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A THEORETICAL ASSESSMENT OF TRANSPORT EMISSIONS FROM INSTITUTIONAL BUILDINGS IN A NORWEGIAN MUNICIPALITY

Oskar Fahlstedt*, Rolf André Bohne

Norwegian University of Science and Technology, Høgskoleringen 7A, 7034, Trondheim

* corresponding author: `oskar.fahlstedt@ntnu.no`

Abstract. Municipalities are key actors in reaching the sustainable development goals 9, 11, 12, 13 set by the United Nations. The aim of this paper is to develop, on a theoretical level, a sustainable building refurbishment framework for municipalities. The focal point of the framework is reduction of embodied and operational carbon emissions deriving from buildings, including travel-induced emissions. The institutional buildings governed by a Norwegian municipality are the case study objects in this study. The framework that is currently is used in the municipality value the building stock based on the quality and cost of refurbishing them. No framework currently includes travel-induced emissions in the evaluation. The intention is to provide a holistic framework that includes this aspect when deciding if a building should be refurbished or demolished. The omission of transport emissions can lead to truncation errors in assessments. The transport to and from the school generates higher emissions in certain scenarios. Based on the knowledge in the assessment, a theoretical framework that assesses this is developed.

Keywords: CO_2 abatement, travel-induced emissions, location, institutional buildings, municipality.

1. Introduction

1.1. Energy refurbishments

The built environment is responsible for as much as 70 % of human-induced greenhouse gas emissions (GHG) [1, 2], and the United Nations (UN) predicts that 70 % of the world population will live in cities by 2050 [1, 3]. Additionally, predictions are that 85–95 % of European buildings in operation today will still be in operation by 2050, and most are of inadequate energy standards [4]. Thus, they are responsible for a large share of total carbon emissions and sensible actions are refurbishing existing building stocks to lower energy use and indirect carbon emissions. There is no lack of research providing deep-refurbishment methods and frameworks [4, 5]. However, yearly refurbishment rates are at 1 % across Europe, and for deep refurbishments (refurbishment intended to lower energy use by a minimum 60 %), rates are between 0–0,2 % [4]. Furthermore, an overwhelming body of literature focuses on optimizing on a building scale. Thus only emphasizing mitigation of embodied and operational emissions whilst there are reasons to believe that other emission sources are significant when the scope expands from building to urban scale [6].

1.2. Transport emissions and buildings

Anderson et al. [5] calculate the emissions for three different building types in Munich, Germany. The authors adopt a process-based (streamlined) LCA framework and “expand” it to capture a new impact category they describe as “induced impacts”, which refer to impacts deriving from embodied and use phase emissions from transportation. The buildings are typical for each location in the city which are multi-family houses (city center), row houses (city periphery), and single-family houses (districts / rural areas). The study analyzes the embodied and operational emissions deriving from buildings and user transportation. The scope is not limited to operational transport emissions, as the embodied emissions for transport and infrastructure can represent a large share of total transport emissions. The calculated induced impacts represent 46 to 54 % of total emissions. Furthermore, after a sensitivity analysis, it is concluded that moving any of the three building types further away from the city center will increase total emissions [5].

Yu et al. [7] argue that building and city scale has been highly researched, while studies on urban precincts (e.g., districts) are not sufficiently covered in the literature. The authors state that assessment on this scale should include [7, p. 2] “1) embodied emissions that are associated with the construction, maintenance and end-of-life treatment of all precinct objects; 2) operational emissions that are generated from the operation of all precinct objects, 3) occupant-related transport emissions that are generated from daily commuting, business trips and personal travels”. A precinct in Adelaide, Australia, is the case study, and occupant-related transport and personal travels have the largest share of emissions (40 %), followed by building operational (32 %) and embodied emissions (28 %).

Anderson et al. [5] and Yu et al. [7] argue that it is important to include mobility emissions. Fenner et al. [8] share the same opinion and perform a Life-Cycle

Carbon Emission Assessment (LCCO$_2$A) to calculate embodied, operational, and commuting emissions for a campus building in the USA. However, without considering the embodied impacts of transport as they are perceived as negligible compared to operational emissions. The authors conclude that the emissions deriving from operating the building are the highest. Although, not without reservations for a different outcome if a building with the latest energy standards is assessed instead [8].

In a study performed in Norway, Lausselet et al. [9] evaluated the application of zero-emission neighborhoods (ZEN). They identify the operational phase and mobility of inhabitants as the most important factors for transforming existing neighborhoods into ZEN but also highlight other important factors (see [9]). Bastos et al. [10] investigate the importance of including mobility when assessing buildings in Lisbon and discovered that emissions from transportation can exceed the emissions deriving from the building itself. The study investigates one apartment building in the city center and one semi-detached house in a suburban area. The suburban house has the highest emissions, and relocating it to the city center would reduce emissions significantly. Thus, in the investigated scenario, it makes more sense to focus on transportation rather than building emissions [10]. In another study by Drouilles et al. [11] is the energy efficiency of five buildings in Switzerland's urban, peripheral, and rural areas is analyzed against national energy targets. The results reveal that energy use in the buildings is twice as high as the national goals. Furthermore, including daily mobility of occupants to and from buildings increase emissions by 40 % in the investigated areas.

