albeit a necessary step in the right direction, the nZEB initiative alone will not lower the emissions, and each member state still needs to define what 'nearly zero' means to them, thus leading to varieties in energy usage in nZEB across Europe [9]. It is not only the building design that is detrimental to a successful nZEB, as user behavior influences the energy use significantly [10–12]. Following the nZEB, there is the development of zero energy buildings (ZEB) which refer to buildings that produce their energy from renewable energy sources to cover energy demand [13]. The challenge with low-energy buildings is that they demand more materials than a conventional building to reduce heat loss through thermal transmittance. It increases the total share of embodied emissions in the building and on-site renewable energy production to lower operational emissions, e.g., photovoltaic panels (PV-panels), increase the embodied emissions further [14,15]. The zero-emission building (ZEB*) is, per its predecessors, a low-energy building that relies on energy generated from renewable sources. The energy is produced on-site, and any surplus is exported to the electricity grid, which then enables the ZEB* to compensate for the emissions it generated over its life cycle [15–18]. However, reducing the emissions is not limited to buildings since it is an issue for the entire built environment [3]. Thus, the building research community has expanded the scope even further when moving from a building scale of ZEB* to zero-emission neighborhoods (ZEN). It entails making holistic assessments of emissions deriving from multiple and different building types

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instead of the single ZEB* [19]. A ZEN produces, stores, and exports its energy while being carbon neutral over its lifetime. The ZEN is not limited to the buildings contained within its boundary as it also includes utilities like water, sewage, user mobility, ICT services, and waste management [18–20]. Moreover, life cycle assessment (LCA) is the method used when calculating how a neighborhood can achieve carbon neutrality over its life time [21].

1.1. The refurbishment of exiting building stocks to align with climate goals

In Europe, 85%–95% of existing buildings are predicted to be operational in 2050, and a majority are not fulfilling current energy standards [5,10]. The EU has realized the urgent need for refurbishing the existing building stock to reach the reduction targets for 2030 and 2050 [5,10,22,23]. However, renovation rates are approximately 1% across the EU, and for deep renovations (i.e., renovation indented to lower energy use by a minimum of 60%), the rates are between 0–0,2% [5]. Thus, there is potential for improvement, which is not only limited to the reduction of emissions [5,22]. There also are economic and social benefits from refurbishments as it is an opportunity to rethink building design to create a healthier user environment and opens up necessary employment opportunities in the post-COVID-19 society [3,5,24]. Here, it is necessary to illuminate how interchangeable the terms refurbishment, renovation, and retrofit are. From hereon, the term 'refurbishment' is used as it better describes the act of improving the characteristics and functionality of a building, and it aligns with prevailing standards [25]. There is no scarcity of research aimed at lowering carbon emissions deriving from buildings through the development of different frameworks and methods for deep-refurbishment [5]. This research, for example, is often aimed at lowering operational and embodied emissions through improved efficiency of HVAC systems or improved structural systems (i.e., green concrete or replacing steel with wood). It can also be improved building envelope (i.e., avoiding heat loss or gain) and material use or improved composition of material properties to lower impacts on the environment [26–29]. Additionally, greening methods for individual buildings (e.g., green roofs and facades) are also prevalent in research, with reported success in reducing carbon emissions because of reduced demand for mechanical cooling [30]. Furthermore, applied methods frequently involve case studies on a single or small cluster of buildings that use computer software to simulate outcomes given by different retrofit packages. Consequently, results are specific for the building investigated and are non-generic when studies are conducted on a relatively small scale [31]. Thus, as mentioned earlier, some research advanced from the building to the urban scale and assessed more than one building as well as other facets of the built environment [18–20,32]. The implementation of clustering and characterization techniques enables researchers to create archetypes for large building stock. Archetypes circumvent the problem of data scarcity about individual building features and save researchers from time-consuming simulations that also demand extensive computational power [33,34]. It shortens the lead times from planning to action and aid policymakers in making mitigation decisions for building stocks [35,36]. However, it is arguable if emissions from a heterogeneous built environment can be assessed adequately with generic quantitative methods [23,37].

1.2. The lack of holistic building refurbishment assessments

The ZEN initiative for reducing emissions from the built environment is crucial, but it is still in the design and implementation stages. However, the main challenge is that the current studies foremost have focused on new neighborhoods and buildings [18–20] while the urgency is to refurbish exiting stock [5,28]. Therefore, ZEB* or ZEN is not enough, as reliance on new construction for carbon mitigation is not a satisfactory solution. Even if refurbishments are included in the ZEN framework, there is an urgency for even more focus on the existing building stock since the reported refurbishment rates in the EU are low [5]. Moreover, research aiming to lower emissions through refurbishments seems to lack the holistic perspective provided in ZEN frameworks as optimization through the use of archetypes seems to be performed on a building scale [18–20]. Hence ignorance of other aspects might result in more beneficial sustainable decisions if the scope is not expanded past the building scale. Therefore, it is necessary to investigate if previous research has approached refurbishments on an urban scale. Because then it is possible to learn from the essential aspects and potentially find the gaps to ensure future studies follow a sustainable path. The research with ZEN has foremost focused on energy while a smaller share has paid attention to emissions [19]. The research that takes emissions into account has remained on the building scale. The main argument is that research needs to attend to the other parameters contributing to a sustainable built environment [19,24]. The carbon abatement pathways for building stocks must be sought with care as the consequences of inadequate refurbishment decisions prevail for a long time [20]. Even if extensive research has been performed on the refurbishment of buildings and substantial knowledge already exists, the rate they are being transformed is not satisfactory for reaching the climate goals. Hence, the objective of this study is to find the gaps in the methods used, the scale analyzed, and sources for carbon emissions addressed in the existing refurbishment literature through a scoping review. Previous reviews on building refurbishments have analyzed parts of the issues [38–43] described, but none has taken the holistic perspective indented in this study.

1.3. Goals and structure of the article

The study's first goal is to understand the methods that have been applied to mitigate carbon emissions from buildings. The second goal is to determine if the studies are applied on a building or urban scale while determining the benefits and challenges. The third goal is to analyze how carbon emissions are addressed once the scope is expanded from the building to the urban scale. Finally, with this knowledge, the fourth goal is to find trajectories that aid future refurbishment strategies in making holistic assessments that avoid sub-optimization and increase the reduction rate of emissions. To guide the scoping review, are two questions asked:

- What research has been performed with the intention to lower emissions from buildings on both building and urban scale?
- What are the research gaps?

The structure of the article continues as follows. Section 2 presents the methodology of the scoping review. In Section 3 are the results presented from the analysis of the content in the articles which is then followed by a discussion in Section 4. Finally, from the knowledge obtained are the two research questions answered with suggestions for future research in Section 5.

2. Materials and methods

As argued by Munn et al. [44], the use of scoping reviews a preferred method when the research intends to overview an existing body of literature within a specific field to find potential research gaps. A scoping review is also an adequate method when the research questions asked are broad and holistic without the intention of confirming or denying existing practices within the selected field [44–46]. Therefore, it was determined to be a suitable method for this study considering the two research questions asked. The scoping review in this paper is adapting the framework developed by Arksey and O'Malley [47] which later saw further development from Levac et al. [45]. The structure and steps for retrieving the literature are inspired by Arksey and O'Malley [47, p.22]. The framework utilizes five steps which are (1) identifying the research question, (2) identifying relevant studies, (3) study selection,

Table 1
The table provides an overview of the scientific database and operators used when conducting the keyword search. As demonstrated, it was necessary to use different operators for each database.

Database	Operators
Scopus (S)	Article title, Abstract, Keywords
Science Direct (SD)	Title, abstract or author-specified keywords
Web of Science (WoS)	TS[a]=()
Google Scholar (GS)	Keywords (Publish or Perish Software)

[a]TS = topic.

(4) charting the data, and (5) collating, summarizing, and reporting the results [45,47]. The first step (denoted as 0 in this methodology) was presented in Section 1 and step five is covered in Section 3, 4, and 5. Thus, this section will cover steps 2–4 (denoted as steps 1–3 in this methodology). The presented methodology differentiates between mechanical steps, i.e., without the influence of subjectivity from the author, and when there is bias due to subjectivity. In addition to the obtained literature sample was a backward and forward snowball procedure performed [48].

2.1. Step 1 - Identifying relevant studies

The first step of the scoping review can be perceived as mechanical since there is no subjectivity influencing other than the two research questions that form the search string containing the keywords. The following keywords constructed the search string: (Retrofit OR Refurbishment OR Renovation) AND (CO2 mitigation OR CO2 emissions reduction OR Greenhouse gas mitigation OR Environmental impacts or Global warming) AND (City development OR Municipality development OR Urban development OR Sustainable development) AND (Buildings) AND (Location). After this, guidelines for the search were set up with the year of publication limited between 2015 and 2021, the argument for not including literature further back than 2015 is the belief that research concerned with emissions reduction in the built environment through refurbishment has intensified after the Paris agreement in 2015 [49]. Hence, significant progress and innovation are assumed to be recent, which makes analyzing further research back, which relies on even older research, not reasonable. The framework developed by Wohlin [48] was adapted for forward and backward snowballing of the sample. The literature was limited to articles to ensure high quality, and the written language was limited to English. The scientific databases and their operators are presented in Table 1.

