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Spatiotemporal tracking of building materials and their related environmental impacts

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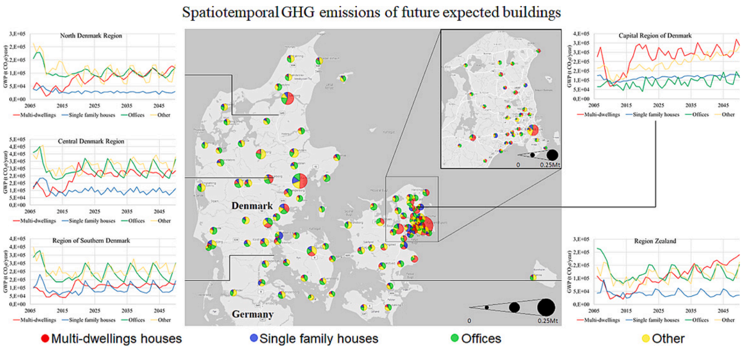
HIGHLIGHTS

- Spatiotemporal forecast of all building types in each Danish municipality
- Material type and quantities required from future buildings in each Danish municipality
- Prognosis of yearly embedded impacts across the country towards 2050
- Expected impacts from new building in each Danish municipality
- GHG emission disaggregated per building types, components, materials, and life cycle stages

GRAPHICAL ABSTRACT



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ABSTRACT

Urban development will increase the demand for new buildings expected to cause significant environmental impacts in the coming decades. Spatiotemporal prediction for new buildings, their typologies, resource quantities and types required for construction, and the associated impacts are crucial to effectively tackle strategies to reduce the related greenhouse gas emissions. Within the context of Denmark, this study establishes a prognosis of expected yearly embedded impacts across the country towards 2050 based on Business as Usual (frozen policy) trends. Through the Holt-Winters method's additive version, the study forecasted the future amount of building types in each Danish municipality. The embedded impacts disaggregated into building types, components, materials, and life cycle stages are calculated from the material intensity coefficients of real projects. Considering a 'business as usual' scenario, the prediction shows an increase in demand by 6.5 % for new gross floor areas compared to the number of current buildings constructed in the past years. The GHGs from the upstream processing of materials correspond to 7 % of current consumption-based yearly emissions in Denmark. To strive for sustainable development, the findings of the study help inform stakeholders in the built environment to better correlate the material mechanism 'supply-demand' for circularity and where efforts to minimize the impacts should be prioritized.

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1. Introduction

The building and construction sector is a large consumer of non-renewable natural resources and is responsible for 37 % of global greenhouse gas (GHG) emissions (UNEP, 2021; Cabeza et al., 2022). As urban development will continue to expand in the coming decades, resource consumption and environmental impacts related to processes of the construction of new buildings will be hotspots needing to be addressed in mitigation strategies. Understanding and predicting the spatiotemporal development of future construction, material flow needs and prognoses of yearly impacts across the country is essential in planning for circular strategies and low-carbon solutions. For instance, forecasting future demand for different types of materials can help identify the risks of depletion and the opportunities to meet future material demand with reused components from demolished buildings (Deetman et al., 2020), as well as highlighting the most significant contributors and opportunities related to decarbonizing the building and construction industry (Heeren and Hellweg, 2019). Previous research have used different methods to predict the demand for materials from new construction. Müller (2006) developed a generic dynamic material-flow mode of analysis to predict future changes in building stock in the Netherlands. The applied model uses the population as an external variable driving force to predict the concrete demand from future dwellings. The predictions are based by considering the future scenarios provided from United Nation population division, and assumptions related to the useful floor area pre dwelling and the number of occupants. It deserves to be highlighted that the model determined the future needs as a function of population growth but does not apply forecasting methods. Following the same methodology, and having similar objectives, Bergsdal et al. (2007) and Hu et al. (2010) dynamically analyzed the overall demand for concrete from the building stock in Norway and Beijing. The population growth scenario was taken from statistics Norway, while they assumed that the number of persons per dwellings could not be less than two and considered an equal allocation as present for the floor area per person. Considering probabilistic scenarios related to the construction lifetime (building lifetime and renovation profile), Sandberg et al. (2014) examine the future renovation activities of the Norwegian building stock. The scenarios related to population growth and person per dwellings are the same with the study presented by Bergsdal et al. (2007). Using the same approach to predict future material flows for Switzerland, Heeren and Hellweg (2019) assessed the expected greenhouse gas emissions from the construction of new buildings and refurbishment of existing ones. The data of population growth scenario were extracted from Swiss Federal statistical office, while the floor area per capita were assumed as it is equal as present. Moreover, in this study they do not predict the spatial distribution of new buildings and the related environmental impacts. Considering the same increase trend as UK population, Drewniok et al. (2023) modeled the expected changes of the building stock and the related environmental impacts. For two scenarios, Fishman et al. (2014) projected the future material stock for Japan and United States as function of population and gross domestic product (GDP) scenarios provided by United Nations and US Census Bureau. In the first scenarios they assumed that the inflows in the consecutive years will be equal to the average of 1995–2005. While in the second scenario the inflow rates are calculated in relation to the projected population rate changes. They highlighted that such projection should not be considered forecasting or prediction but ‘what if’ scenarios. With an extended objective in a later study, Fishman et al. (2016) predicted the need for materials using the Autoregressive Integrated Moving Average (ARIMA) approach. They examined the global speed of the accumulation of material stock for 45 countries without providing details of the buildings and material types. Furthermore, they compared the results obtained from ‘what if’ scenarios with those obtained from the application of ARIMA method. For both United States of America and Japan the results from ARIMA method were found close to results obtained by the deterministic scenario calculated in relation to the population growth. However, the results obtained by the deterministic scenario calculated by considering constant inflow in the consecutive year felt in the confidence interval of the ARIMA forecast. Based on results, they concluded that ARIMA method can provide reasonable results compared to projections obtained from deterministic methods using ‘what if’ scenarios. With an extended objective of their study focusing on different residential building types, Marinova et al. (2020a) analyzed the dynamics of the material stock by dividing the world into 26 regions. To that end they applied deterministic method by considering the IMAGE integrated assessment models and the Shared Socioeconomic Pathways (SSP2) scenario, which essentially describes a “business as usual” evolution of socio-economic parameters in IPCC assessment reports (see Riahi et al., 2017).

Building on this study and following the same approach, Deetman et al. (2020) model evolutions of the global material stock of other building types. The model and scenario predict the future floor area of various building types. A set of material intensity coefficients (MICs) indicating average amounts of various types of materials per m^2 is used to estimate the material flows. However, they do not analyze the expected environmental impacts of the materials required from future buildings. At the city level, Huuhka and Kolkwitz (2021) map patterns of construction and demolition for various building types in Tampere, Finland, based on the evolution of records from a national building registry. Marcellus-Zamora et al. (2016) developed a novel approach for materials stock analysis through the analysis of land-use. They applied the method for the case of Philadelphia for the period between 2004 and 2012. Li et al. (2022) model the historical evolution of the building stock in Odense-Denmark by consulting archive maps, cadasters and satellite images, extracting polygons for all buildings on each map, and identifying which polygons are added, removed, or modified by automatically comparing maps from different years. This procedure helps identify service life distributions for various building types, understanding historical drivers for construction and demolition, and estimating the corresponding material flows using MICs derived from case studies. In the context of the Netherlands, Yang et al. (2022) model yearly demolitions by assigning a service-life parameter to each building based on a random probability distribution. Then new construction is calculated by first estimating evolutions in population and the demand for floor area per person and comparing the total needs of the floor area with the current stock. With the help of the Open Dynamic Material Systems Model, Arehart et al. (2022) analyzed the future demand for structural building materials plus associated upfront embodied carbon emissions in the United States.

Although the literature provides several studies analyzing the building stock and material flow dynamics in future years, they present several limitations. They do not forecast the spatial distribution of different future building types in small municipalities within a country. Nor do they develop a prognosis of yearly embedded impacts towards the future based on Business as Usual (frozen policy) trends. Consequently, the literature needs more analysis addressing spatiotemporal material-flow dynamics and related environmental impacts disaggregated into building types, components, materials, life-cycle phases and end-of-life. Motivated by this knowledge gap, the present paper proposes a spatiotemporal mapping of material flows and environmental impacts linked with future construction in Denmark. The novelty of this study lies in its use of publicly available data from the Danish building registry on the country scale, analyzing and identifying which building parts and materials require prioritization in mitigation strategies.

In the rest of this paper, future constructions are first estimated based on past trends and are mapped geographically. Then the corresponding demand for construction materials estimated on MICs is obtained from recent case studies and is mapped on to various materials categories and building parts. Finally, the environmental impacts linked with this material demand are estimated using a life-cycle assessment (LCA).