1.3. The goal of the study

No silver bullet exists for reducing emissions in the built environment. Instead, it is necessary to implement a wide array of solutions holistically with urban and building research working in synergy to lower carbon emissions from the built environment. Therefore, the work of governing bodies such as municipalities is crucial. They withhold a significant mitigation potential that is necessary to utilize for reaching the climate goals. The European Union (EU) is striving to be carbon neutral in 2050, and Norway is aligning with the goal as well [12–14]. The energy mix is a determinant factor for reaching this goal, and every country adheres to its own set of prerequisites for producing renewable energy [15]. Thus, proven methods are not necessarily generic, and instruments to reach carbon neutrality are most likely country or even region specific. The literature has demonstrated the importance of transport emissions in holistic assessments of buildings [5, 7–11, 16]. The objective of this paper is twofold. First, investigate the importance of induced travel emission in a refurbishment strategy with a Norwegian municipality as a case study. Second, develop a theoretical framework as a suggestion for how to travel-induced emissions could be included together with operational and embodied emissions when finding refurbishment strategies for existing building stock. To guide the research, two questions are asked:

(1.) How important is it to include transport emissions in refurbishment and new building assessments in countries that rely on low-carbon electricity?

(2.) How can transport emissions be included in a refurbishment framework?

2. Materials and methods

2.1. Case study – Bærum Municipality

A case study approach was used in a Norwegian municipality when documents, building audits, strategies, and cost calculations were scrutinized. Important information was also obtained through conversations with municipal officials and consultants managing the building stock.

2.1.1. Background

Bærum municipality is located in the periphery of the Norwegian capital Oslo. Hence, it is an attractive area to live in because of the work opportunities offered and the short commuting distance to the capital. Thus, it has seen a steady population growth [17]. The population in the municipality is close to 130 000 [18]. The urban morphology is suburban and rural with detached houses although, some areas are densely populated with multifamily homes (MFH) and commercial buildings [17]. In regards to housing, the composition is 29 % single-family homes (SFM), 13 % semi -detached homes, 17 % row-houses, 3 % other, and 37 % MFH. There are over 100 000 light-duty vehicles registered in the municipality, with primary fuel sources of the cars being 28 % gasoline, 25 % diesel, 23 % electric, and 24 % other (mainly hybrid cars) [18]. As of 2016, 63 % of total emissions derive from light-duty vehicles (LDV), and with the inclusion of heavy-duty vehicles (HDV), it increases to 87 %. This is significant compared to the 3 % from heating the buildings, 4 % from construction machinery, and 6 % other (agriculture, waste management, energy supply, and anaerobic digestion from landfills) that constitute the remaining 13 % of total emissions [19]. The municipal real estate portfolio comprises a vast range of buildings with a combined area of 800 000 m^2 to an insured value of 17.6 billion NOK excluding the value of infrastructure and land [20]. Nevertheless, the population is predicted to grow 11 % by 2030 and increase demand for public buildings. This is a concern for the municipality due to the scarcity of publicly owned land to build on [17, 19–21].

In 2014, the municipality appointed an external consultancy firm to evaluate the condition of the existing building stock, and they concluded that, on average, 24 % of the buildings achieve satisfactory

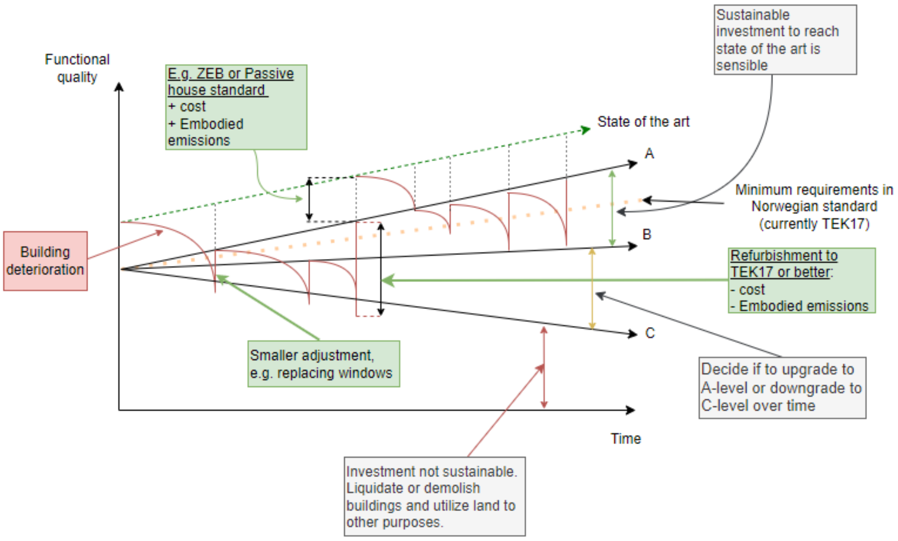

Figure 1. ABC-framework adapted from Svein Bjørberg in [20].

standards [20, 22]. The buildings were evaluated according to the Norwegian standard for "Condition survey of construction works – Content and execution" (NS3424:2012), and results are reported on a consequence scale from 0–3. A score of 1.0 or less states that there are only minor consequences to be expected considering the standard of the building, but if the receives a score between 2.0–3.0, then there is a risk of medium to severe consequences. They are, for example, related to safety (structural safety, fire safety), health/environment (indoor air quality), aesthetics (surfaces), and economy (renovation, maintenance) [23]. According to the results from the study, average building condition is lower than comparable municipalities, and there is also a discrepancy within the range of buildings not reaching acceptable standards [20, 22].