To aid the search for articles in Google Scholar (GS) the 'Publish or Perish' software (PoP) was used to perform the searches, with the maximum number of results limited to 100 most cited for each search string [50]. To the authors' knowledge, there was no possibility to limit the search to only include articles in the software, and all non-articles were removed manually at a later stage. The search string contained too many Boolean operators or was too complex for some databases. Hence, instead of using the whole search string, combinations were used. The keywords were structured into 27 different search strings, with one of the keywords from each parenthesis for each search string. For example, was one search string structured in the following manner: "Retrofit AND CO2 mitigation AND City development AND Buildings AND Location" and another like this; "Refurbishment AND Greenhouse gas mitigation AND Urban development AND Buildings AND Location." Once preliminaries were determined, the searches were performed in the four databases, and to circumvent the problem of retaining an unmanageable number of articles, the filtering tools available in the scientific databases containing operators such as "limit-to" or "refine" were used to exclude research fields deemed non-relevant to the topic at hand.

In some instances, the number of articles was still not manageable even when using the filtering tools available in the databases. Therefore, the decision was made that if searches in the scientific databases generated more than 100 articles, they were ignored, and a new search string was entered into the database. The same procedure was utilized when searches generated zero hits. However, if a search generated 100 articles or less, they were imported reference management tool EndNote [51]. The method was used in four of the databases as the Publish or Perish software enables manual limitation to no more than 100 sources of literature per search string [50]. To make the process efficient and manageable, the removal of duplicates was continuous. The removal of duplicates was used throughout the whole process. The whole process resulted in a sample of 1299 articles.

2.2. Step 2 - Study selection

The second step of the methodology is when the subjectivity of the authors presents itself as exclusion criteria were necessary to narrow the literature sample to align with the scope of the study. The exclusion of articles was performed by first reading the abstract and keywords. The articles were then skimmed in their entirety to get an overview of the content. The articles were excluded when the topics covered in them were considered out of scope and did not provide any answers to the first research question. The procedure resulted in exclusion criteria which are presented in Table 2. The exclusion of articles was performed in a step-wise procedure (see Fig. 1). The first and second steps were simultaneously performed, which involved the removal of any grey literature, books, or conference paper obtained from the use of PoP while reading the titles and keywords of the articles. It resulted in a significant reduction to 233 articles. In the third step, abstracts were read, and it limited the sample to 96 articles. The fourth step involved skimming through articles to get an overview of the content which resulted in 88 articles for further analysis.

2.3. Step 3 - Charting the data

The 88 articles were scrutinized and categorized into an Excel matrix in the third step. The columns were color-coded and divided into four areas based on the nature of the data. The first color-coded columns contained information about authors, their origin, the article's title, publication year, and their published journal. The second color column broke down articles based on their structure. Notes were taken from each section in the articles, together with annotations of the tools, software, and frameworks used. The third color was used for columns containing any additional information that might be of interest, followed by a deeper analysis of the implications made in the articles. The last and fourth color-coded columns of the Excel sheet contained three types of information. First, the background to understand the topics presented in the articles, and second, any notable arguments made by the authors. The third column contained any new ideas obtained from reading the articles.

The third category of color-coded columns also contained a short note about the quality and potentiality of including an article in the next exclusion round by marking it red, yellow, or green. The red color deemed an article 'out of scope', yellow code equaled 'unsure', which means it needed to be thoroughly examined again in the next round, and coded green meant that it was moved in the next round. The articles were excluded in two rounds. First, all articles marked with red were removed. In the second round, the articles marked with yellow were reread before deciding whether to include them in the last sample. The procedure resulted in a reduction to 62 articles and, based upon that sample, a backward and forward snowballing [48], journal subscriptions, and tips from experts on the topic of the sustainable built environment. The backward and forward snowballing through the reading of headings in the reference lists of the 62 articles. Thus, the snowball procedure was under subjective influence during the whole procedure.

Table 2
In the table below are the exclusion criteria presented when analyzing the sample of articles obtained from the keyword search.

Articles with a focus on refurbishment to improve indoor air quality.
Articles not including buildings in their assessments
Articles limiting their scope to optimization through the use of one material type or component.
Articles with a limited scope to greening strategies such as green roofs, walls, floors, etc.
Articles covering refurbishments aiming to reduce urban heat island effects.
Articles limited to water consumption or waste.
Articles that are solely investigating heritage buildings.
Articles that only evaluate the applicability of computer software or certification programs.
Articles that only focus on refurbishment for resilience.
Articles with a limited focus on social or economical sustainability without any environmental aspect.
Articles with a limited focus on building user behavior.
Articles that only investigate the role of management or the construction process of buildings.

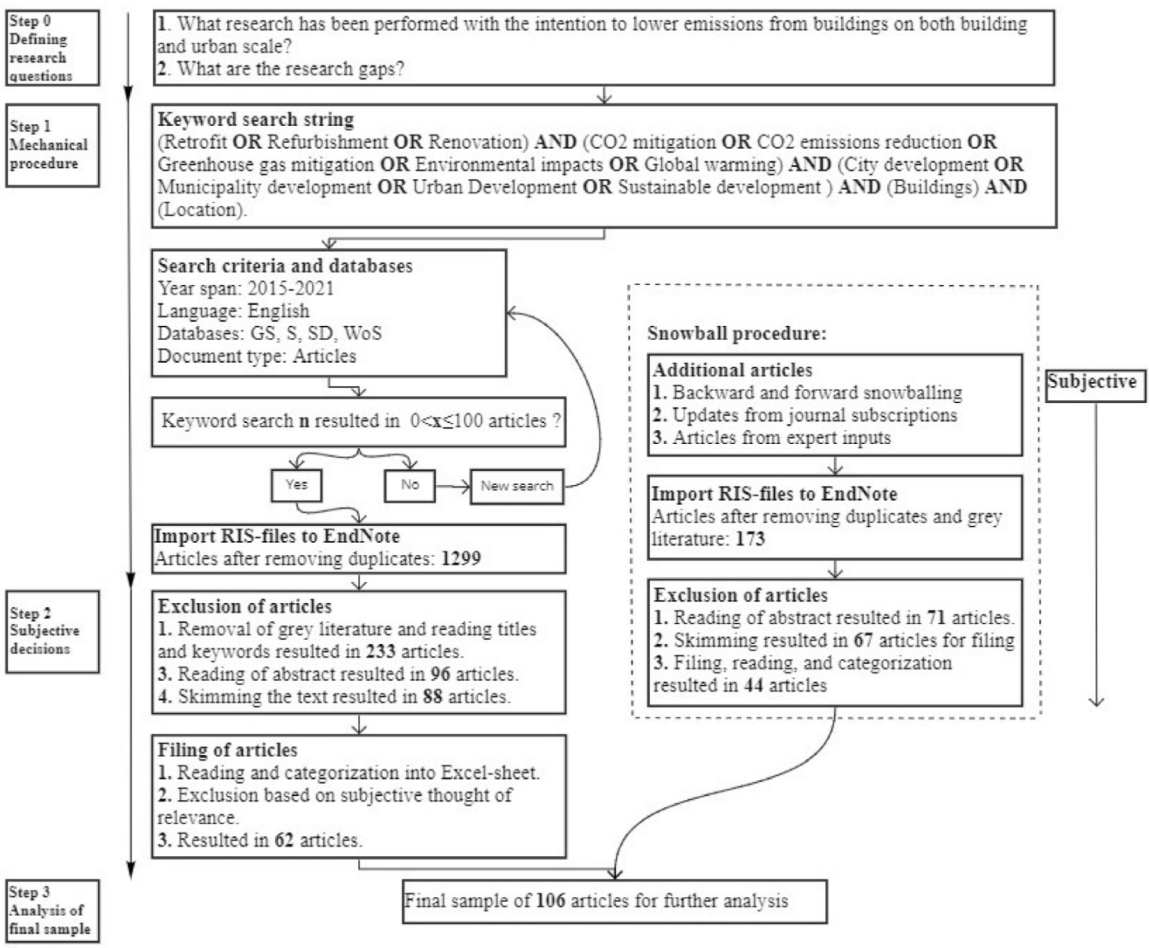

Fig. 1. The figure above explains the scoping review and snowball methodology. The points from steps 0–3 in the research methodology applied are on the right-hand side. It explains how forming the research question resulted in a keyword search string used to retrieve the literature from the selected databases. The process resulted in 1299 articles, and after four exclusion rounds, the sample was down to 88 articles for further analysis. The reading and categorization of the articles resulted in a sample of 62 articles. Moreover, after the snowball sample was taken from the 62 articles in the scoping review, a final sample of 106 articles to include in the review.

The snowballing procedure resulted in a sample of 173 articles after removing duplicates and any grey literature. The exclusion phase started with reading the abstracts, which narrowed the sample to 71 articles. After reading the main ideas, the sample was down to 67 and annotated into the Excel matrix with the same procedure as the scoping review sample. The process resulted in 44 additional articles, resulting in 106 articles when combining the results with the scoping review. The methodology of the scoping review is presented in its entirety Fig. 1. At this point, the process reached a saturation point was met since the data did not provide any new insights, and increasing the sample size would complicate rather than benefit the forthcoming analysis of the literature [52].

2.4. Limitations

First, a scoping review is more compromising than a systematic review which is both a strength and weakness [44,45]. Although, for the intended goal of this study, the flexibility of the scoping review was needed. Second, the citation indexes were not a determinant factor when selecting the articles except articles from GS in the publish or perish software. Furthermore, if citation indexes had been prioritized for the other databases used in the review, then, indeed, would the composition of the final sample of articles look different. Third, the study is limited in time, and new publications appear every day. Thus, the result would be non-identical if the work is reproduced.