2. Methods

Relate to the method applied to predict the future needs of floor areas, the existing studies can be classified in two group as defined by Fishman et al. (2016). The deterministic method defining scenarios ‘what if’, largely applying the method recommend by Müller (2006), which correlates the future needs of new floor areas with the population growth scenarios or SSPs (Bergsdal et al., 2007, Hu et al., 2010, Sandberg et al., 2014, Heeren and Hellweg, 2019, Drewniok et al., 2023, Fishman et al., 2014, Marinova et al., 2020b, Deetman et al., 2020, Arehart et al., 2022). The second group use forecasting method to predict the future needs of floor areas (Fishman et al., 2016). Although the literature are missing studies comparing the results from different methods in the case of analyzing the building stock, Fishman et al. (2016) found that using deterministic method (simplified approach) or complex forecasting method like ARIMA will bring to same conclusions. Quasi similar conclusions are also provided in other field of studies where the aim has been the calculation of forecasting method’s reliability (Armstrong, 2001a, Bandeira et al., 2020, Meade, 2000, Mancuso and Werner, 2019). Reviewing the factors influencing the choice of forecasting method, Armstrong (2001b) recommendations was the use of simple methods unless substantial evidence exists that complexity will increase the accuracy of the data predictions. Considering the lack of studies comparing the accuracy of forecasting methods in prediction of future building needs, the recommendations of Armstrong (2001b), Bandeira et al. (2020), the discussion with expert in the field, we have adopted in this study the Holt-Winters method, as a choice between very simplified approaches (naïve method) and complex methods (ARIMA). Furthermore, the choice of the method is also based by considering that the new areas of different building typologies constructed in the past years (1982–2021) has not shown any significant correlation with the population (see details in appendix) as previous studies (Müller, 2006, Bergsdal et al., 2007, Hu et al., 2010, Sandberg et al., 2014., Heeren and Hellweg, 2019, Drewniok et al., 2023., Fishman et al., 2014) has assumed as an external variable driving force to predict the future needs. At the end the Holt-Winters additive model is used to forecast the future based on historical data about buildings constructed in past years in different Danish municipalities. Then using the life-cycle assessment (LCA) method, the environmental impacts of the materials and components of future buildings are calculated. The material intensity coefficients (MICs) of seventeen building types are coupled with the results from the forecasting to calculate the future needs for materials as adapted in previous studies (Marinova et al., 2020a, Deetman et al., 2020, Huuhka and Kolkwitz, 2021, Li et al., 2022).

2.1. Forecasting method

Several forecasting methods have been published in the literature (Makridakis et al., 2008) and used in predicting the dynamic material flows of building stock (Müller, 2006; Sandberg et al., 2014; Fishman et al., 2016; Marinova et al., 2020b; Huuhka and Kolkwitz, 2021; Li et al., 2022). Although selecting an adequate approach takes time and depends on many factors, in most cases the results have insignificant differences when various forecast methods are applied (Armstrong, 2001b). In the case of data series containing trends and seasonality, the Holt-Winters method is considered a robust approach for forecasts of the future. Based on the nature of the data series, the Holt-Winter approach can be used in multiplicative or additive versions. The literature recommends the Holt-Winters method’s multiplicative version for seasonal fluctuations, changing proportionally to the level and additive variation when the seasonality is constant (Hyndman and Athanasopoulos, 2021). The additive model is more suitable for this study, given the nature of the seasonal component of the buildings constructed in Denmark in recent years. In this model, the forecast value $\hat{y}_{i+h}$ of expected newly constructed buildings for h periods ahead is a function of smoothing equations for level u_i, trend v_i, and seasonal components s_i:

$$\text{Level}: u_i = \alpha(y_i - s_{i-c}) + (1-\alpha)(u_{i-1} + v_{i-1}) \tag{1}$$

$$\text{Growth}: v_i = \beta(u_i - u_{i-1}) + (1-\beta)v_{i-1} \tag{2}$$

$$\text{Seasonal}: s_i = \gamma(y_i - u_i) + (1-\gamma)s_{i-c} \tag{3}$$

$$\text{Prediction}: \hat{y}_i = u_{i-1} + v_{i-1} + s_{i-c} \tag{4}$$

$$\text{Forecast}: \hat{y}_{i+h} = u_i + hv_i + s_{i+h-ch'} \tag{5}$$

where: α, β, γ are respectively the smoothing factor, trend smoothing factor and seasonal component smoothing factor taking values between 0 and 1; c is the length of seasonality; h' is the integer part of $(h-1)/c$.

The parameters α, β, γ are obtained from the optimization of mean squared error (MSE) calculated using the equation:

$$\text{Mean squared error}: \text{MSE} = \sum \left(\frac{e_t}{n}\right)^2 \tag{6}$$

with $e_t = y_i - \hat{y}_i$ the difference between the prediction and the historical data of constructed buildings and n being the number of historical data. Zaiontz (2020) developed the Excel formatting tool used in this study. Historical data about the areas of different building types constructed in Danish municipalities in recent years are given in two granular forms. The aggregated areas for each building type’s construction in Denmark are available in the national database for 1982 to 2022. However, disaggregated information for each municipality is only available for 2006 to 2022 (Statistics Denmark, 2022). The forecasting method applies to the data from 2006 to 2022 in forecasting the future expected areas of different building types in all Danish municipalities. Furthermore, the forecasting is also applied to the available data for 1982 to 2022, which are used as a validation baseline of the results obtained from the more granulated historical data. Details about the forecasting results for all building types are provided in appendix.

2.2. Life cycle assessment

The life-cycle assessment (LCA) method, following EN-15978 (2011), is applied to calculate the environmental impact in case studies of buildings. An attributional LCA is used that allocates the impact to the product system (Hauschild et al. 2018). This study defines the functional unit as a one-square-meter gross floor area per year (m^2/year). For reasons of simplification, the reference service life of all building types is considered to be fifty years. Since this paper focuses only on the assessment of the embodied impacts of new buildings, the system boundary of the study is limited to the life-cycle of the product stage (A1–A3), transport (A4), construction processes (A5), replacement (B4), demolition (C1), transport (C2), waste processing (C3) and disposal (C4). Coupled information provided in the architectural and engineering design plans, BIM models and bills of quantities ensure complete and reliable values of the quantities of materials and components employed in each building case study. The downstream impacts of the replacement of components and materials during the building’s use are calculated based on reference lifespans obtained from the generic Danish data (Aagaard et al., 2013). Detailed information related to the quantities of materials employed in each component for each building typologies are provided in appendix. Although there is a lack of information about the processes related to the transportation, construction, demolition and waste-processing of building materials for the Danish context, their impacts are assessed through default values. Given the size of Danish municipalities (Copenhagen capital has a radius from the center equal to 30 km), transporting materials to the construction site (A4) is considered to take place over a default distance of 25 km. At the same time, a distance of 5 km is assumed for transporting materials to the waste-processing site (C2). The impacts of building construction (A5) and demolition (C1) are taken into consideration at ratios of 5 % and 2 % of material production respectively (Hoxha et al., 2016; Lützkendorf et al., 2014). End-of-life scenarios for waste-processing and disposal follow the recommendation provided in national guidelines and the Ecoinvent database (Wernet et al., 2016). The unit processes available in the Swiss Ecoinvent database V3.9 are used for the background system of the life-cycle inventory (LCI) which are detailed in appendix. To ensure a good representative for the Danish context, the selected unit processes are those of Western European countries, including Switzerland. To ensure accuracy in the assessment first were prioritized the unit process representative for the Danish context. When, there was a lack of data related to Danish context that those representatives of European countries and Switzerland were prioritized. The detailed information related to the selection of unit process in the Ecoinvent database are provided in appendix. Furthermore, in the appendix are indicated the end-of-life scenarios for each material and the representative reference followed whether it was from national guidelines or ecoinvent database. The study is focused on assessing all environmental indicators recommended by the EN-15978 norm to avoid burden-shifting by focusing only on the GWP indicator. However, given the urgency of the problem related to climate change, analyses are conducted in detail for the GWP indicator. The assessment and analysis are performed using SimpaPro software V9.4 (Pré Consultants, 2018) and Excel (Microsoft Corporation, 2018).