The municipality is currently categorizing buildings into three levels (A, B, or C) depending on the total score from a quality assessment tool [20]. They are analyzed based on technical quality, adaptability, functionality, plot, and surrounding area. Thus, it provides the municipality with an overview of the building stock that makes known where actions are needed to retain and increase the value of their buildings. Furthermore, buildings categorized as A-level buildings in the framework are perceived to be worth the investment to reach the adequate standard demanded to align with the sustainable building strategy. The investment to upgrade from C to A is too high. Thus, C-level buildings are kept until they pass their functional lifetime. After that, they are liquidated or demolished, and the land can fulfill other purposes [20, 22]. Buildings categorized to B-level are under evaluation if they should be upgraded into A-level or downgraded to C-level instead. Thus, they are important since categorizing a building into the wrong category can result in a non-sustainable solution [20].

School	GFA [m^2]	HFA [m^2]	OE [kWh]
1	4639	3935	4,98E+05
2	7662	6170	9,66E+05
3	7215	6390	1,13E+06
4	5933	5084	7,60E+05

Table 1. Information about the four B-level schools.

2.1.2. Institutional B-level Buildings

Four schools previously categorized by the municipality as B-level buildings were assessed. The schools are of varying sizes, with indoor climates deemed inadequate, and none of the buildings have been refurbished in the last 25 years. None of the schools falls below 1.6 in the quality assessment [20, 23]. Schools 1, 2, 3, and 4 house 298, 529, 117, and 525 children, respectively. The approximate cost for refurbishing them is 81 million NOK and school 1 is the most expensive to refurbish. The children in the municipality are assigned to the schools based on the school district their homes are located in. School 3 is for children with special needs. Thus, it does not belong to a specific school district since children are assigned based on their individual needs. Information regarding the gross floor area (GFA), heated floor area (HFA), and operational energy (OE) use for 2019 are provided in Table 1.

2.2. Adapting the ABC-framework

Figure 1 presents the adapted framework, with each line representing a requirement for the buildings. The red line in Figure 1 illustrates building degradation over time to different levels followed by refurbishment actions. Moreover, ideally, the school building should reach a higher quality level afterward.

All school buildings that fall below C-level should be liquidated or demolished at some point as no sustainable investment is viable, and a downtrend arrow

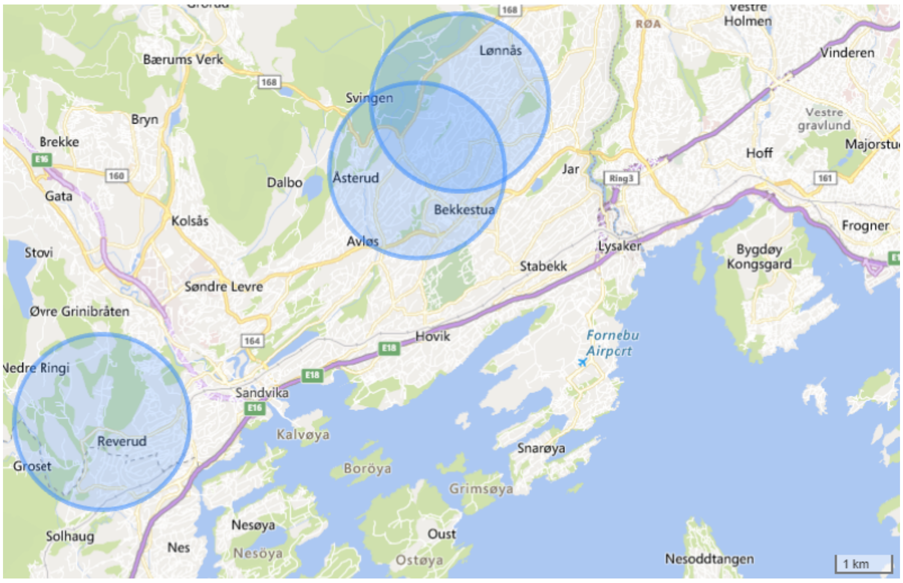

Figure 2. Example of assumed distances between homes and schools at 1.5 km radius.

illustrates the deterioration. The minimum requirement of the building is to achieve the Norwegian technical standard (TEK17) [24], and an A-level building should ideally surpass that minimum requirement. The vector for B-level buildings slightly increases in quality over time due to technical requirements becoming more stringent. The dotted line illustrates the minimum requirement from the Norwegian technical standard for school buildings. The green dotted line represents the state-of-the-art school building with the best energy efficiency and lowest emissions. Thus, as time progresses, the demand for higher functional quality increases since knowledge and technology advance. Ideally, the municipality refurbishes a B-level school to A-level that performs better than the requirements in the technical standard.