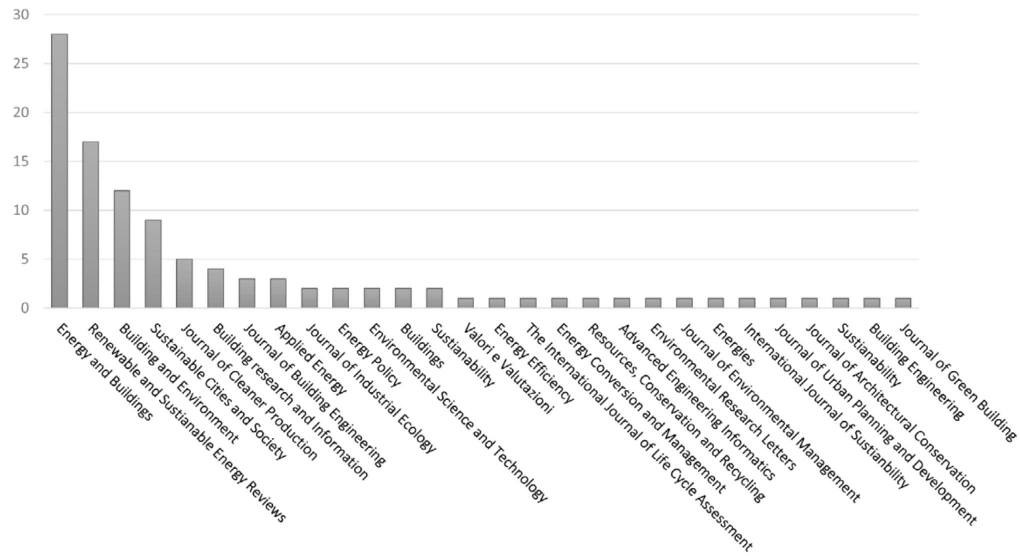

Fig. 2. In the figure are the journals that the reviewed studies are published in presented and the results show that 69% of the articles are published in five different journals.

3. Results

The following section of the study proceeds to present the result obtained from the scoping review. As no articles published earlier than 2015 were retrieved from the keyword search there was no reason for presenting a trend line over the number of publications per year. Furthermore, among the 44 articles retrieved from the snowball procedure were articles published earlier than 2015 included, but they are only a small sample based on the structured search and therefore not representative. In Fig. 2 are the journals the 106 reviewed articles were published in are presented.

3.1. *The scientific journals and case study locations of the reviewed sample*

The scientific journals varied between 28 different journals. The majority of the studies (69%) were published in five journals. They are 'Energy and Buildings' (28), 'Renewable and Sustainable Energy Reviews' (18), 'Building and Environment' (12), Sustainable Cities and Society (10), and Journal of Cleaner Production (5). The remaining 31% were published in the remaining 23 journals with 4 publications or less.

The locations of the case studies performed in the articles are presented in Fig. 3 which demonstrates that most studies are performed in Europe. Italy is the country in Europe with the highest representation (15), although when considering regions, most studies were performed in the Nordic countries (18). Next is North America, with six studies performed in the United States and five in Canada. A few of the studies took place in Asia, with one in Turkey, Iran, China, Taiwan, and South Korea. In Oceania, three studies were performed in New Zealand and one in Australia. No case studies were discovered in Africa or South America based on the findings in the sample.

3.2. *Methods utilized in the reviewed articles*

The methods used in the entire sample of 106 articles were divided based on if they used qualitative, quantitative, or mixed methods (see Fig. 4) and further broken down into five main categories: 'Life cycle method, literature review, 'multi-objective optimization, energy simulation', and 'other'.

The most utilized method in the sample is 'life cycle methods' (LC-methods). They were all quantitative, [31,53–89] except two that also include qualitative elements through literature reviews [58,90]. Articles adopting LC methods are categorized as such since they are investigating environmental impacts, cost, and energy use over the whole life cycle, and further dissection of the articles using LC methods is available in Section 3.2.1. Literature reviews are the second most frequent method of choice among the articles. All but three are conducting qualitative literature reviews [39,42,43,91–108]. The three articles identified using mixed methods are in one case using machine learning to aid a systematic scoping review [109], another performs a scientometric literature review with the tool 'CiteSpace' to visualize and map research intended to lower carbon emissions in the built environment between years of 1970–2017 [110]. The third article provides a systematic literature review with a meta-analysis of the carbon footprint o new and refurbished buildings [111]. The third approach, denoted as 'Multi-objective optimization', refers to articles that use a combination of methods to find the refurbishment solution concerning two or more parameters to create a Pareto front [85–88,112–130]. It is necessary to clarify that four of the multi-objective optimization articles were classified as articles using LC-methods as well since they combine them to find the optimal refurbishment solution [85–88]. The multi-objective optimization methods is further elaborated in Section 3.2.2. The two final methods identified in the literature are studies either performing energy simulations to investigate the impact of refurbishment based developed scenarios [131–143] or categorized as 'Other' methods [144–153]. The category 'other' represents articles with no clear distinction of how their methods should be categorized. For example, are six articles developing their methods [144–149]. And Wang et al. [150] use panel discussions and structured workshops to develop a framework based on a 100-year perspective for the future built environment. In a study, by Drouilles et al. [152] is 'peri-urban typical dwelling' defined to investigate necessary improvements in housing and mobility to meet the Swiss climate goals. Finally, a spatial planning study conducted by Dujardin et al. [151] investigates housing energy use and home-to-work mobility impacts on a large scale through the use of statistical data.

3.2.1. *Life cycle methods*

The term LC-methods is broad as it includes the articles using a life cycle approach in their studies. Hence, a deeper analysis of the articles within this category is necessary. Dividing the articles into categories based on their data collection provides an overview. Thus, categorization of the articles using LC methods was based on if they used bottom-up (process-based), top-down (economic input–output), or mixed methods (hybrid) when structuring the inventory data. Moreover, the number of impact categories varied amongst the studies.

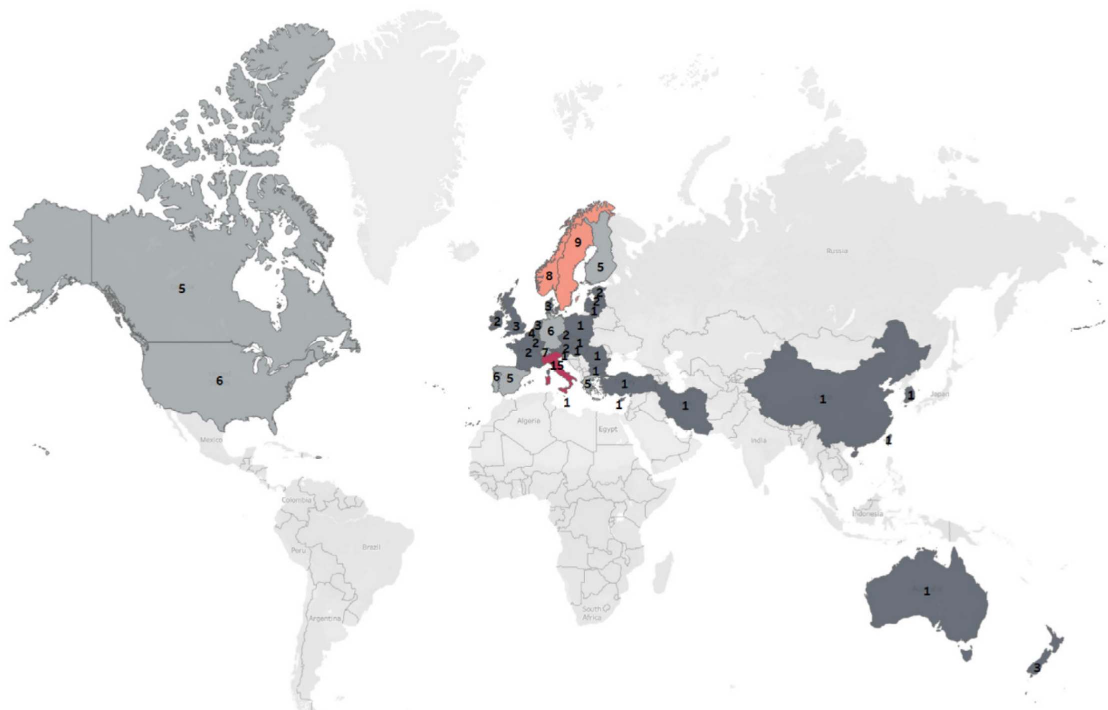

Fig. 3. In the figure above are the locations that the studies were performed presented. The results show that the majority of the studies were performed in Europe and North America while a few were conducted in Asia and Oceania. No studies were obtained from Africa or South America.

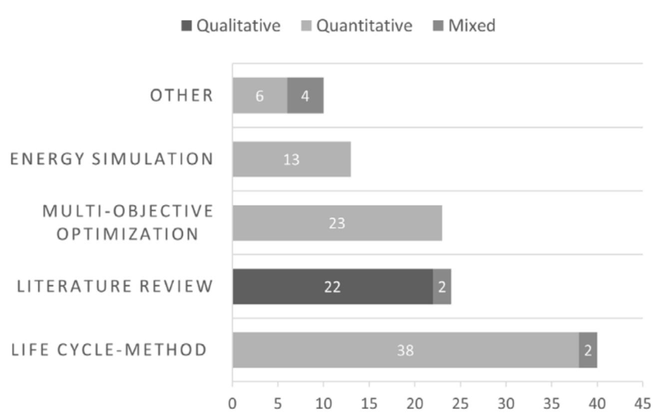

Fig. 4. The figure presents the type of methods discovered in the reviewed sample, indicating whether studies applied quantitative or qualitative approaches.