2.3. Case studies

To develop a baseline scenario of yearly embedded impacts across the country towards 2050 based on Business as Usual, we have analyzed the material intensity coefficients (MICs) for seventeen building types. The chosen conventional case studies for each building types have been built in Denmark during the last ten years. These cases are representative of actual and near-future construction technologies and materials employed in buildings erected in Denmark. To fully ensure the representativeness of the selected case studies, the projects for the building types of single-family houses, multi-dwellings, offices, schools and hospitals chosen from a pool of sixty actual Danish buildings (Zimmermann et al., 2021) have material-use quantities close to the average in all cases. In addition, a terraced house project is selected for analysis due to the lack of a precise definition for the building typology 'other residential building'. The other types are chosen from 250 real buildings constructed in Denmark, for which the data have not yet been published. Moreover, almost all projects have been accredited with a DBNG certification (Green Building Council Denmark, 2014). The architectural and engineering plans, BIM models and invoice documentation with quantities are those provided by private companies. Farm buildings, carports and outhouses are exceptions here, the materials employed in their cases being extracted from architectural and engineering plans that are freely available in the Danish Building Project Archive (Weblager, 2022). Almost all the buildings have one to five floors and a reinforced concrete structure. A summary of the quantities of the materials per square meter of gross floor area for all building types analyzed in this study is summarized in Fig. 1. The quantities are differentiated between three material groups: the external envelope, internal elements, and systems and equipment. Based on the results presented in the figure, the quantities of the materials do not show a clear trend in quantity per square meter, nor for the material groups. However, materials employed in external envelopes contribute the most to the overall weight of the building except for cultural buildings, daycare institutions, hotels and factories. In contrast, the systems and equipment make an insignificant contribution to the building mass. It deserves to be highlighted that the selected projects do not fully cover the systems and equipment employed in the buildings although previous studies have shown that they can have significant influence on the final results (Hoxha et al., 2020; Hoxha et al., 2021; Maierhofer et al., 2022). Information presented in Fig. 1 coupled with the data about the relative contribution of components, materials, life cycle stages and probable end of life scenarios presented in appendix, provides all the data used in this study for the building projects used to predict the future needs for materials and their associated environmental impacts.

3. Results

Fig. 2 gives the area in square meters of different building types constructed in Denmark over the last thirty years and the corresponding future forecasts until 2050. On average, between 1982 and 2021 Denmark constructed around 7.7 million m^2/year, with a minimal amount of 4.68 million m^2 in 1994 and the peak of construction coming in 2008, with 11 million m^2. The average was 1.55 million m^2/year for single-family houses, or 20 % of all new buildings. An almost equal percentage of farm buildings ranked as the second typology of erected buildings, equal to 1.52 million m^2/year. Multi-dwellings accounted for 16 % or 1.24 million m^2/year as the third most constructed building typology, followed by offices and factories with respectively 1.04 million m^2/year (13.5 %) and 0.85 million m^2/year (10.9 %). The remaining building types (20 %) share small, constructed floor areas in

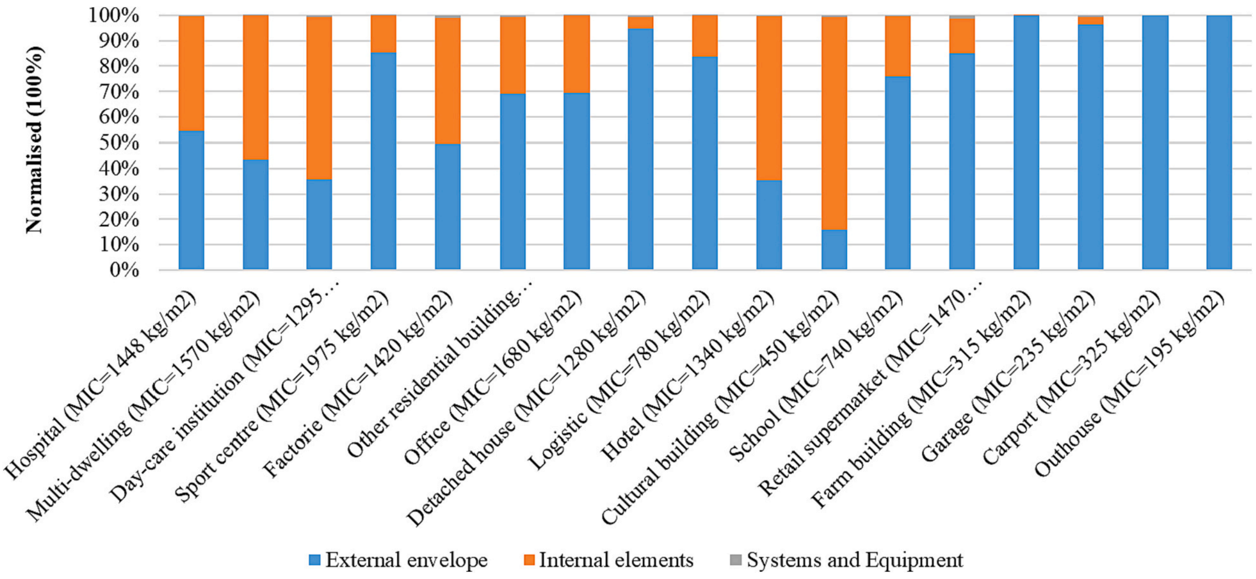

Fig. 1. Material intensity coefficients of 17 building types.

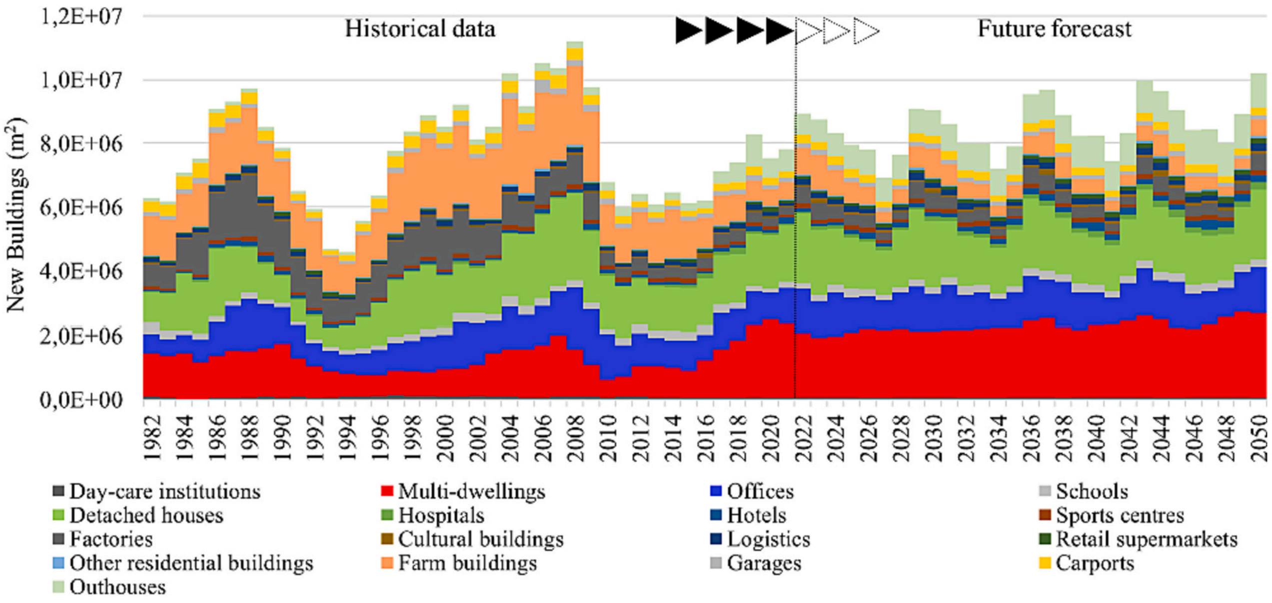

Fig. 2. Historical data on constructed buildings in Denmark and future forecasts.