2.2.1. Building emissions

The energy use from 2019 for each school was available in the case study. However, no information regarding the school's embodied emissions was available. Thus, allocating the share of emissions from the existing school buildings is difficult. Therefore, the impacts from the previous production and construction stages were disregarded in this study. An archetype was used instead. It was based on average data from Schools 1, 2, and 4, resulting in a gross floor area of 6078 m^2 and a heated floor area of 5063 m^2. It is assumed to be a B-level where 524 children attend the school. Two improvement scenarios were developed for the school and are presented below:

(1.) Scenario 1: Building a new school building that performs 20 percent better (88 kWh/heated m^2a) than the minimum energy requirement for schools in [24]. Embodied emissions (A1–B5) are assumed to be 6.9 kg CO_2eq/m^2a. It is assumed that the school demand refurbishment after 30 years and embodied emissions are 65 percent lower (2.42 kg CO_2eq/m^2a) at that point [25, 26]. Even more stringent energy requirements are assumed to be in place after 30-years making the school 40 percent more efficient (66 kWh/heated m^2a) than the requirement in the exiting energy standard for schools [24]. The end-of-life phase was not included in the assessment.

(2.) Scenario 2: A refurbishment scenario with the same energy requirements (88 kWh/heated m^2a) as in the new building scenario. The embodied emissions are assumed to be lower (2.42 kg CO_2eq/m^2a) since less material will be needed when refurbishing than constructing a new building. The refurbished building demands an additional refurbishment after 30 years with additional embodied emissions (2.42 kg CO_2eq/m^2a). The school must adhere to the more stringent energy requirements (66 kWh/heated m^2a) as the scenario with the new building.

The electricity mixes used in the study are from the Norwegian energy market. The first electricity mix is based on delivered electricity from the Norwegian grid without any Guarantees of Origin (GOs), and it has the highest carbon content in this study [27]. The second is a prediction for the average carbon content in Norwegian electricity between 2015–2075 when importing from the European continent. Third, the same scenario as the previous one, although electricity is only produced in Norway [28]. The fourth is a low carbon scenario based on the reported average carbon content in the Norwegian electricity mix during 2020 [29].

(1.) 402 g CO_2eq/kWh [27]

(2.) 136 g CO_2eq/kWh [28]

(3.) 18 g CO_2eq/kWh [28]

(4.) 8 g CO_2eq/kWh [29]

2.2.2. Transport emissions

A highly theoretical approach was used for the transport scenarios when it was assumed that all households were within a 2.5 km radius of the school. No specific routes were analyzed, and for simplicity, trip lengths were divided into 0.5, 1.0, 1.5, 2.0, and 2.5 km. As demonstrated in Figure 2, Schools 3 and 4 from the case study are located in such a manner that when the uptake radius is 1 km and increasing, they intersect one another. Thus this is not a correct approach, but for simplicity, this approach is used as a theoretical exercise. It was assumed that round trips were made, meaning the children were dropped off and picked up each school day. The transport modes were limited to the car (gasoline, diesel, and electric) and bus (diesel and gas). The 2019 values for carbon emissions [g CO_2eq/pkm] deriving from transport using fossil fuels in Norway were extracted from [30]. No specific adjustments to the transportation modes regarding modal share or improved fuel efficiency were made. The electric vehicles were assumed to use the same electricity mix as the buildings. For each distance, a share of students going by car or bus was assumed. These were between 10–50 % for each transport distance.

2.2.3. Calculations

The calculations was performed as follows:

$$\begin{aligned} TBE_n = {} & (EM_1 \times GFA) \\ & + (OER_1 \times ELM \times HFA) \\ & + (EM_2 \times GFA) \\ & + (OER_1 \times ELM \times HFA) \end{aligned} \tag{1}$$

$$\begin{aligned} TBE_r = {} & (EM_2 \times GFA) \\ & + (OER_2 \times ELM \times HFA) \\ & + (EM_2 \times GFA) \\ & + (OER_1 \times ELM \times HFA) \end{aligned} \tag{2}$$

$$TTE = S \times SD \times TU \times DD \times 2 \times ETM. \tag{3}$$

Abbreviations:

EM_1 Embodied emissions new building [kg CO_2eq/m^2a]

EM_2 Embodied emissions refurbishment [kg CO_2eq/m^2a]

GFA Gross floor area [m^2]

OER Operational energy requirements [kWh/m^2a]

ELM Electricity mix [kg CO_2eq/kWh]

HFA Heated floor area [m^2]

S Number of students [p]

SD School days a year

TU Transport utilization [%]

DD Driving distance [km]

ETM Emissions transport mode [kg CO_2eq/pkm]

The TBE represents "total building emissions", and the "n" denotes the new building while "r" is the refurbishment scenario. These are the total embodied and operational emissions deriving from the building. For the new building, embodied and operational emissions are divided into two periods (30 years each) since the embodied emissions are after construction and lower after refurbishment. In the refurbishment scenario, the lower embodied emissions are calculated for both periods, while the operational phase differs. This is because the OER is assumed to be stricter once the building needs to be refurbished again after 30 years. TTE stands for "total transport emissions" and represents total emissions deriving from the operational phases of the selected transport mode. As mentioned earlier, distances to the school were assumed to be in the range of 0.5–2.5 km and utilization of the transport mode in the range 10–50 %. Furthermore, the operational transport emissions were subtracted from the building emissions. To get an easy overview, tables were made (see Table 2, 3 and 4) and a negative value marked in red means that operational emissions from transport are higher than embodied and operational from the buildings.