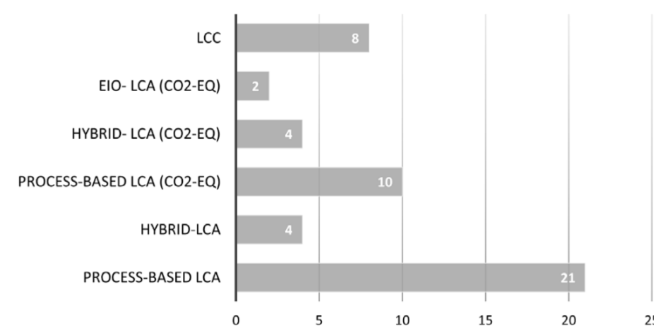

Fig. 5. The figure present is the breakdown of the LC methods used in the analyzed articles. The methods are divided based on the approach for collecting the data and whether they assess one or several impact categories. Eight of the studies also applied Life cycle costing (LCC) combined with LCA.

Therefore they were separated between articles solely investigating carbon emissions (CO2-eq) and multiple (more than two). The final result of LC methods used among the articles is summarized in Fig. 5.

The categorization of studies was straightforward for the most part, as studies often clearly stated how they obtained their data. Although troublesome at other times due to articles not clarifying how they collected their inventory data. It was decided that articles collecting data about one building and then extrapolating that data to create archetypes for representation of a more extensive building stock were using bottom-up methods. Moreover, articles using the same approach but combining statistical data are described as hybrid methods. The articles that relied on statistical or energy consumption data on neighborhood-level were identified as top-down methods even if they did not specify it. Finally, eight articles used life cycle costing (LCC) as well, meaning that they are categorized as using both LCA and LCC in Fig. 5.

A total of 40 articles were determined to use LC methods, and eight articles also combined LCA and LCC. Out of the eight articles combining LCA and LCC. Four of them were identified as using 'Multi-objective optimization methods [58,59,76,82] since they aimed to achieve Pareto-optimization. Furthermore, two articles applied two LCA methods in their studies when Yu et al. [53] compared the results between a hybrid and process-based approach and Ottelin et al. [75] primarily used hybrid LCA except when calculating the emission deriving from the construction of housing, then an economical input–output LCA method was used. A summary of the different LC-methods, scope and number of impact categories are provided in Table 3. The scope varied between building neighborhood, city, and municipal scale, and the type of buildings assessed were single-family homes (SFH), multi-family homes (MFH), rowhouses (RH), office, and institutional buildings.

The majority of studies (21) performed process-based LCA (PLCA) to investigate the environmental impacts of refurbishing an building(s). In the second group are four studies using hybrid-LCA (HLCA) to calculate

Table 3
The table below contains the articles from 2021 to 2007 that use LC methods in their research. The table presents the LC methods and scopes applied and the number of impact categories included in the studies. The articles applying LCC in their assessments are marked within the parenthesis under the 'No. Impacts' column.

Authors by year (2021–2007)	LC-method and Scope	No. Impacts
1. Yu et al. [53]	PLCA and HLCA of three neighborhoods	1
2. de Oliveira Fernandes et al. [54]	PLCA of SFH, MFH, and RH archetypes.	11
3. Rodrigues and Freire [86]	PLCA and LCC of MFH, SFH, RH in three cities.	5 (and cost)
4. Kayaçetin and Tanyer [55]	HLCA of three neighborhoods.	1
5. Ghose et al. [56]	PLCA of 119 office building prototypes.	12
6. Hu [57]	PLCA of an university campus.	5
7. Ghose et al. [63]	PLCA of an office building.	12
8. Feng et al. [58]	PLCA and LCC of SFH in Vancouver, Canada.	15 (and cost)
9. Prabatha et al. [59]	PLCA and LCC of SFH in 13 Canadian cities.	1 (and cost)
10. Fenner et al. [60]	PLCA of an university building.	1
11. Lausselet et al. [62]	PLCA of a ZEN.	1
12. Mastrucci et al. [90]	HLCA of a municipality in Esch-sur-Alzette, Luxembourg.	1
13. Lausselet et al. [61]	PLCA of ZEN.	1
14. Ghose et al. [154]	PLCA of 17 office buildings.	12
15. Huang et al. [64]	PLCA of a city.	1
16. Drouilles et al. [65]	PLCA of MFH, SFH, and mobility in Switzerland.	2
17. Österbring et al. [66]	HLCA of MFH in Gothenburg, Sweden.	15
18. Conci et al. [87]	PLCA and LCC of five MFH in Damstadt, Germany.	1 (and cost)
19. Berg and Fuglseth [67]	PLCA of a SFH.	1
20. Moschetti et al. [88]	PLCA and LCC of an nZEN office building in Bergen, Norway.	2 (and cost)
21. Marique and Rossi [68]	PLCA of an office building.	2
22. Lavagna et al. [69]	HLCA of MFH and SFH (three climate zones in EU).	15
23. García-Pérez et al. [31]	PLCA of the metropolitan area of Barcelona	6
24. Wrålsen et al. [70]	PLCA of MFH.	11
25. Assefa and Ambler [71]	PLCA of university library.	7
26. Bastos et al. [72]	PLCA of MFH and SFH.	2
27. Passer et al. [73]	PLCA MFH.	3
28. Pombo et al. [85]	PLCA and LCC of MFH in Madrid Spain.	7 (and cost)
29. Gauk and Roose [74]	PLCA of peri-urban area.	2
30. Ottelin et al. [75]	HLCA in inner, outer, and peri-urban areas.	1
31. Vandenbroucke et al. [76]	PLCA and LCC of student housing.	1 (and cost)
32. Anderson et al. [77]	PLCA of MFH, RH, and SFH.	1
33. Beccali et al. [78]	PLCA of SFH.	6
34. Famuyibo et al. [79]	HLCA one MFH, one RH, and one SFH.	2
35. Saner et al. [80]	EIO-LCA of housing in Wattwill municipality, Switzerland.	1
36. Stephan et al. [81]	HLCA of neighborhood in Melbourne, Australia.	2
37. Heeren et al. [82]	PLCA and LCC of building stock in Zurich, Switzerland.	2 (and cost)
38 Pauliuk et al. [89]	PLCA of SFH upscaled to represent the Norwegian building stock.	2
39. Norman et al. [83]	EIO-LCA of the city of Toronto and Markham, Canada.	2
40. Itard and Klunder [84]	PLCA of two neighborhoods.	10

environmental impacts on a larger scale, such as multiple buildings (three)[79], on a neighborhood scale [81], on city scale [66], and country scale [69]. The same scale was prevalent in the four HLCA studies that investigated one impact category [53,55,75,90]. Among the remaining 16 articles, only investigating a single impact category (CO2-eq) is the process-based method, the most frequent, with two studies using EIO-LCA [75,80].

3.2.2. Multi-objective optimization methods

The 'Multi-objective optimization' method is the second category that is necessary to explain more explicitly than in Section 3.2. It refers to the 21 articles from the scoping and snowballing that utilized a combination of methods to find the optimum building refurbishment solution by measuring at least two parameters. The articles investigated optimum refurbishment solution based upon at least two [85–87,112,115,116,118,120,123,124,126–129] but sometime three measurements [88,113,114,117,119,122,125,130,135]. A summary of the optimization measurements (cost, energy, emissions, thermal comfort) and methods used in the 21 articles to find the optimal solution is provided in Fig. 6.

Every article (23) used at least some type of monetary measurement (LCC, global cost, or investment cost) and measured it against energy use (16), carbon emissions (11), or thermal comfort (2). Furthermore, about half of the articles (12) used Pareto-optimality to find the solution where improving one parameter will come with trade-offs with the other [85,87,113,117,119,120,122,123,128,136]. To circumvent the problem of the extensive time needed to simulate different outcomes from a variety of solutions, some applied mathematical optimization methods. These are artificial neural networks (ANN) [113,126], genetic algorithm (GA) [112,113,122,126,127], combination of GA and A*-algorithm (GAA*) [125], multi-objective mixed integer nonlinear programming model (MINLP) [117,126], Non-dominated Sorting Genetic Algorithm (NSGA-II) [130], and Latin hypercube sampling (LHS) [114]. The articles (9) that did not use any of these approaches to find the best solution utilized energy simulation software to investigate refurbishment packages or developed scenarios and combined it with global cost (GC) calculations according to the existing EN 15459-1:2017 framework [114–116,122,123,155] or with LCC methods [119,124,127,128]. Finally, as previously mentioned in Section 3.2.1, four articles combined LCA and LCC frameworks to find the optimal solution [58,59,76,82].