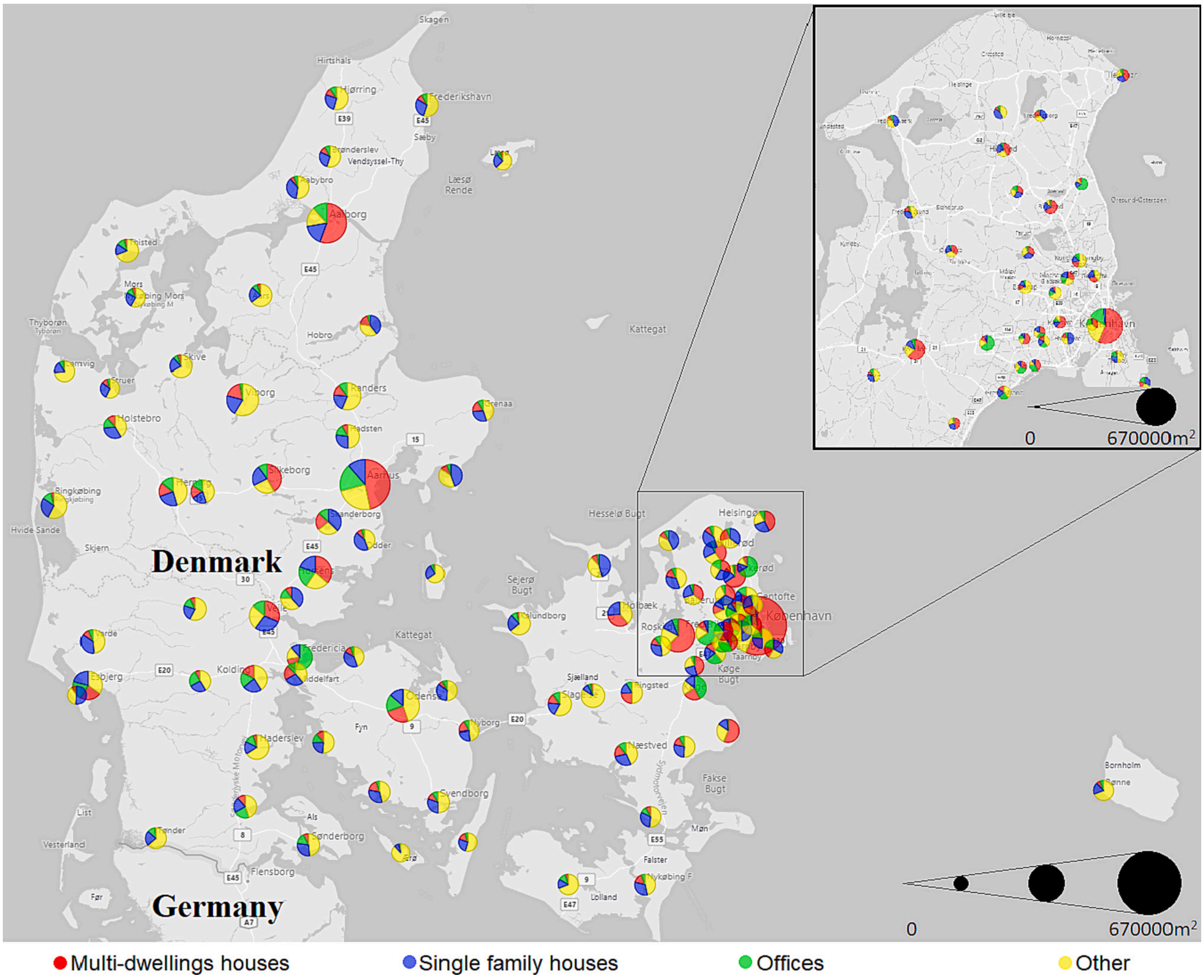

Fig. 3. Spatial distribution of expected new buildings in Denmark per average year (2022–2050).

recent years. Overall, historical data on building types show a vague trend in recent years, except for increased trends for outhouses and hospitals, and a decreased trend for factories. A significantly increasing trend over the last thirteen years of multi-dwellings is observed. Moreover, the data show twelve years of seasonality between 1982 and 1994 and 1995–2008. Among all building types, multi-dwellings, offices, schools, single-family houses and hotels have significant seasonality. Around 8.2 million m^2/year (6 % higher than the average of past years) will be built in the coming years, of which 26 % are multi-dwellings, 20.9 % single-family houses, 13.8 % offices and 10.5 % outhouses. Reflected in historical data over the next year, a slight increased trend detected in total building areas is mainly due to the multi-dwelling, hospital, hotel, supermarket, and outhouse types. Furthermore, the forecast data show a seasonality of eight years driven by single-family houses, offices, schools, factories, farm buildings and cultural buildings. Details about the forecasting results for all building types are provided in appendix.

With a focus on multi-dwellings, single-family houses, offices and other building types, Fig. 3 summarizes the distribution of expected new building area in Denmark on average from 2022 to 2050. The Central Denmark Region has the largest building area expecting to be covered by buildings in the following years. With a surface area of 13,053 km^2, this region is expected to build an average of 2.45 million m^2/year, or 28 % of the overall floor area of new buildings. Around 1.87 million m^2/year, or 22 %, are expected to be built in the Capital Region of Denmark, with a surface area of 2568 km^2. Almost the same area of buildings will be constructed in the Region of Southern Denmark with a surface area of 12,191 km^2. The Zealand region, with a surface area of 7273 km^2, is expected to cover 15.8 % of the overall area or 1.35 million m^2/year. The other building areas (0.97 million m^2/year) will be covered in the North Denmark Region, with a surface area of 7933 km^2. Related to the ratio of "expected built areas over the region's surface area," the Capital Region ranks first, followed by North Jutland and then the Central, Zealand and South Regions. Among the municipalities, Copenhagen is expected to have 8 % of the overall area, followed by Aarhus with 6 % and Aalborg with 4 %.

Moreover, in each municipality of Odense, Roskilde, Horsens and Viborg, 3 % of new floor areas will be built on, while in the other municipalities fewer than 2 % of new buildings will be erected. It should be stressed that, in the municipalities with the largest expected new areas, the share of multi-dwelling types is up to 45 %, while in the other municipalities, the other building types (outhouses, factories, farm buildings, etc.) present the largest expected newly built areas, followed by single-family houses. The offices have an almost homogenous share of new floor areas expected to be built on, ranking third or fourth in the hierarchy. Details about the spatiotemporal of all building types for each Danish municipality are provided in appendix.

Fig. 4 gives further details of the material types and corresponding quantities for the future yearly requirements of each building typology, their components and their expected waste management in the end-of-life phase, related to actual Danish scenarios. In total, the construction of new buildings in Denmark will require around 9.9 million tons/year (99 %) and around 0.14 million tons/year (1 %) to replace components during the use phase. Multi-dwellings will be responsible for 35 % of the overall material requirements, followed by single-family houses with 23 %, offices with 20 %, factories with 6 % and the other categories with fewer than 2 % each. One unexpected result is the large quantity of materials required by the slabs, especially those used in single-family houses. The slab requires around 2.5 million tons or 25 % of the required mass of all building types. The considerable weight of materials required by this component can mainly be justified because the single-family house is a one-story building.

Consequently, the slab mass significantly contributes to the overall building weight. Furthermore, the aggregate layer employed in the slab is another reason for ranking this component with the most extensive need for materials. Intermediate floors are components requiring an average of 1.9 million tons of materials per year. Based on the results in Fig. 3, the material required by floors are especially needed in multi-dwellings and offices. With almost similar requirements, external wall components require 18 % of the overall material need. Internal walls, mainly parts of multi-dwellings, are responsible for 13 %. With the same share of requirements, the analysis identified the foundations. Roofs

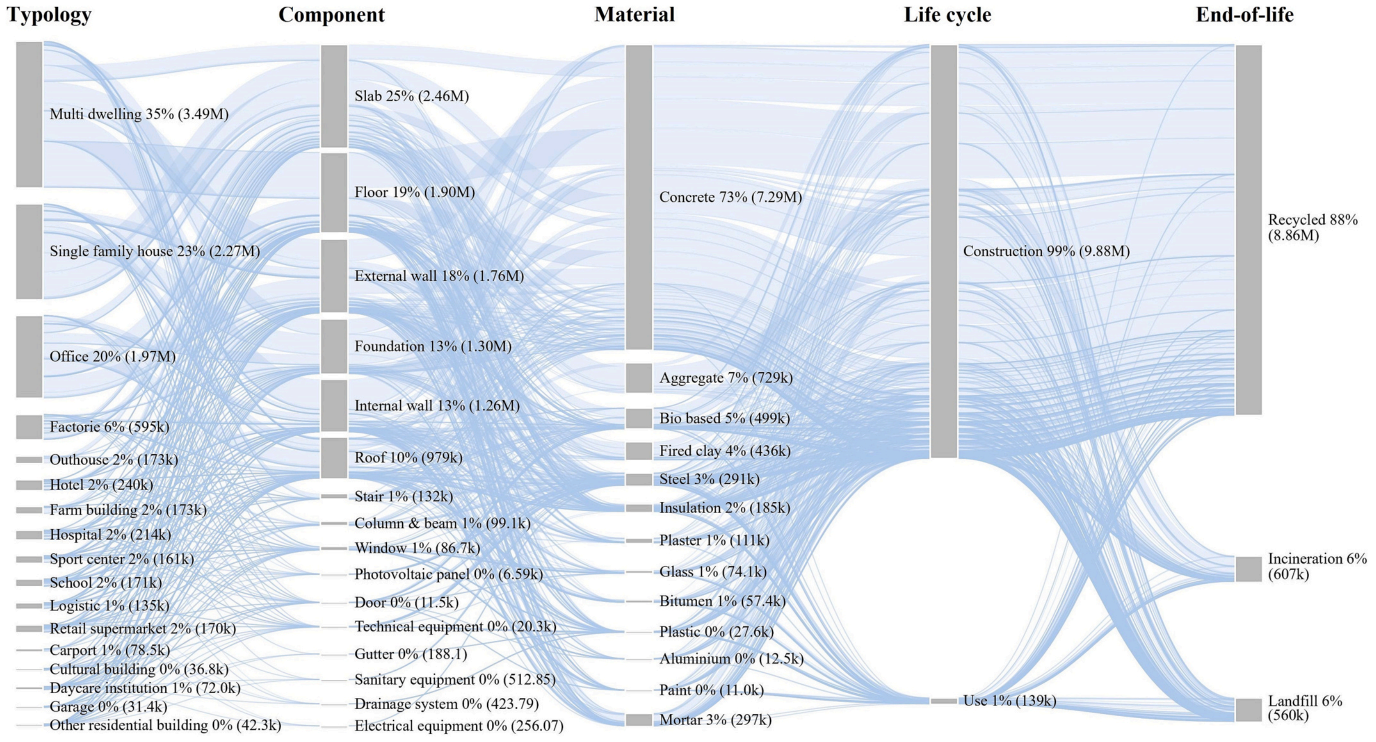

Fig. 4. Material flow analysis of expected newly buildings in Denmark per average year (2022–2050).