3. Results

The overall results showed that building emissions are always higher than the ones from transport for the first two electricity mixes (i.e., 402 and 136 g CO_2eq/kWh). The results changes once the building is supplied with low-carbon electricity mixes (18 or 8 g CO_2eq/kWh). In Figure 3 are total emissions from the school building provided.

The results reveal the significance of embodied emissions when the school is supplied with a low-carbon electricity mix. As seen, the new school generates higher emissions over its lifetime due to the initial embodied emissions. The gap between total emissions increases in the scenarios where low-carbon electricity is used compared to the two higher alternatives.

Users / Distance	**10 %**	**20 %**	**30 %**	**40 %**	**50 %**
Gasoline car [kg CO_2eq] in 8 g CO_2eq/kWh scenario.					
2.5 km	4.27E+05	3.06E+05	1.86E+05	6.52E+04	-5.53E+04
2.0 km	4.51E+05	3.54E+05	2.58E+05	1.62E+05	6.52E+04
1.5 km	4.75E+05	4.03E+05	3.30E+05	2.58E+05	1.86E+05
1.0 km	4.99E+05	4.51E+05	4.03E+05	3.54E+05	3.06E+05
0.5 km	5.23E+05	4.99E+05	4.75E+05	4.51E+05	4.27E+05

Table 2. In the table above, the results for the refurbishment scenario for the first 30 years presented. The emissions from transportation to and from the school are only higher (see red marking) than the embodied and operational emissions from the building if half of the children go by car over a distance of 2.5 km or greater.

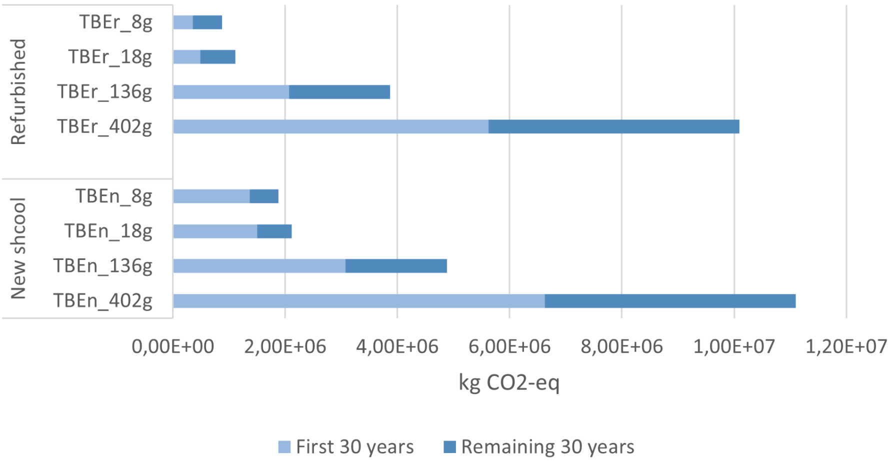

Figure 3. Total emissions from the school building for the two scenarios with each of the four electricity mixes analyzed.

Users / Distance	10 %	20 %	30 %	40 %	50 %
Gasoline car [kg CO_2eq] in 8 g CO_2eq/kWh scenario.					
2.5 km	4.00E+05	2.80E+05	1.59E+05	3.85E+04	-8.20E+04
2.0 km	4.24E+05	3.28E+05	2.31E+05	1.35E+05	3.85E+04
1.5 km	4.48E+05	3.76E+05	3.04E+05	2.31E+05	1.59E+05
1.0 km	4.72E+05	4.24E+05	3.76E+05	3.28E+05	2.80E+05
0.5 km	4.96E+05	4.72E+05	4.48E+05	4.24E+05	4.00E+05
Diesel car [kg CO_2eq] in 8 g CO_2eq/kWh scenario.					
2.5 km	4.13E+05	3.06E+05	1.99E+05	9.17E+04	-1.56E+04
2.0 km	4.35E+05	3.49E+05	2.63E+05	1.77E+05	9.17E+04
1.5 km	4.56E+05	3.92E+05	3.28E+05	2.63E+05	1.99E+05
1.0 km	4.78E+05	4.35E+05	3.92E+05	3.49E+05	3.06E+05
0.5 km	4.99E+05	4.78E+05	4.56E+05	4.35E+05	4.13E+05

Table 3. In the table, the results are based on the refurbishment assumptions after 30 years presented.

Users / Distance	10 %	20 %	30 %	40 %	50 %
Gasoline car [kg CO_2eq] in 8 g CO_2eq/kWh scenario.					
2.5 km	8.27E+05	5.86E+05	3.45E+05	3.45E+05	-1.38E+05
2.0 km	8.75E+05	6.82E+05	4.89E+05	4.89E+05	1.04E+05
1.5 km	9.23E+05	7.79E+05	6.34E+05	6.34E+05	3.45E+05
1.0 km	9.71E+05	8.75E+05	7.79E+05	7.79E+05	5.86E+05
0.5 km	1.02E+06	9.71E+05	9.23E+05	9.23E+05	8.27E+05
Diesel car [kg CO_2eq] in 8 g CO_2eq/kWh scenario.					
2.5 km	8.53E+05	6.39E+05	4.24E+05	2.10E+05	-4.41E+03
2.0 km	8.96E+05	7.25E+05	5.53E+05	3.82E+05	2.10E+05
1.5 km	9.39E+05	8.11E+05	6.82E+05	5.53E+05	4.24E+05
1.0 km	9.82E+05	8.96E+05	8.11E+05	7.25E+05	6.39E+05
0.5 km	1.02E+06	9.82E+05	9.39E+05	8.96E+05	8.53E+05

Table 4. The table above presents the results for the whole (60 years) period.