3.3. Building scale and types analyzed in the reviewed sample

As aforementioned in the introduction of this review some studies are moving from a single building perspective to include more than one. Therefore are the scales refurbishment studies are applied, building types assessed and ownership analyzed in this section. In the sample of 106 articles, 61% assessed more than two buildings, and 19% had a single building perspective, while the remaining 20% of the articles did not clarify. A summary of the building types covered in the case studies from the literature sample is presented in Fig. 7. From the results in Sections 3.2.1 and 3.2.2 it was discovered that several articles performed refurbishment case studies on neighborhood [53,84,136], city [31,59,64,66,114,124], regional [90,116] or even country scale [54,56,65,79,

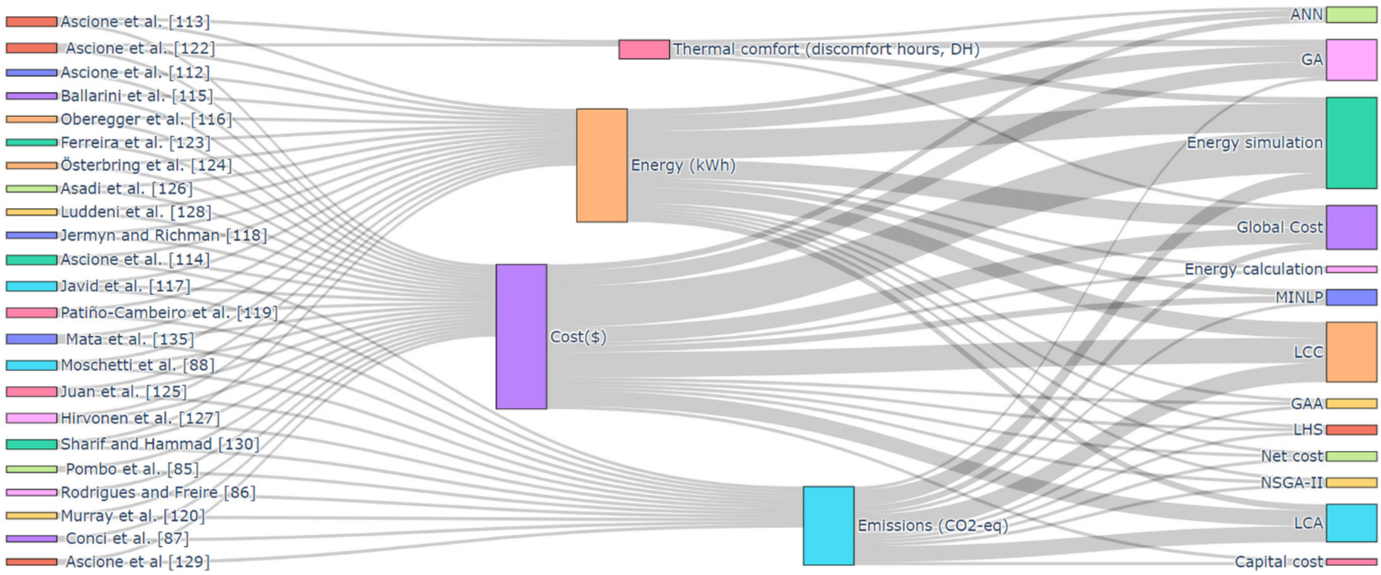

Fig. 6. The figure above presents the four parameters used in the literature to find the optimal solution and the methods and techniques applied in the studies.

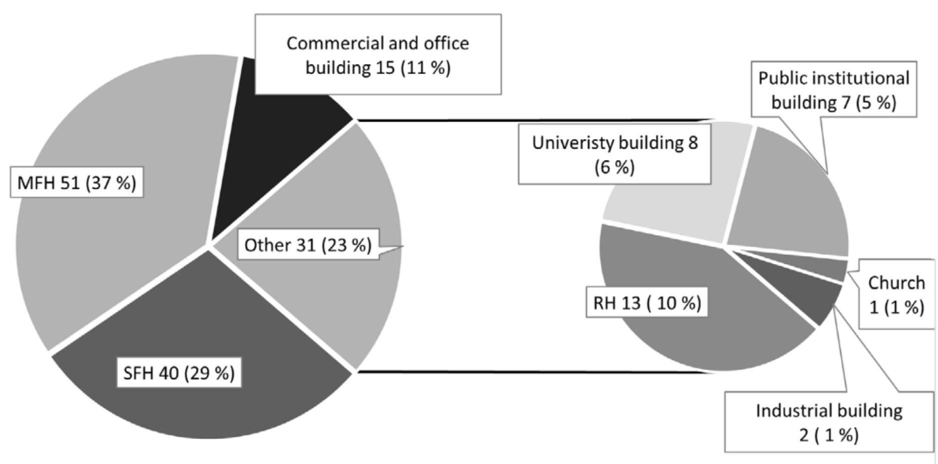

Fig. 7. In the figure above are the building types that were identified in the sample of 106 articles presented. As demonstrated in the figure, most of the studies perform research on SFH and MFH. Whilst less research is performed on buildings categorized into the 'other' category.

85,115,128]. The studies used archetypes [54,59,65,79,114], building-by-building aided by geographical information system (GIS) [31,66,90,116,136] (see [96]) for further explanation), and top-down statistical data [53,56,64,85,114,115,124,128] to calculate the effects of refurbishments of large building stocks.

Furthermore, the most common building types are MFH (37%) and SFH (29%). Among the non-residential buildings are commercial, and office buildings represented 21 times (11%). The less researched buildings among the reviewed articles are categorized under an umbrella term named "Other". Among them were 12 RH, eight university buildings, one church, and two industrial buildings. Furthermore, there were four public schools, two care homes, and one hospital categorized under the term"public institutional buildings". An attempt was made to determine how the buildings were governed. The intention was to detect whether either private or public actors might be overrepresented among the building owners. However, this proved to be difficult as most of the studies did not state the ownership type. The building owner could not be determined in 61% of the articles, and when it was possible, they were 18% public, 7% private, and 14% a mix between the two.

3.4. Induced-mobility emissions

The introduction (Section 1) explained that reducing embodied and operational emissions in buildings have seen active research. However, as studies now widen their scope to become more 'holistic', it is intuitive to investigate any other sources of carbon emissions derived from buildings. Thus, this section presents the findings among the authors in the 106 articles that considered other sources than embodied and operational building emissions.

A total of 11% (i.e., 12 articles) investigated other sources of carbon emissions and 10 of them expanded the scope to include the mobility of building users. In one of the articles, Anderson et al. [77] asserts that substantial emissions are omitted when performing assessments on either a building (e.g., optimization measures) or urban scale (e.g., density, transportation, and infrastructure). Therefore, the authors investigate the relationship between buildings and the surrounding urban environment and introduce the concept of induced impacts caused by the location of the buildings. From hereon is the terminology 'induced-daily-mobility' presented by Drouilles et al. [152] adapted and reformulated to 'induced-mobility emissions' used to describe this source of emissions. The term refers to emissions deriving from the transportation activities of a user that travels to and from

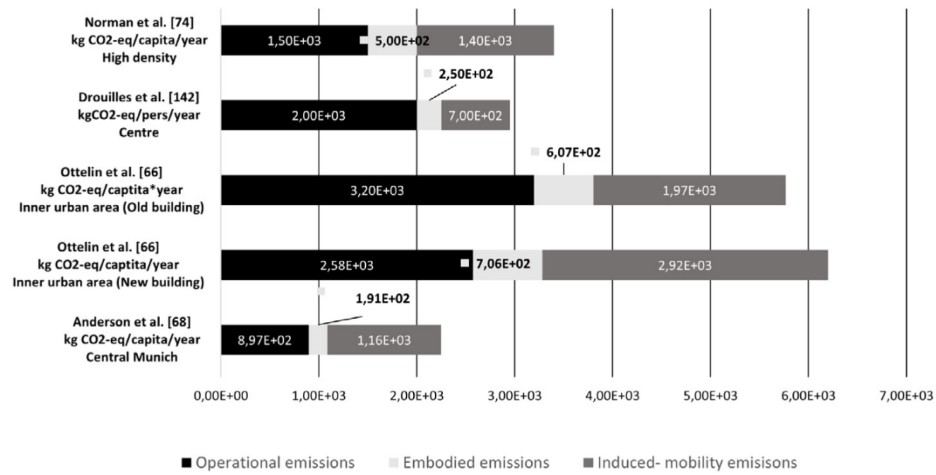

Fig. 8. In the figure are the share of embodied, operational, and induced-mobility emissions presented from the studies that evaluated emissions in areas interpreted as dense. The results demonstrate that induced-mobility emissions constitute a significant share of the total emissions deriving from the buildings in central areas. In one scenario, the induced-mobility emissions are higher than the operational emissions from the buildings [77].

the building by different modes of transport. The results from the studies indicate that induced-mobility emissions are contributing to a significant share of the total emissions due to the location of buildings and should not be ignored [53,60,61,65,72,74,75,77,80,81,83,152]. In an attempt to analyze the share of the total impacts (in kg CO2-eq), the results of five studies were collated [75,77,81,83,152] into Fig. 8 and 9. They were selected because the authors in the articles calculated embodied, operational, and induced-mobility emissions. The five articles used similar scenarios or urban scales in their assessments. Thus, it was possible to summarize the studies that investigated emissions in high to low-density areas. For example Drouilles et al. [152] calculated emission and energy scenarios for inhabitants living in central, suburban, peri-urban, rurban, and rural areas of Switzerland. Their results for the central, suburban, and peri-urban scenarios were collated in Fig. 8 and 9 since being comparable to the other studies that were selected. The results from the five analyzed studies are divided into two categories based on the urban morphology being investigated in them. In Fig. 8, the studies performed in densely populated areas are presented, while Fig. 9 presents the reported emissions in the articles investigating carbon emissions in areas with an urban morphology that is perceived as less dense.