demand around a million tons of material per year, while each other component will require less than 1 % of the overall material need. Cement-based materials account for the most significant quantity demanded in the new buildings. Related to material typologies, the weights of concrete and mortar required in future construction are respectively 7.3 million tons and 0.3 million tons, each representing 73 % and 3 % of the overall mass. The mass of aggregates is around 7 % of the overall required weight, bio-based materials 5 %, fired clay 4 %, steel 3 % and the remaining materials less than 1 %. The results show that almost all the materials needed (99 %) are for the construction of the building. Related to the expected materials' end-of-life phase, 88 % will be recycled, 6 % landfilled and 6 % sent for municipal incineration. These results are identical with those published by the Danish Environmental Protection Agency, for which construction and demolition waste in Denmark was broken down into 87 % recycled, 6 % incinerated, 6 % landfilled and 1 % subject to special treatment (Environment and the Ministry of Food, 2018). Further detailed analysis shows that some materials used in the construction of buildings have an end-of-life scenario of municipal incineration. In contrast, the other materials employed in the construction and replacement of components of buildings are recycled or landfilled.

Fig. 5 presents the basic scenario of yearly related emissions from the expected new buildings in Denmark. From all building types, the impacts of climate change assessed through the GWP indicator total 4 million tons of CO$_2$e/year. Around 77 % of these impacts result from material production and building construction and will be released yearly from 2022 to 2050. Although the other 23 % of impacts are from the processes of replacement and end-of-life, and therefore happen later, they are consequences of the choices made of which materials and components to use in constructing the buildings. In addition to GWP, the other indicators of photochemical ozone formation, acidification, ozone depletion, human toxicity, particulate matter and ionizing radiation related to air pollution have the values respectively of 14.7 million kg NMVOCe, 22.8 million mol H + e, 260 kg CFC11e, 80 CTUh, 500 disease inc. and 249 million kBq U-235e. Regarding these indicators, the impacts related to the materials employed in new buildings and their construction are responsible for 60–75 % of impacts. The related indicators of the resource use of water, fossils, minerals and metals have respective values equal to 10 milliards m^3 depriv. 100 milliard MJ and 10 tons Sbe. For these indicators, the impacts of building materials and construction processes are responsible for 60–78 %. The indicator of land use has a value of 10 milliard Pt, of which 93 % comes from the materials and construction of buildings. The last group of indicators related to water pollution and, more precisely, the eutrophication of fresh water, marine and terrestrial water and the ecotoxicity of fresh water have impacts equal to 1 million kg Pe, 1 million kg Ne, 10 million mol Ne, and 100 milliards CTUe. The impacts of materials and construction processes are responsible for 70–75 %.

Given the importance of climate change prevention in the following, the results are only given for the GWP indicator. Fig. 6 shows the spatial distribution of the upstream impacts for the most expected building types of multi-dwellings, single-family houses, offices and others (factories, schools, daycare institutions, farmhouses, etc.). Out of 2.8 million tons of CO$_2$e/year, the central Denmark region is responsible for 29 %, the capital region 23.6 %, the southern region 21.4 %, the Zealand region 14.5 % and the north region 11.5 %. However, from the results presented in Fig. 5, it is evident that the capital region of Denmark has a large density related to the new buildings per region's surface area and consequently the related upstream impacts. Further detailed analysis of the expected impacts of municipalities shows that around 9 % of the

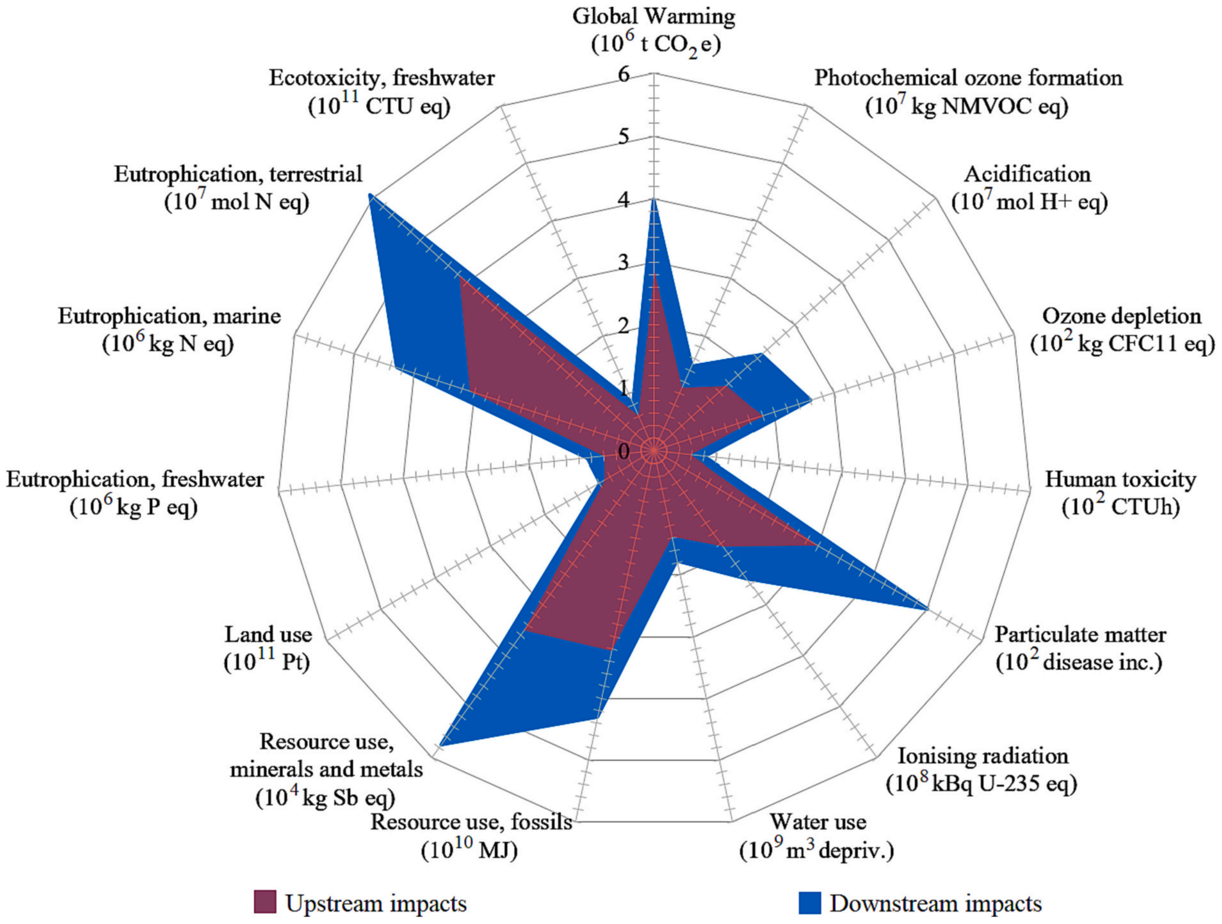

Fig. 5. Environmental impacts of expected newly constructed building in Denmark per average year (2022–2050).