3.1. First 30 years-low carbon mix

The results for the first 30 years are presented in Table 2. The values in the tables present the total emissions [kg CO_2eq] when *TTE* is subtracted from each *TBE* scenario. The operational emission from transportation is only higher than the emission from the school if at least 50 % of the children travel by car while having a one-way distance of 2.5 km. Furthermore, it only applies to the refurbishment scenario since emissions from the new building are always higher.

3.2. Remaining 30 years-low carbon mix

The embodied and operational emissions are the same for the remaining 30 years for both the building scenarios (see Table 3). The emissions from transportation by gasoline cars are the same as in Table 2 although higher since more time has passed. Furthermore, since the embodied and operational emissions are assumed to be even lower, the emissions from the diesel car exceed the building emission given that 50 % travel 5 km (2.5 km to and from the school) each day.

The results for the whole 60-year period are in Table 4, and it shows that emissions deriving from the car only exceed emissions from the school if at least 50 % go by car over a distance greater than 5.0 km (2.5 km to and back from the school).

3.3. Sensitivity analysis

The results revealed that transport emissions only exceed building emissions under specific circumstances. The impacts from the operational phase of the school are already low, making the embodied emission decisive. Thus, lower embodied emissions were assumed instead. In the original scenario, embodied emissions from refurbishments are 65 percent lower than the reference value of 6,9 kg CO_2eq/m^2a obtained from literature [26]. The case study revealed that the energy use of School 1 is just above the requirements in TEK17 [24]. Only minor refurbishments were assumed instead, and embodied emissions were set to be 80 percent lower than the reference value. A low-carbon electricity mix (8 g CO_2eq/kWh) scenario was tested with gasoline and diesel cars. The results for the whole period (i.e., 60 years) are presented in Figure 4.

The figure shows the results for the first 30 years (left side), after another 30 years (middle), and the total emission on the right-hand side. The share of car users in the diagram (30–50 percent) with distances between 1.5–2.5 km is when transport emissions can be

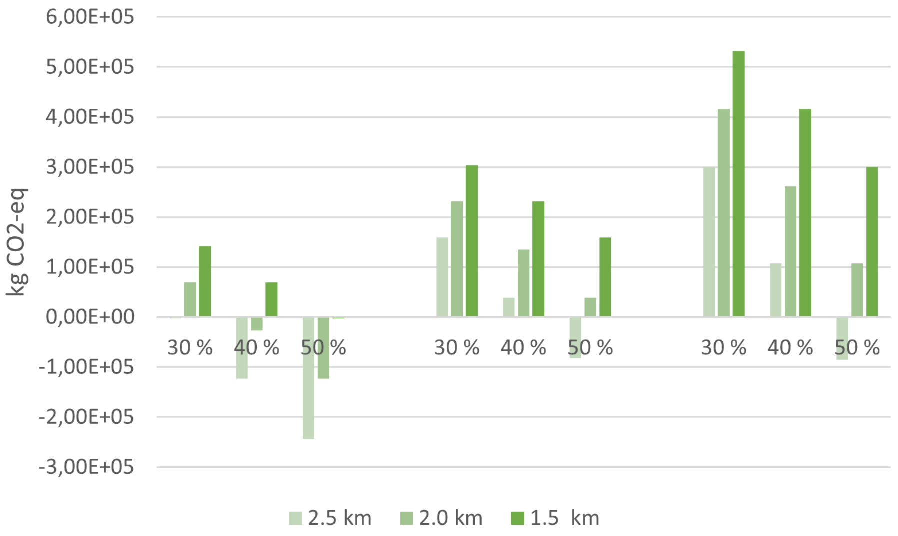

Figure 4. In the figure are the result for the first 30 years (left), the remaining 30 years (middle), and total emissions (right-hand side) when embodied emissions are reduced 88 % compared to the reference value for the first period presented.

higher. Since the role of embodied emissions was important, another analysis was performed. Now minor refurbishment (80 percent lower embodied emissions) was assumed for the first period. However, for the second period, it is refurbished to align with the energy requirements (66 kWh/heated m^2a) more material is needed. Thus, embodied emissions were assumed to be 4.36 kg CO_2eq/m^2a which follows guidelines for the use of "climate friendly" materials [25].

The results (see Figure 5) reveal that car use emissions exceed the building emissions under specific circumstances during the first 30 years. Once the building is refurbished after 30 years, the transport emissions never exceed the ones from the building. Even if the electricity mix with the lowest carbon content is supplied to the building.