The results demonstrate that embodied emissions are the lowest emissions in all studies and operational emissions are the highest in all except for one case [77]. The authors in Anderson et al. [77] calculate emissions with the use of building archetypes for three urban scenarios and building types in Munich, Germany. One dense scenario with MFH in central areas, another with an RH in the periphery, and the third scenario with an SFH at the district level representing Munich's rural and suburban areas. The study included embodied emissions from transportation as well as the infrastructure needed for the modes of transport, which was unique since the other articles only considered the operational emissions deriving from induced mobility. Another approach by Ottelin et al. [75] calculated the impacts of consumption for inhabitants living in new and old housing located in central (inner urban areas), suburbs (outer urban areas), and peri-urban areas. The housing and mobility emissions are included in consumption. A notable finding in the study is that emissions deriving from new housing in central areas are higher than for old housing. Three categories for housing and mobility are included in the collated result presented in Fig. 8 and Fig. 9. The emission categories denoted by Ottelin et al. [75] as 'construction' is interpreted as embodied emissions. The categories described as 'housing energy' and 'housing other' were interpreted as operational emissions. The 'private driving, fuels', 'private driving, other', and 'holiday travel' were categorized as induced-mobility emissions in this study. The category presented as 'public transit' was assumed negligible since the values were small and not annotated in the article [75]. In the study, by Stephan et al. [81] the three sources of emissions (embodied, operational, and induced-mobility) are calculated for a suburban neighborhood in Melbourne, Australia, with a 100-year perspective. They calculated one base case (BC) scenario and three other development scenarios for the neighborhood. The results from the BC were included by dividing the calculated lifetime emissions for the neighborhood by 100. A similar study by Lausselet et al. [62] was discovered in the sample as well, although not presented in Fig. 8 or Fig. 9 since it was not possible to provide a fair representation of their results. The study developed scenarios for housing and mobility in future ZEN in Norway and concluded that emissions deriving from mobility are the highest for the baseline case of a ZEN in a Norwegian context. The last study not covered in Fig. 8 and 9 is from Norman et al. [83] which compared the emissions for the development of high and low-density areas, with the former being presented in Fig. 8 and the latter in Fig. 9. The authors calculated the annual emissions per person and square meter, with the results per person being presented in Fig. 8 and 9.

The results changes with a less dense urban morphology, and the induced-mobility emissions become higher than the operational in half of the cases [75,77,83]. The explanation is that the less dense areas increase the travel distances and dependency on the carbon-based modes of transport. It is revealed in the study by Norman et al. [83] when the scenarios for high and low-density areas in Toronto are benchmarked against each other. The study by Ottelin et al. [75] compares housing emission scenarios based on inhabitants' consumption when living in new and old housing. The results reveal that the share of induced-mobility emissions is higher than operational emissions in the scenarios with new buildings. In the article by Anderson et al. [77] the emissions increase overall for the periphery and district of Munich, although the relation between the emission categories does not change. In the article by Drouilles et al. [152] are the induced-mobility emissions lower than the operational although surpassing the national target (960 kg CO2-eq/pers/year) set for 2050 in the peri-urban scenario but not in the suburban case. The induced-mobility emissions do not surpass the operational emissions in any scenarios. The article by [81] was not included in Fig. 8 since the study was solely performed in a suburban scenario.

As mentioned earlier, 12 articles evaluated more than two sources emissions related to buildings, although their results were not presented in Fig. 8 nor 9 due to not fulfilling the requirements mentioned earlier. Nevertheless, it is worth mentioning their findings. The first study

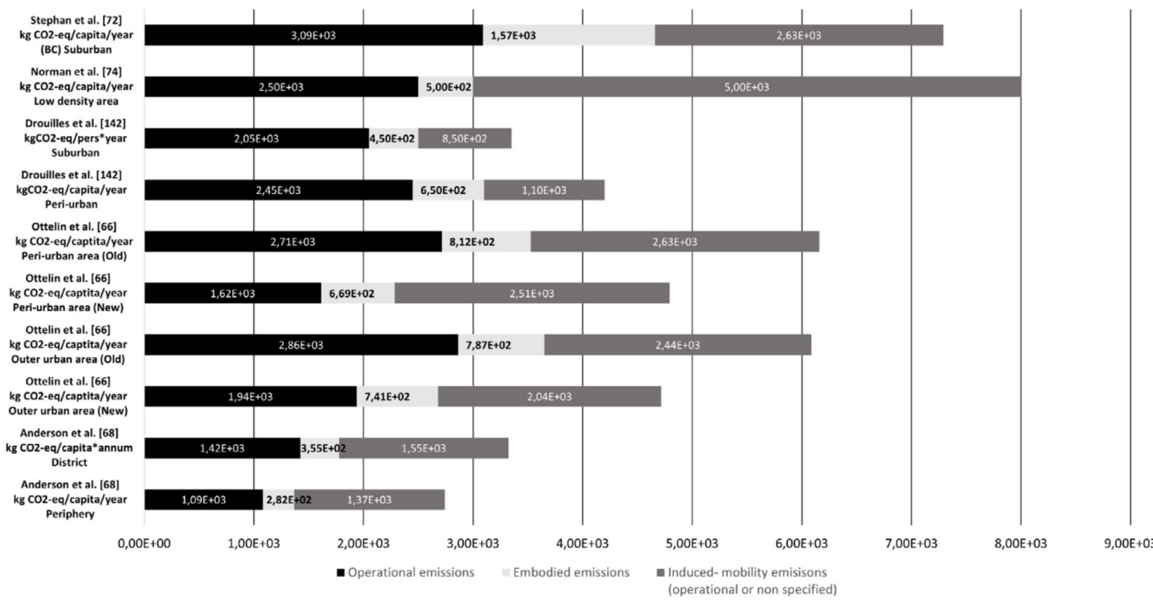

Fig. 9. The figure shows the share of embodied, operational, and induced-mobility emissions presented from the studies that evaluated emissions in areas that were interpreted as less dense. In 50% of the scenarios, the induced-mobility emissions exceed the building operational emissions. The article by Stephan et al. [81] has been added since it investigates emissions in a suburban neighborhood. Furthermore, Ottelin et al. [75] demonstrates how the share between the emission sources changes once new energy-efficient buildings are addressed instead of old ones based on the consumption of the inhabitants. Anderson et al. [77] expanded the scope for mobility when including embodied emissions from the vehicles and necessary infrastructure.

not represented in Fig. 8 and 9 were by Yu et al. [53] who reported induced-mobility emissions are the highest in their study case study of a precinct outside Adelaide in Australia, with the lifetime set to 50 years. In the article by Gauk and Roose [74] emissions were calculated for three different housing types (MFH, SFH, and semi-detached) in the peri-urban area of Tartu in Estonia. They presented the results as per dwelling and square meter. They concluded operational emissions to be the highest, followed by transport which will increase if the urban sprawl pattern continues in the city. Fenner et al. [60] calculated the embodied, operational, and induced mobility emissions for a campus building in Gainsville, Florida, USA, and concluded that the operational phase is contributing to the majority of the emissions although the importance of induced mobility emissions will increase as building energy efficiency improve.

Furthermore, among the 12 articles that calculated induced-mobility emissions, they considered the location of buildings through the separation of commuting and leisure trips. However, Saner et al. [80] calculated in similarity to [75] total emissions based on consumption and created rasterized maps with average LC-emissions for housing and mobility per hectare and person in Wattwil municipality, eastern Switzerland. They used the software MATSim to simulate operational transport emissions induced by commuting, shopping, and leisure from inhabitants, thus making a distinction between shopping and leisure [80,156]. In the assessment performed by [75] consumption was included, in which induced-mobility emissions are a part. The role of the location for housing was investigated for consumption as a source of emissions from residents living in new and old housing in three types of urban areas. The assessment includes embodied, operational, and induced-mobility emissions as well as other consumables. An HLCA reveal that residents living in inner urban areas have higher kg CO2-eq/year per capita than the less densely populated areas, even if they live in old or newly built homes. Hence, the authors illuminate that building densely populated areas are not a generic recipe for reducing induced-mobility emissions, but rather should optimization be grounded in the prerequisites of each area-type to enhance the strengths of both urban and suburban areas, which in turn enhance the overall sustainability [75].

The articles that included induced-mobility emissions performed their studies on an urban scale and primarily focused on the carbon emissions over a lifetime or per year. The articles that included a refurbishment stage in their assessments [65,72,75,77,81,152] did it as part of the use stage in the building life cycle [157]. However, none of the articles solely investigated the potential reductions of refurbishing an existing building while including the three emission sources. Drouilles et al. [152] concluded that refurbishments are necessary to achieve the emission abatement target for 2050 in Switzerland, when investigating a scenario of aligning buildings with the highest energy label. In another article from Drouilles et al. [65] a comparative LCA of new and refurbished buildings are conducted through the use of MFH and SFH archetypes. The authors analyze the whole building stock of Switzerland with the inclusion of induced mobility emissions and conclude that an 85% reduction of GWP (kg CO2-eq) is possible. The remaining articles that excluded the refurbishment stage did so because of data scarcity [53] or no reason given [60,74]. Others stated how imperative refurbishments are for the decarbonization of the built environment. For example, Saner et al. [80] claims that the best method for reducing the emission of buildings in Wattwill is by refurbishing them and keeping the square meter per capita limited. The authors in [62] claim that future LCA models on a neighborhood scale needs to include refurbishments to understand the impacts of existing buildings that will evolve in neighborhoods over time.