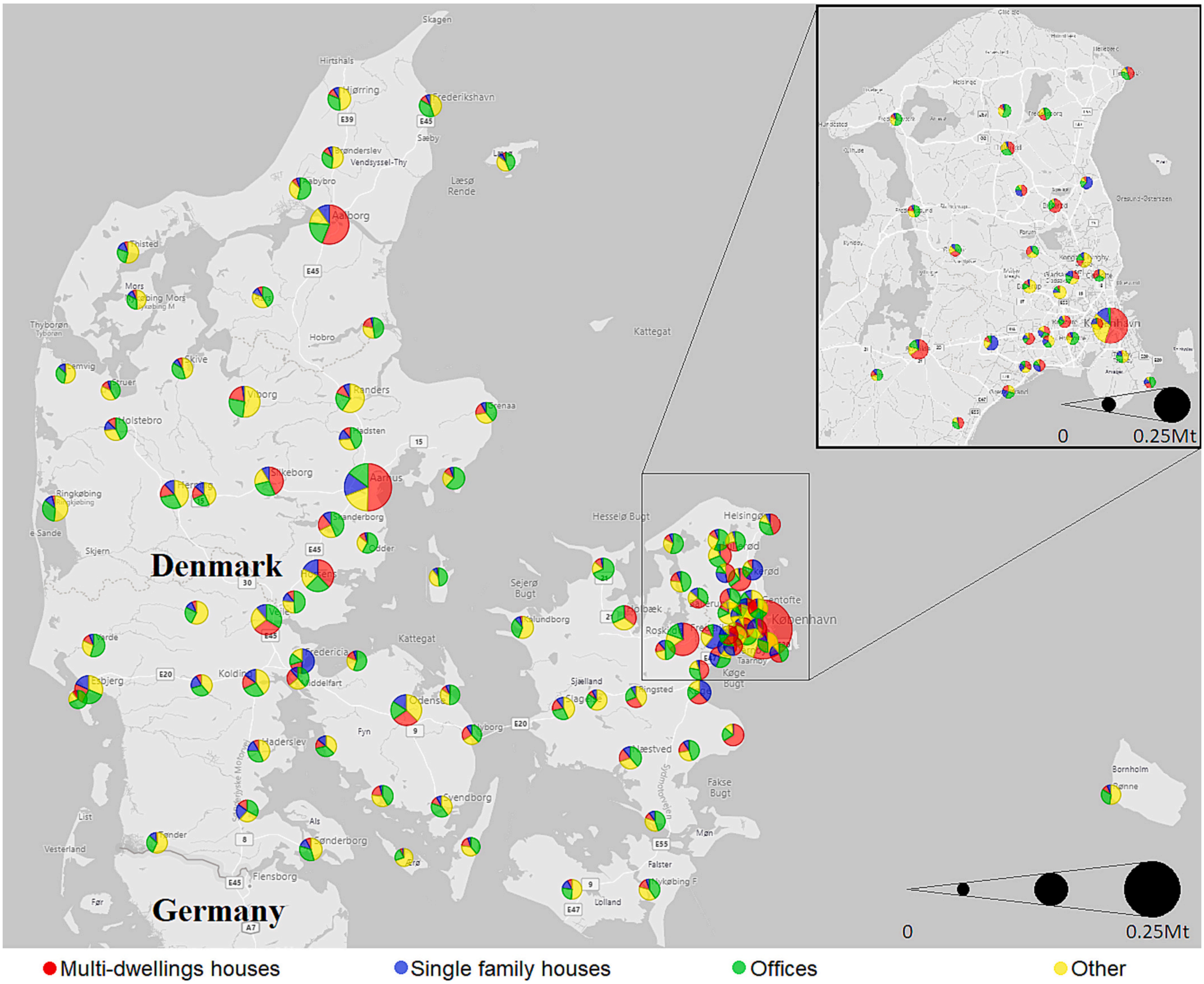

Fig. 6. Spatial distribution of upstream impacts expected by new buildings in Denmark per average year (2022–2050).

overall impacts are expected to be related to future buildings in Copenhagen, 6 % in Aarhus, 5 % in Aalborg, Horsens, Viborg, Odense and Vejle 3 %, and for all other municipalities less than 2 %.

Furthermore, more than 50 % of impacts are from multi-dwellings in the municipalities with the largest expected areas of coverage by buildings. Each building type, namely offices, single-family houses and other (factories, schools, daycare institutions, fam houses, etc.), presents around 15 % of the overall impacts. In other municipalities, conversely, the upstream impacts are from the expected single-family houses and other typologies (factories, schools, daycare institutions, fam houses, etc.). Quasi-similar results come from the expected downstream impacts, the spatial distribution of which is presented in Fig. 7. Processes related to the replacement of materials are expected to emit 1.2 Mt CO_2e/year.

Based on the obtained results, the most significant upstream and downstream impacts are expected in Denmark's biggest municipalities by multi-dwellings, offices and single-family houses. These three typologies represent more than 80 % of the expected impacts, and thus they should be prioritized in the strategy to implement low-carbon solutions. In the other municipalities, the reduction of impacts is more complex since they are related to fourteen building types. However, in these municipalities, the expected single-family houses are the second target where the implementation of low-carbon solutions can significantly influence the reduction of impacts. Details about the spatiotemporal distribution of the impacts from all building types for each Danish municipality are provided in appendix.

For a more detailed analysis, Fig. 8 summarizes the overall impacts of building types disaggregated into components, materials and life-cycle phases. The processes related to the life-cycle of multi-dwellings will release 1.13 million tons of CO_2e/year or 29 % of the overall impacts. Single-family houses are the second contributor to the future expected impacts, being assessed at 1.04 million tons of CO_2e/year. Significant impacts will come from offices, highlighted as 16 % responsible for impacts, followed by factories with 7 %. The remaining building types have insignificant impacts, with contributions lower than 4 %. Analysis of the environmental impacts of building components ranks the roof as the most significant contributor, equal to 19 %. For almost all building types, this component similarly influences the overall impacts. However, it is worth noting that the roof component of the office typology is a more significant contributor. The reason for this is that the office is a single-floor building where the contribution of the roof's impact is significantly greater than that of other components. The slab is the second component with a 17 % overall contribution, followed by external walls with 13 %, floors with 11 %, foundations and internal walls each by 9 %, and other with lower values. Photovoltaic panels and technical equipment contribute 8 % and 5 % respectively. Compared to

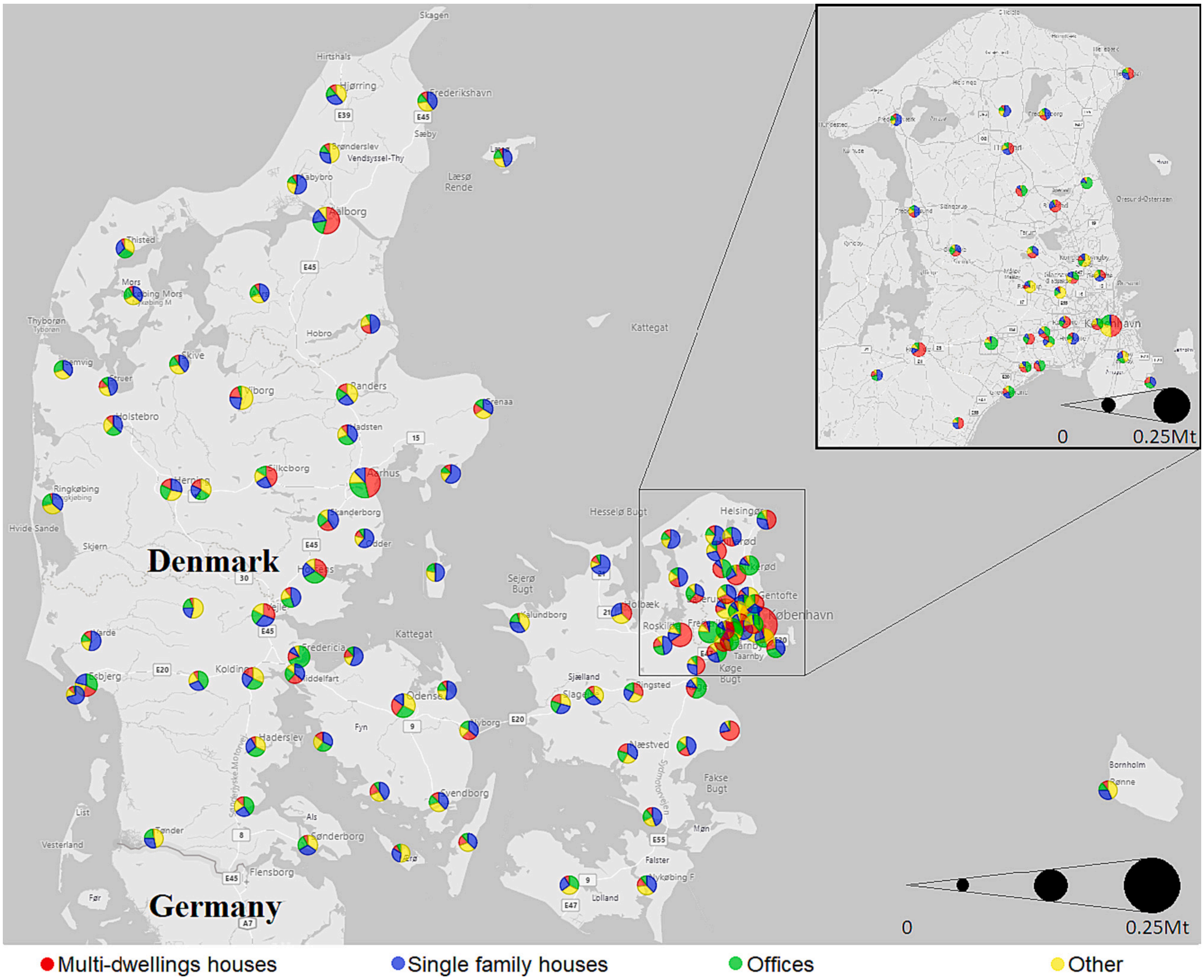

Fig. 7. Spatial distribution of downstream impacts expected by new buildings in Denmark per average year (2022–2050).

previous studies, the results obtained for the technical equipment do not vary significantly considering the simplification made in these analyses, while the impact of electrical equipment the gap is larger (Hoxha et al., 2020; Hoxha et al., 2021; Maierhofer et al., 2022).