4. Discussion

4.1. Expanding the scope from building to urban scale

The situation in the assessed municipality is similar to the rest of Europe. It manages a large building stock, and refurbishments are needed [4]. With the scarcity of land and a growing population in the municipality, the argument for refurbishment is even stronger [19]. The literature reported that emissions from user transport should be included in assessments since they make a significant share of the total emissions [5, 7, 9, 10]. However, emissions deriving from user transport to and from the schools were only higher when the embodied and operational emissions were assumed to be very low, and half of the children are driven to school each day over a distance greater than 2.5 km. Thus, the transport was less significant than predicted when considering previous studies [5, 7, 9, 10]. Fenner et al. [8] reported that operational emissions were higher than transport emissions. However, the authors highlighted that their results could be different with a high-performing building scenario. This study investigated a high-performance building scenario, and results showed that building emissions were higher except under certain conditions. The school had to be supplied with a low-carbon electricity mix while having low embodied emissions. The aspect of embodied transport emissions was excluded in this assessment as well as in the one by Fenner et al. [8]. However, Anderson et al. [5] included them and showed that they are significant and thus ought to be considered in future assessments.

The theoretical approach taken in this study means that it has limitations. For example, the archetype school was based on average values, while transport routes and modes were based on assumptions. Future studies should aim towards finding applicable refurbishment packages and new building scenarios for one of the existing B-level schools. The case study discovered that schools were divided into districts so that transport routes could be analyzed in greater detail. Thus, indicating the benefit of assessing schools. This is because households are confined within a specific area which means that it is possible to calculate accurate transport distances to their assigned school. This shows the strength of this approach since it enables holistic perspectives with solutions that help to reduce the total emissions on a municipal scale. Combining the framework the municipality in the case study currently uses with the approach taken in this study avoids sub-optimization. The ABC-framework identifies and sets the goals for the exiting stock whilst expanding the scope to include transport avoids carbon lock-ins. Moreover, using the school districts makes it possible to optimize the location of a school within a district and evaluate if it is better to refurbish or build a new building at another location.

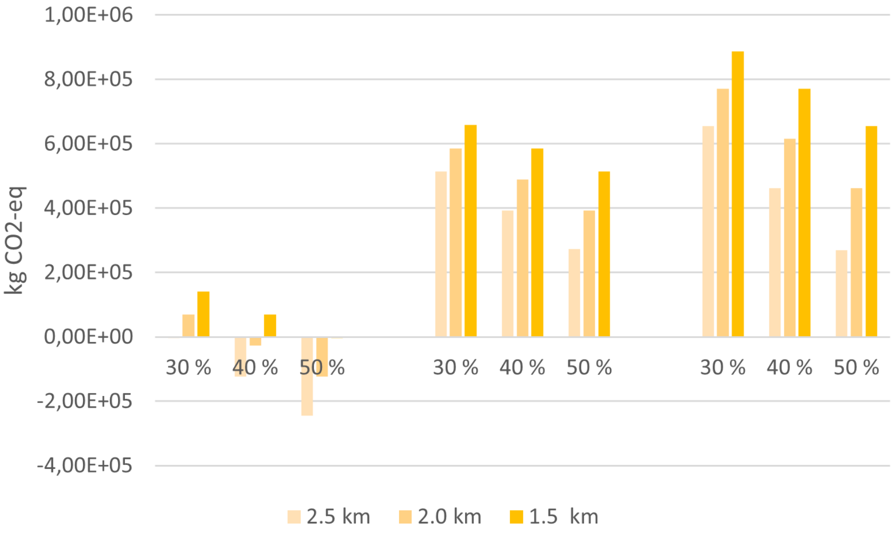

Figure 5. In the figure are the result for the first 30 years (left), the remaining 30 years (middle), and total emissions (right-hand side) when embodied emissions are assumed to increase due to more extensive refurbishments needed after 30 years.

4.2. Potential barriers for implementation

The assessment in this study aimed to develop a theoretical framework, and more work is required. Higher accuracy is achieved using bottom-up methods with on-site measurements [8, 31]. Nevertheless, Bærum municipality manages a large stock [20], and considering the urgency to reduce carbon emissions [12–14], it is not an economically sustainable strategy to address every building individually. Therefore, it is necessary to decide a break-even point where the strategy should move towards using the top-down method based on statistical data to create archetypes [5] or potentially achieve more accurate results through clustering techniques [32]. Murray et al. [32] claimed high accuracy of using clustering techniques to find archetypes of the Swiss building stock. However, the techniques demand knowledge, and if it is not accessible among municipality officials, external support is needed, which can be costly. This potential barrier of how to transfer knowledge from the scientific community to decision-makers (DMs) and city planners was not covered in the literature. Thus, it should be investigated in future studies.

There is some ambiguity about whether the current ABC framework demands deep user knowledge. If the DMs consider it to go beyond their skill level, a sophisticated black-box model is potentially beneficial as it theoretically can achieve high accuracy without demanding extensive technical knowledge about building physics. The municipality could then decide upon KPIs, with data about building characteristics and location generating potential emissions based on the input. Another option is to extrapolate data from a small sample or to use statistical data to create archetypes for their stock and then run energy simulations to find suitable refurbishment packages, which are methods already present in literature [11, 31]. However, complex machine learning techniques are often used to manage the computational power, which in turn demands extensive theoretical knowledge of the users [16].