The section has presented a deeper analysis of the results in the articles that calculated induced-mobility emissions. It has demonstrated a significant mitigation potential of total carbon emissions, although, considering the studies, variations in how to approach induced-mobility emissions exist. Finally, it is essential to elucidate the fair share of literature reviews in the sample that also provided discussions of induced-mobility emissions [43,60,93,94,96,104,137]. Fenner et al. [91] describe how the induced-mobility emissions constitute a significant share of the total emissions deriving from a building over its lifetime and urge future research to include them in life-cycle assessments. Three review articles state a need to expand from building to urban scale as potential improvements for reducing emissions are omitted with a single building perspective. It is, therefore, necessary to bridge the gap between studies performed on the two scales to investigate the link between buildings, user transportation, and urban form to make informed decisions about the best carbon mitigation strategy [93,94,96]. Lotteau et al. [104] conduct a critical review of life cycle assessment studies on a neighborhood scale and divide the neighborhood into four fields (buildings, open spaces, networks, and mobility). They discovered that 28% of reviewed papers account for all steps and only 14% account for buildings and mobility. In the review article by Vilches et al. [43] it is claimed that more research is needed that combines or compares transport and building emissions as it is not currently covered in the sustainability of construction works standard (EN-15978:2011) despite being a significant contributor to total emissions. In a forecasting article are Wang et al. [137] explaining that future buildings will be connected to the transportation network and, therefore will it be more robust couplings between user transportation and the building itself.

4. Discussion

4.1. The location of refurbishment studies

Most of the reviewed articles conducted their research in Europe, and three explanations might be possible. First, the reports from the EU reveal that the European building stock has, in a sense, already been built. Thus, it is already or will be old when the deadline to reach the carbon abatement goals for 2050. Hence, it is necessary to refurbish the existing building stock to reach that goal [6,20,22,23]. Second, the EU demonstrates motivation to take the lead in reducing emissions deriving from the built environment and urges countries to refurbish existing stock and increase the low refurbishment rates [6]. Third, the reported situation is most likely representable for the whole European building stock, thus not limited to EU member states [4,6] since studies occurred in non-member states such as Norway which is also explained by the shared vision for reducing emissions in the built environment [16,18,20]. Ten studies were performed in North America, and all of them except one within the yearly limit range (2015–2021) set for the scoping review [39,42,43,91–111]. It might also indicate that this is a 'recent' research topic and less debated, or perhaps is the same urgency to reduce emissions from the existing building stock not as prevalent. In the remaining parts of the world, few studies were applied, indicating that the building stocks are in an expansion phase or simply because the topic is less frequently researched. However, the scoping review had certain limitations (See Section 2), and an extension of the yearly limit and sample size would deny or confirm this notion.

4.2. A life cycle approach

A frequent approach used among the articles in the sample was the LC method. They are adequate for evaluating the environmental and economic burdens coupled with the emission abatement strategies for existing building stocks. It was sought for and recommended to use life cycle assessment (LCA) for determining the best path to carbon neutrality in buildings and neighborhoods [19,21]. The results presented in Fig. 4 reveal that they were also applied frequently among the articles analyzed in this review as well.

It was a strenuous task to analyze the LCA methods used in the articles as the description of which and how they were applied varied. Thus, a discrepancy might be prevalent between how the LCA methods were interpreted in this review and the authors' intention in the analyzed articles. Therefore, a simplified approach was used to categorize their approaches for collecting their inventory data. The results showed that studies using PLCA assessed fewer buildings while the studies using HLCA generally assessed impacts on a larger urban scale. However, most of the analyzed LCA studies utilized a PLCA that is data-intensive and problematic when aiming to assess multiple buildings on an urban scale. Hence, Ghose et al. [154] calculated 12 impact categories for 17 office building refurbishments in New Zealand which later increased up to 119 office buildings [56,154]. To avoid collecting inventory data from every building, were archetypes used which was a recognized technique for overcoming the problem of insufficient data. Nevertheless, the built environment is heterogeneous, and even though archetypes enable the assessment of multiple buildings, data availability is still an issue [33,34]. Pasichnyi et al. [33] describe how data availability in the segmentation (classification of building types) and characterization process determines the accuracy of the results. A realization from the article sample was that most of the analyzed articles utilized archetype techniques limited to specific building types [54,56,59,61,154] while only a few expanded to an urban scale [31,65,66,79,82,89]. Thus, indeed, it seems like it is difficult to find generic methods to calculate emission shares in the heterogeneous built environment in an accurate manner [23,37].

The number of impact categories varied among the studies, with a mean of five while the median was two. The studies performed on a neighborhood, city, or national scale included few impact categories, with carbon emissions (CO2-eq) being the most common. There is no denying that reducing carbon emissions in the built environment is of utmost importance and that governmental organs such as the EU is communicating the urgency to reduce CO2-eq [4,6] have certainly increased the research as well. Nevertheless, there is a risk of problem shifting when only focusing on a few impact categories. The most sustainable outcome from an environmental perspective is potentially omitted as the optimal refurbishment packages for reducing CO2-eq might cause other impact categories to increase [21]. Thus, future studies should include more impact categories even if governmental bodies such as the EU are urging the reduction of a specific impact category (e.g., CO2-eq) to meet the climate goals for 2050. Expanding the LC methods to an urban scale is challenging, and more research would benefit the cause of finding the optimal approach. Most of the studies applied a PLCA, while the HLCA seems to have the best potential as it benefits from both top-down and bottom-up methods. Finally, higher clarity of the scope and application of LC-methods are sought in future studies since it would make the results easier to interpret, replicate, and compare.

4.3. The challenge of finding the optimal refurbishment strategy

Using multi-objective optimization indicates that cost is an issue for implementing an optimal refurbishment strategy, considering that all the articles applied cost as one of the parameters. The use of cost as a parameter was especially prevalent in the articles that analyzed private housing [85–87,112,115,116,118–121,123,124,127] which means that cost is as important or even more critical than reducing carbon emissions and energy use. The results of the scoping review revealed that 61% of the articles investigated MFH or SFH, which was reflected in the multi-objective optimization studies, since much effort, was made to overcome the economic threshold for private homeowners in conducting refurbishments [85,112,115,118,119,121,123,127]. In the introduction, it was mentioned that it is difficult to achieve a fair representation of the heterogeneity in the built environment [23,37] once the scope is widened to an urban scale. Pombo et al. [85] illuminated the difficulty of fair representation of entire building stocks and relied on the most common building type in the Spanish stock instead. Findings in the literature also described the difficulty of having a balance between accuracy and scale [96]. To make more accurate assessments, five articles from the review applied a building-by-building approach aided by GIS [31,66,90,116,136]. Mastrucci et al. [96] describes in their review that it improves accuracy although data-intensive, thus not applicable when the scale becomes too large. Hence, as mentioned by Pasichnyi et al. [33] and Ali et al. [34] in Section 1 archetypes demand less computational power, thus allowing more assessments on large scales, but the lack of detail makes results less accurate. The issue was explained that the classification and characterization of buildings, to a large extent, depend on qualified guesses [96]. The use of machine learning might improve the accuracy over time, considering the results presented in Section 3.2.2.

Finding the optimal refurbishment strategy for an exiting building is time-consuming, and many studies attempted to avoid this through machine learning methods with multi-objective optimization. This approach was proven helpful as it enables almost unlimited opportunities for testing building refurbishment scenarios [117,125,126,130]. However, it does not circumvent the demand for data as training the algorithms is data-intensive [126] and requires deep knowledge from the user [113,126] which makes the learning curve steep. Thus, at this point, it is questionable how it will exceed from the realm of the scientific field to the public and private sector. The usability of multi-objective optimization is high when the scope is expanded from building to urban scale as the possibility of potential solutions increases, and Pareto-optimality is an effective method of communicating the best refurbishment solution. The application of many different techniques reveals no standardized method for finding Pareto optimality. The primary focus is currently on three parameters (energy, cost, and carbon emissions), including thermal comfort in a few cases. Hence, future studies should continue the evolution of multi-objective optimization as there are many possibilities for the inclusion of other parameters that could help fill the gap of dimensions not currently considered on an urban scale.

4.4. The municipalities and a sustainable built environment

The studies to find the Pareto optimal solution aimed at emission or energy reduction solutions considering the cost of the actions taken. Moreover, the majority (61%) performed case studies investigating homes (MFH and SFH). Thus, it seems that the optimal refurbishment strategy is determined by the capital of the building owner, even if it might not be the best refurbishment solution from an environmental perspective. Furthermore, considering that every building owner has their prerequisites regarding available capital to invest in refurbishing existing buildings, it is burdensome and time-consuming to find the optimal strategy for multiple buildings. This time and cost aspect is perhaps partly an explanation for why the refurbishment rates are low in Europe [6]. However, this is only a notion, and no answer about the role of the building owner can be provided in this regard. Therefore, it is recommended to consider the aspect of the building owner incentive for refurbishment in future studies. Few studies in the sample of 106 articles analyzed mentioned the governance of the buildings. However, considering the over-representation of homes, it is assumed that fewer performed assessments on public buildings. Although this study could not confirm and thus future studies should investigate it further. For example, public buildings, like school buildings, were less frequently investigated than MFH and SFH in the articles analyzed. It is an exciting thought to change the perspective from private homeowners to public buildings on a municipal level. Unlike private building owners, an investment on the municipal level can be perceived as less exposed to financial risk. Municipalities have the opportunity to lead the way for the private sector. They can make "securer" investments since working with longer time horizons and, in general, larger building stocks than private owners, which entails making a more significant contribution to reducing emissions deriving from buildings. Moreover, school buildings are, in a sense, less complex compared to dwellings since the user profile and the building are generic. The refurbishment packages for reaching ZEB* standard can perhaps be more generic than private dwellings since the user profile can be considered the same or similar for all school buildings. Municipalities can lead the way in the future by setting an example, by decarbonizing their buildings. Fenner et al. [60] conducted a study on a university building with an urban perspective and discovered operational emissions to be dominating, although a building with a higher standard (e.g., ZEB*) could potentially change the outcome. This study did not investigate refurbishment strategies but provided another perspective—the importance of the location of public buildings such as schools when determining the optimal refurbishment strategy. Hence, more research is needed on this perspective since building users travel to and from public buildings such as universities and schools daily. Moreover, if the goal is to achieve ZEB* or ZEN standard, then the mitigation potential might be more significant if mobility is included in the assessments [20]. The development of a framework for how municipalities potentially can evaluate if this is necessary and perhaps a more significant reduction of emissions on an urban scale which is necessary considering the low refurbishment rates in general [6,19].