Further analysis of the materials employed in buildings signals out concrete with an impact rating of 26 % of the overall impact, followed by steel with 25 % and insulation with 21 %. However, for the steel materials, the contribution from the photovoltaic panels is hypothetically considered to be in steel, technical equipment and the reinforced steel used with concrete. Bio-based materials, glass and bitumen contribute 4–6 %, whereas the other materials have an insignificant influence on impacts. Concerning building life-cycle phases, production (A1–A3) contributes 66 %, replacement (B4) 16 % and the end-of-life phase (C4) 8 %. The other life-cycle phases of transport (A4 and C2), construction (A5), demolition (C1) and waste-processing contribute (C3) 0–3 % and can be considered insignificant. Details about the GWP indicator for each building types are provided in appendix.

4. Discussion

4.1. Projection of new construction and related environmental impacts

This study has projected expected new construction and related environmental impacts in all Danish municipalities in a business-as-usual scenario. The results indicate that new buildings could be responsible for 4 $MtCO_2e$/year in Denmark in the coming decades. Around 2.8 $MtCO_2e$/year are caused by processes related to building construction, and 1.2 $MtCO_2e$ by building refurbishment and end-of-life phases, which are expected to happen after the study period. Official consumption-based accounts of GHG emissions in Denmark indicate that the “building and construction” sector was responsible for 9.1 $MtCO_2e$ in 2020 (Danish Energy Agency, 2023). This corresponds to about 15 % of consumption-based emissions, making it the second largest emitting sector behind “public and private services” (25 %) and ahead of “food, drinks and tobacco” and “direct emissions from households” (11 % each). The value from the Danish Energy Agency differs significantly from our estimate. One likely explanation is a difference in system scope. First, the foreground system in our LCA does not cover e.g. external works and infrastructure, which would be covered in the consumption-based statistics. Second, we use process-based background environmental data, while official climate impact statistics rely on input-output tables. This difference in background data can explain significant differences in results (Säynäjoki et al., 2017). The choice to use process-based environmental data was made for consistency with common building LCA practices in Denmark (and with the national LCA tool LCAbyg). This enables a future integration of LCA with the model, such as modeling how specific changes in material production and design practices would influence projected impacts (Alig et al., 2020).

Denmark’s consumption-based emissions are projected to decrease by 27–60 % by 2035 (Danish Energy Agency, 2023), but this projection

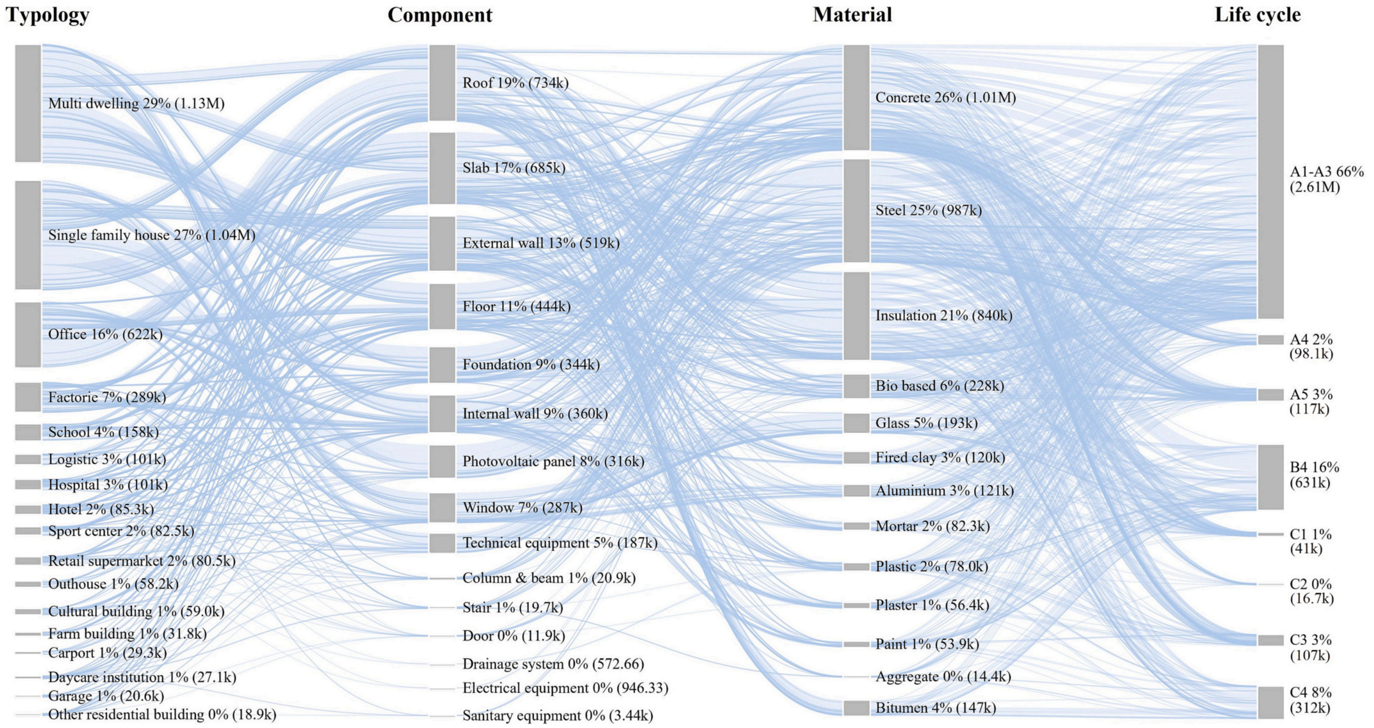

Fig. 8. GWP (tCO_2e) of expected newly constructed building in Denmark per average year (2022–2050).

is not broken down between sectors. A consideration of production-based emissions can give an indication of the expected scale of decarbonization in various sectors of the economy. Projected production-based emissions from “manufacturing and construction” correspond to a stable share of total emissions until 2035 (between 10 % and 11 %). Similarly, transport corresponds consistently to around 30 % of emissions. However, emissions from heat and electricity production are projected to drop from 10 % of emissions in 2021 to 0 % in 2035, while emissions from agriculture, forestry and fishery are projected to increase from 33 % to 48 %. This indicates that agriculture and forestry are expected to occupy a larger share of the emission budget in the future.

The Planetary Boundaries offer another useful point of reference to compare the model’s results (Steffen et al., 2015). Petersen et al. (2022) estimate that the planetary boundary related to climate change is compatible with global annual GHG emissions of about 2.61 $GtCO_2e$. Allocating this global budget to Denmark based on population (equal per capita allocation) gives an annual carbon budget for all of Denmark of about 2.1 $MtCO_2e$ (alternative allocation methods exist e.g., in Häyhä et al., 2016). The yearly projected emissions from new construction would already overshoot this national budget, which implies a need for radical change.

4.2. Relevance of the model for research and practice

The present study provides estimates that can be used as a baseline to support the prioritization of mitigation measures and the development of decarbonization scenarios in the building sector. Low-carbon solutions tested in a single case study can be upscaled at the level of the entire country and compared to the baseline scenario. This can be used to identify a mitigation potential for a range of possible solutions, combined or in isolation, while avoiding burden shifting from GWP to other environmental indicators. In the short term, the model is primarily intended to support other academic projects, as part of an ongoing research effort to develop building stock models for circularity and sustainable urban development in Denmark (Lanau and Liu, 2020; Li et al., 2022; Francart et al., 2023). In the longer term, these models could become important decision support tools for sustainable urban planning and policymaking at the local, regional and national level.

For policymakers, the model is useful to highlight hotspots of impact and support a discussion of issues to prioritize. For instance, multi-dwellings and offices will be hotspots of resource use and emissions in large cities, with single-family houses also representing a significant share of impacts across the country. Strategies or solutions to mitigate resource use and GHG in the building sector should focus on minimizing the environmental burdens of these building types. However, incremental reductions in material use and emissions per m^2 in new construction are unlikely to be enough to reach ambitious sustainability targets. The model also highlights the often-neglected need for demand-side interventions to reduce the amount of new construction. Between 2015 and 2020, the Danish population increased by about 20,700 people/year. Maintaining the current population growth rate, the expected building of 8.2 million m^2/year is unsustainable: it would represent about 400 m^2 constructed for each person added to the population. Therefore, it is crucial to change construction trends and build much less than we do today by making a more effective use of areas for building, in addition to adopting cleaner construction techniques. The priority should be given to preserving and adapting existing buildings, avoiding demolition and reusing building components.