5. Conclusion

In Section 1 two research questions were asked, and this section intends to answer them. The built environment is heterogeneous and varies depending on region, municipality, city, neighborhood, and building type, which is also the situation in Bærum municipality. Therefore, implementing holistic life-cycle frameworks covering both building and urban scales is recommended. It will aid DM in finding emission abatement strategies with less risk for carbon lock-in due to sub-optimization at the building scale. The results from this study reveal that the induced emissions from transportation can exceed embodied and operational building emissions. However, this was a theoretical exercise with a fictional school building, and further research with better data is needed. A sensitivity analysis demonstrated the importance of embodied emissions once a building uses low-carbon electricity. Moreover, in the assessment, the hypothesis that transport emissions would be higher than building emissions was not the case. However, the work indicates the potential for higher reductions of GHG-emission on an urban scale when the method is applied. Finally, the social aspect was not considered, but it should be in the future. For example, the economic situation determines the modal choice, and what the user perceives as valuable will set other requirements that ultimately influence emissions.

The literature findings and information obtained from the case study have led to the development of a theoretical framework (see Figure 6). It consists of

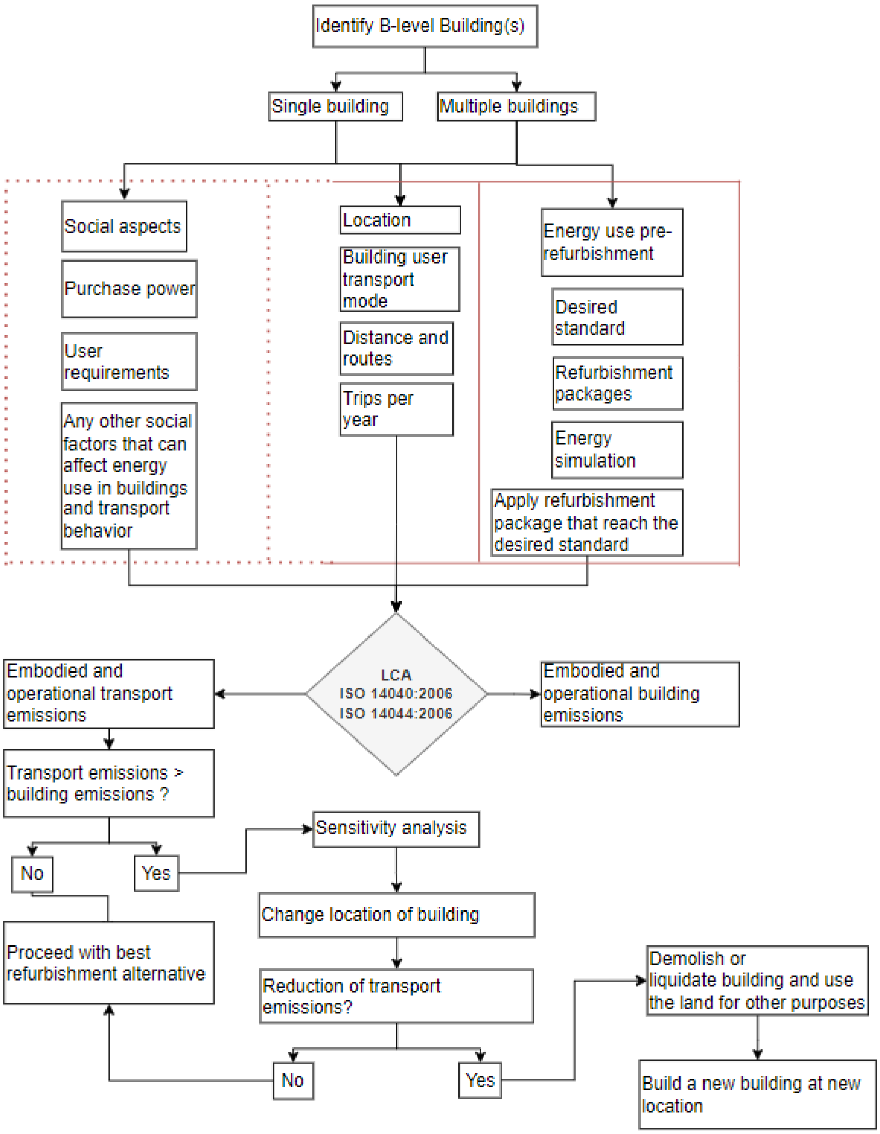

Figure 6. Theoretical framework based for holistic assessment of refurbishment strategies for existing buildings.

three main emission drivers, the location of the building, the building itself (embodied and operational energy), and purchasing power (i.e., "social" for now) of inhabitants within each of the catchment areas of the schools. It is a suggestion for future detailed assessments. The social aspect was added impromptu due to the idea that household income will be deterministic for the accessibility of certain modes of transport. However, this aspect needs further development before being implemented hence the dotted line. The aforementioned emission drivers then determine the necessary inventory data for the calculation of environmental impacts. Furthermore, emissions deriving from transportation are measured against emissions from refurbishing the building. A sensitivity analysis should be performed in situations when transport emissions are higher than the ones from the investigated building(s). This since greater reduction potential might be achieved if the services of the building (institutional in this case) are established at another location. For the school buildings, it insinuates that the school should be moved to a more suitable location. To move a building is drastic. It foremost refers to moving the service provided to location optimization strategies to reduce emissions that are not limited to the building scale but include transport from building users.

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