4.5. Inclusion of other emissions sources when the scope is expanded

The induced-mobility emissions are the most insightful finding from this study. Because the aspect of induced-mobility emissions revealed that carbon emissions deriving from the user's mobility are high due to the location of the buildings, and these emissions are either the highest or second-highest among the studies that assessed them. Vilches et al. [43] touched upon the issue in 2017 and asked for more research. However, few studies in the sample researched the topic. Thus, whether holistic assessments can be ensured if they are omitted? It is necessary to make holistic assessments of buildings to avoid the risk of sub-optimization and carbon lock-in effects that will remain for the functional lifetime of the building. Most of the studies focused on single and multiple buildings but omitted mobility and consumption. So there is a potential for more efficient carbon reduction if they are calculated as well since it might make more sense to lower induced-mobility emissions than operational or embodied emissions. Especially when considering the fair share of studies performed in the Scandinavian countries that rely on low-carbon electricity mixes [61,62,66,75,89]. It is not only prevalent in Scandinavia as decarbonization of the electricity mix is a global endeavour [3]. Fenner et al. [60] concluded that future energy-efficient buildings might change the relationship between operational and induced mobility emissions. The results from Ottelin et al. [75] indicate that the importance of induced-mobility emissions increases once old housing is replaced with new energy-efficient housing as operational emissions are lowered. Thus, for countries relying on low-carbon energy, it is essential to be aware of these aspects since, from a broader perspective, the induced-mobility emissions might be higher than those related to the building when applying carbon mitigation assessments on an urban scale. Moreover, the necessary decarbonization of the electricity mixes will further change the relationship between operational and induced-mobility emissions. Hence based on the finding, it is recommended to be aware of this if the aim is to achieve a holistic perspective in future assessments.

That few refurbishment articles included induced-mobility emissions in their assessments is a clear research gap. However, the 12 articles that included them were primarily not aiming at finding the best refurbishment solution any more than considering the stage in the existing standard when assessing buildings over their whole lifetime. Moreover, they also had an urban planning perspective for developing new neighborhoods, albeit the problem is the existing buildings. Therefore, future building refurbishment studies should take the holistic perspective of urban studies and include the induced-mobility stages in future frameworks. The total potential for reduction of CO2-eq might be higher if this perspective is considered in the studies. The ZEN framework includes user mobility when making assessments on a neighborhood scale [15,18,20,61] and considering future refurbishments assessments. It makes sense to adhere to these guidelines to include induced-mobility emissions since higher reduction on an urban scale might be achieved. Thus, the argument about the location of buildings when investigating the most beneficial refurbishment strategy. By referring back to the perspective of assessing buildings on the municipal level, it could be better to change the location of the building instead of refurbishing it. The induced-mobility emissions might be reduced to a higher degree than the emissions savings of the building if another location is considered. However, the relocation of a dwelling is complex, and, therefore, the suggested strategy should be investigated for non-residential buildings. It is suggested that further research should investigate the role of induced-mobility when finding the optimal refurbishment solution for public buildings. The carbon abatement strategies for existing buildings indeed should expand from the building to the urban scale to ensure a sustainable future and that it might circumvent the low refurbishment rates [6,15,20,77] even if there are difficulties in comparing the results in Fig. 8 and 9 since they perform the assessments with different prerequisites. The relation between embodied, operational, and mobility emissions differentiated a lot. The reason can be partially explained by the building types, energy mixes, energy systems, and materials used. However, induced-mobility emissions were foremost assessed regarding the operational phase, which resulted in higher operational emissions in dense areas. Nevertheless, the studies that also considered embodied emissions of transport modes and infrastructure revealed that the relationship could change between emissions deriving from mobility and the operational phase. Lastly, where to cut the system boundary seems to be an issue for the articles that included induced-mobility impacts, and more research is needed on these topics.

4.6. Limitations

In Section 2.4 are limitations to the method used when scoping the literature explained. The method used is holistic and achieves the goal of providing an overview of what previously has been done and spotting the gaps. However, it cannot determine the underlying causes of the results presented, but it guides future work. The language in the analyzed articles was limited to English, thus potentially omitting knowledge in other languages. Finally, the fifth limitation is that valuable insight might have been missed since grey literature and books were excluded, although without the same quality assurance as peer-reviewed articles.

5. Conclusion

5.1. What research has been performed with the intention to lower emissions from buildings on both building and urban scale?

Reducing emissions from the built environment is imperative for a sustainable future, and a partial strategy is to refurbish existing building stocks. Despite the extensive building refurbishment research and governmental incentives, the refurbishment rates are low in Europe. This article has explored the advantages and disadvantages of the different methods that have been applied in 106 refurbishment studies. The majority use life-cycle methods, and the bottom-up approach is frequently applied because of its level of detail. Furthermore, archetypes are used to calculate the environmental impacts of multiple buildings on neighborhood, city, municipal, and country scales. However, archetypes make the building stock homogeneous, not representative to the heterogeneous built environment ,and involve qualified guesses. The hybrid life cycle methods circumvent the truncation error in bottom-up methods by including statistical data. A building-by-building approach aided by GIS enhances detail but rarely leaves the realm of buildings. Not expanding the scope to include other facets of the built environment in refurbishment studies puts them at risk for sub-optimization. When included in assessments, the induced-mobility emissions constitute a significant share of the total emissions. Not being aware of this mitigation potential is a flaw in previous studies. The application of machine learning techniques is a practical approach for simulating different outcomes from developed refurbishment packages. It saves time, and finding the optimal solution for large building stocks is possible. Presenting the results in a Pareto front is adequate for finding the best solution for two or more parameters. It improves quality, but it does not solve the issue of demand for data quantity. The economic incentive for building owners is a threshold for refurbishment. The role of publicly owned buildings should be assessed more as the incentive to refurbish for private owners might be low due to cost barriers. Thus, municipalities could have a significant role in the building refurbishment transition as they govern large building stocks and are perhaps less dependent on a quick return on investment.

5.2. What are the research gaps?

The scoping review performed in this article has identified the following gaps:

- No standardized methods exist for assessing several buildings on a larger scale with a broader scope. The methods applied vary, and the advantages and inaccuracies exist due to trade-offs between quantity and data quality. Most studies are aware of the issue, but more research is needed to overcome the discussed boundaries.
- Few studies included induced-mobility emissions, and this review implies that future research should include them when investigating refurbishment scenarios. The induced-mobility emissions are either the largest or second-largest emission contributors when considering the placement of buildings. Thus, one should not ignore them in refurbishment assessments. Moreover, as the transition from building to the neighborhood or urban scale progresses, it is necessary to research these emissions further. However, the results from the studies, including induced-mobility emissions, reported varying results, which reveal discrepancies in the approaches used to assess them, although further research is needed before confirming this statement. The potential for a more significant reduction of carbon emissions can be achieved when considering where the intended building will be refurbished. Finding the tipping point where a more significant total reduction of carbon emissions is achieved by rebuilding rather than refurbishing should be determined when assessing existing buildings. It would enhance the probability of the path with the highest carbon emission mitigation potential. Finally, it is unlikely that existing homes will be relocated. Thus the efforts should aim toward finding the optimal location when refurbishing public institutions.
- The refurbishment studies using life cycle methods should make the scope and methods for retrieving inventory data clearer, as ambiguous system boundaries make it difficult to interpret the results in the studies. Although a few impact categories are considered, the studies claim to be holistic when evaluating refurbishment strategies. The majority calculated carbon emissions and energy use. Future studies should include more impact categories to avoid sub-optimizing and problem shifting while ensuring holistic assessments. Additional benefits might be achieved in new insights and opportunities for finding solutions that go beyond the sometimes narrow scope of energy and carbon emissions to ensure a sustainable future.
- The role of publicly owned buildings should be assessed more as the incentive to refurbish for private owners might be low due to cost barriers. Thus, municipalities could have a significant role in the building refurbishment transition as they govern large building stocks and are perhaps less dependent on a quick return on investment. Future studies are necessary to deny or confirm this notion.
- The case studies analyzed in the sample were predominately performed in Europe. Thus, more research in other world regions is sought in future studies.

Finally, this article's contribution and scientific value lie in the holistic approach taken when analyzing the 106 articles. It has analyzed previous work in building refurbishment studies while highlighting the gaps and guiding future studies in sustainable trajectories that align with national climate goals.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.rser.2022.112636.

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