For local authorities, the model could be further developed to provide more relevant insights for sustainable urban planning. This could entail providing spatially disaggregated results and taking the local socio-economic drivers of demolition and construction into account (Huuhka and Kolkwitz, 2021; Li et al., 2022). Local authorities play an important role in driving demolition and new construction. Adapting the model to provide better local-level estimates could help municipalities compare the predicted impact of their current development plans to an emission budget. Local-level actors could also benefit from ongoing research to develop more precise building stock models providing information at the level of building components (e.g., walls, roofs, etc.) (Lanau and Liu, 2020; Li et al., 2022; Francart et al., 2023). Such models can help identify opportunities to reuse components in demolished buildings, overcome barriers to reuse (Tirado et al., 2021, 2022), and support the development of resource cadasters for circularity and urban mining (Oezdemir et al., 2017). For instance, materials or components from demolished primary buildings (residential, offices, schools, etc.) can be reused in secondary buildings (farm buildings, garages, carports, outhouses, etc.) by overcoming the barriers related to construction codes or quality checks on component properties (Rakhshan et al., 2020). According to the Danish Environmental Protection Agency, around 4.2 Mtons of construction waste are produced each year in Denmark (Environment and the Ministry of Food, 2018). Reusing these materials could provide 40 % of the materials needed for new construction and avoid significant environmental impacts. Coupling the information related to the expected new buildings presented in this study with the expected demolished buildings (Jensen et al., 2022) can increase the potential of material use, help match the demand for new materials with available resources, support planning for waste handling facilities, etc.

4.3. Methodological discussion

The resulting findings depend on assumptions related to material amounts employed on each analyzed building typology and their representativeness in the Danish context. Although the chosen building projects represent new construction trends, the MICs represent a single archetype for each typology. Previous studies in Denmark used MICs of 1055, 1221 and 902 kg/m^2 of gross floor area respectively for new apartment buildings, terraced houses and single-family houses (Lanau and Liu, 2020). Higher MICs of multi-dwellings (1570 kg/m^2) and detached houses (1280 kg/m^2) include the case studies of the buildings analyzed in this study. These discrepancies mainly stem from the different construction technologies of different building projects. Lanau and Liu (2020) analyzed projects mainly of fired clay structures that were representative of past construction technologies. In this study, the projects are reinforced concrete structures representing present construction technologies as highlighted by Engelmark (2013). Moreover, for the typologies of single-family houses, multi-dwellings, offices, schools and hospitals, the analyzed projects, selected from a population of sixty case studies (Zimmermann et al., 2021), are significantly representative of present construction technologies. In addition, the impacts for the building types of single-family houses, multi-dwellings, offices and schools are within the range of values obtained by other studies for cases situated in different countries (John, 2012; Passer et al., 2012; Hoxha et al., 2017; Häfliger et al., 2017; Lasvaux et al., 2017; Drouilles et al., 2019; Röck et al., 2020; Scherz et al., 2022). However, for the building types of daycare institutions, factories, logistics, hospitals, hotels, sports centers, outhouses, cultural buildings, farm buildings and carports, the scientific literature lacks data, and consequently the results of this study cannot be compared with them. For these typologies, on the other hand, the findings presented in this study fill a knowledge gap in the literature. The results should be interpreted as a projection of current trends in construction demand, assuming that construction techniques and materials remain similar. The study does not attempt to forecast future construction technologies, only to show what the consequences of future construction and related resource use and environmental impacts might be like if current trends remain unchanged. It also deserves to be highlighted that the results presented in this study are functions of archetypes, assumptions, databases considered. As shown previously in other studies the archetypes, databases and assumption used withing the LCA method can potentially lead to different results (Frischknecht et al., 2020). However, the influence of uncertainties in building's LCA has been found to be to the range of 20 % (Hoxha et al., 2017).

The overall approach of the study is applicable to countries other than Denmark, but it is limited by data availability. Studies based on material intensities per building type have been carried out e.g. in the Netherlands, Germany, China, etc. (Heeren and Fishman, 2019; Oezdemir et al., 2017; Sprecher et al., 2022; Yang et al., 2020). However, deriving reliable MICs is work-intensive and requires a large number of case study buildings in a particular country or region. Second, the type of building data available varies between countries. Denmark has a rather extensive and publicly available building registry (BBR). The large amount of building-level information enables detailed analyses. Other countries might have less building-level data available or might rely on different kinds of data. For instance, Marcellus-Zamora et al. (2016) propose a building stock analysis based on land use type. The most suitable approach depends on the amount and reliability of different kinds of data (e.g. land use data or building-level data), as well as the type of analysis and target audience (building-level analyses might be more suitable to support discussions related to future building design, while land use based analyses might be more relevant for urban planners).

5. Conclusion

This study has presented a thirty-year future forecast of expected newly building types and related materials in Denmark. Considering a 'business as usual' scenario, the anticipation is that an average of 8.2 million m^2/year of new building areas will be constructed. Around 72 % of new surfaces will be related to the multi-dwelling, single-family house, office and outhouse typologies. Further detailed analysis of the spatial distribution of new buildings in Denmark identified the capital of Copenhagen as the municipality where construction of around 8 % of the total floor areas are expected. In the other two prominent municipalities, Aarhus and Aalborg, respectively 5 % and 4 % of new buildings are expected to be constructed. It is worth highlighting that more than 50 % of the new areas in these municipalities are for multi-dwelling purposes. However, in other municipalities, single-family houses are the most expected building typology for residential purposes. Offices and other types (factories, schools, hotels, hospitals, outhouses, garages, etc.) that are estimated to be constructed in the coming years in Denmark share relatively equal contributions to the expected future buildings. Concerning the materials required to construct and maintain the buildings (9.9 million tons/year), concrete presents 73 % of the total mass, followed by aggregates at 7 %, biobased at 5 % and other materials at less than 4 %. Around 75 % of the total amount of materials will mainly be employed in building components for the slab (25 %), external walls (18 %), floors (19 %) and foundations (13 %).

Moreover, the largest share of materials (99 %) is expected to be employed during the construction of the building, and only 1 % will maintain it by replacing some components during the building's use phase. Based on actual Danish waste-management scenarios, 88 % of materials will be recycled, 6 % landfilled and 6 % incinerated at the end-of-life phase. Based on the new areas to be constructed in the following years, this study develops a prognosis of yearly embedded impacts across the country towards 2050 based on Business as Usual (frozen policy) trends. Altogether the processes related to the building life-cycle modules are expected to have average upstream and downstream impacts respectively of 2.8 and 1.2 million tons of CO_2e/year. The spatial distribution of upstream impacts identifies Copenhagen as responsible for 9 % of future greenhouse gases, followed by Aarhus with 6 % and Aalborg with 5 %. The relative contribution of building types on the GWP score per municipality follows the same results of expected new floor areas. Moreover, a strong correlation between upstream and downstream impacts was discovered.

Multi-dwellings were responsible for 29 % of impacts. The building types of single-family houses, offices and factories also significantly contribute 27 %, 16 % and 7 % respectively of the overall impacts. Among building components, the roof, slab, external walls and floors have been found to contribute 19 %, 17 %, 13 % and 11 % respectively. Related to the materials employed in building components, the most significant influences on the impacts are concrete (26 %), steel (25 %) and insulation (21 %). However, the contribution of steel is shared between photovoltaic panels at 8 %, technical equipment at 5 % and mostly reinforced steel at 12 %. Although 99 % of the materials were used in the construction of buildings, the related impacts according to life-cycle modules (A1–A3) have a contribution equal to 66 %. Although only 1 % of the material are used for the replacement (B4) of components, they have a 16 % contribution and the end-of-life phase 8 %, though the impacts of the other life-cycle phases can be considered insignificant.

Finally, it can be concluded that the efforts to minimize the building's impacts should be prioritized for the residential that are expected to be constructed in Copenhagen, Aarhus and Aalborg. Employing thermal insulation materials with low GWP scores and structural materials with lower embodied greenhouse gas emissions than concrete should be prioritized mainly for the slabs, roof, external walls and floors. However, such technical solutions will not be sufficient to mitigate environmental impacts. It is essential to minimize the amount of demolition and new construction, and move towards a more circular building sector. The results presented in this study suggest a baseline scenario of the expected impacts. They are essential for LCA practitioners and government decision-makers by showing where to focus their efforts to decarbonize the Danish building sector effectively. Moreover, the results for the other indicators should be used as a reference to avoid shifting the climate-change problem on to other environmental burdens. The environmental impacts of expected newly constructed building in Denmark, under the scenario ̎business as usual ̋ indicate the necessity of perspective analysis for development of urgent actions to alight construction sector to Paris agreement goals.

CRediT authorship contribution statement

Endrit Hoxha: Conceptualization, Methodology, Data curation, Formal analysis, Investigation, Resources, Writing – original draft, Visualization. **Nicolas Francart:** Validation, Writing – review & editing. **Buket Tozan:** Data curation, Validation, Writing – review & editing. **Emilie Brisson Stapel:** Data curation, Validation, Writing – review & editing. **Srinivasa Raghavendra Bhuvan Gummidi:** Validation, Writing – review & editing. **Harpa Birgisdottir:** Validation, Resources, Writing – review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that there is no conflict of interest regarding the publication of this article.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.168853.

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