Energy & Buildings 276 (2022) 112482

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enb

Operational and embodied emissions associated with urban neighbourhood densification strategies

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ARTICLE INFO

Article history:
Received 2 June 2022
Revised 8 September 2022
Accepted 13 September 2022
Available online 24 September 2022

Keywords:
Densification
UBEM
Embodied emissions
Operational emissions

ABSTRACT

Urban densification increases the number of people living in urban areas and is hypothesized to be a more efficient use of available land than urban sprawl. The objective of this study was to quantify the operational and embodied emissions created as a result of densification. A 'Business as usual' and a 'Concentrated' densification strategy were investigated. When densifying at the neighbourhood level, existing buildings can either be replaced or extended to accommodate the additional inhabitants. The densification strategies were applied to two reference urban design neighbourhoods in Switzerland. The 'Typical' approach assumed that all the buildings were demolished and rebuilt and the 'Preserve-existing' approach involved the extension of existing buildings as much as possible. Construction material choice and modification of the built form were the sources of embodied emissions considered for each strategy. Urban building energy modelling was used to calculate the emissions incurred by heating the buildings and the embodied emissions were calculated using building standards. The operational performance was simulated assuming both a gas boiler and an electric heat pump to determine the influence of the heating system type on the operational emissions. This study found that savings of approximately 30% in embodied emissions can be achieved by extending the existing building stock rather than rebuilding. However, these savings represent a relatively small percentage of the total emissions incurred throughout a building's lifetime and the savings further diminish in the concentrated densification strategies.

1. Introduction

Depending on the population scenario, the total Swiss population is expected to increase between 10–31% by 2050 [21]. In Swiss cities, population growth occurs as a result of positive net migration and the relocation of people from rural areas into the city. Due to ongoing urbanization trends and land use restrictions, the densification of existing neighbourhoods is becoming increasingly important [51]. The importance of efficient land and resource usage through sustainable densification [16] falls in line with the Swiss Energy Strategy 2050 [44], which aims to achieve net zero greenhouse gas emissions by 2050. To be compliant with this strategy, urban planners and architects must be able to evaluate the impact of their design choices on greenhouse gas emissions. While it was shown that there is considerable potential for densification within built-up urban neighbourhoods [57,16], an integrated assessment of the impacts of urban design choices on total emissions is a challenging task. The work in this paper presents an incremental step to address this challenge and investigate the impact of different densification strategies and design choices on operational and embodied emissions (cf. Section 1.1). A further contribution is made to urban building energy simulation, where both operational and embodied emissions are considered in the assessment (cf. Section 1.2).

1.1. Emissions from buildings and neighbourhood densification

The two types of emissions produced by a building are operational, e.g. heating and cooling and embodied, e.g. from the construction and demolition of the building. The majority of energy used over the lifetime of a building is typically in the operational

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https://doi.org/10.1016/j.enbuild.2022.112482
0378-7788/

phase; embodied energy, on the other hand, contributes to less than 25% of the total energy [41,55] but can be as high as 90% for the most efficient buildings [41,8]. Several studies show that with ongoing improvements in the operation of buildings and advances in construction, the ratio of operational to embodied energy is diminishing [41]. For Switzerland, the contribution of construction material to total life cycle emissions of residential buildings is estimated to increase from 19% in 2015 to 39% in 2050 [25]. The carbon emissions caused by building operation have been extensively studied [36,47,50]. However, only a few studies have investigated the link between densification and energy use and these tend to focus on the impact on operational energy [34,26]. Some studies also widen the scope to consider the impact on emissions from other sectors as a result of densification, for example, mobility, which is strongly related to the geographical location and use of the building [53,23,10,38]).

When densifying a neighbourhood, planners are faced with a decision to either extend the existing buildings or demolish and rebuild. Typically, the most economical approach to densification is to demolish all of the existing buildings on the site before rebuilding; however, due to reductions in the availability of raw materials, there is growing interest in re-using materials, applying urban infill and extending or retrofitting buildings [1,42,19]. Unfortunately, there are limited studies on the emissions that occur from densification [22,29], thus, there needs to be a strategy on how to densify urban neighbourhoods with minimal embodied emissions [6].

1.2. Simulating operational and embodied emissions

Urban building energy modelling (UBEM) is the simulation of multiple buildings contained within a district, city or country and is primarily concerned with operational energy. However, there is a growing diversity in the stakeholders, spatial and temporal scales and the methodologies used for the assessment [32]. [40] proposed to take into account embodied emissions in the assessment of the environmental impact of buildings to avoid a performance gap similar to that seen in operational performance. One of the most frequently discussed debates in the construction industry is the use of timber versus concrete construction. Both have their advantages and disadvantages but timber is often evaluated as the option with the lowest relative embodied emissions [32,30]. Timber has also been proposed as a carbon sink due to the carbon dioxide absorbed during tree growth [9]. An approach to evaluating embodied emissions in typical construction elements in Switzerland is outlined in the SIA 2032 standard [52]. The life cycle assessment adopted in the SIA 2032 has been shown to be an accurate estimate based on a probabilistic assessment [43]. [27] recommend a robust, whole-life carbon accounting framework to account for life cycle emissions of buildings. A more recent review reveals that the situation has changed very little and that a 'notable and cross-sectoral effort' is still required for the transition of the building and construction sector that involves the critical stakeholders across the entire building life cycle [41].

1.3. Original contribution and scope of analysis

The importance of considering both the embodied and operational emissions has been highlighted [33]. Our review also revealed the need for a methodology to consider both the operational and embodied emissions when evaluating the sustainability of different design choices for densification. The objective of this study was to extend existing urban building energy modelling tools to consider both operational and embodied emissions for different densification strategies and design options. This study uses existing reference designs as outlined in [16,15] and presents an additional analysis of the results reported by [14].

2. Methodology

2.1. Identification of neighbourhoods for densification

[15] assumed that, within Switzerland, neighbourhoods built during the post-war period (1945–1980) are potentially suitable for urban neighbourhood densification due to their modernistic spatial layout and poor energy performance. In addition to this, many post-war buildings are facing their second renovation cycle. The neighbourhoods were identified for Switzerland and classified into five neighbourhood archetypes to analyse the different densification strategies [16]. For this analysis, examples from the A4 archetype are considered (cf. Section 2.4).

2.2. Densification strategies

The densification strategies investigated in this study are described in detail in Eggimann et al. [16] and can be summarised as follows:

- S0: 'Current neighbourhood'
- S2: 'Business as usual', 60% increase in occupants through the replacement of existing buildings either as a whole or in phases in accordance with the common adaptation of building zones.
- S3: 'Concentrated densification', 75% increase in occupants through the replacement of existing buildings either as a whole or in stages with a maximum density based on contemporary urban development criteria. This strategy might not comply with current legislation as higher floor area ratios are reached than currently allowed.

The densification strategies S2 and S3 are applied for each reference urban design (cf. Section Section 2.3).

2.3. Densification design options

In this study, two design options for each densification strategy were investigated. These are detailed below:

- 'Typical' (T): Status quo of the industry where reducing time and cost are priorities. The 'Typical' design option represents the business-of-usual of the industry for the A4 archetype: a full demolition and rebuild of the entire site with a higher density.
- 'Preserve-Existing' (PE), the majority of existing buildings are extended by a single floor which reduces the number of new buildings required.

2.4. Reference urban designs

Reference urban designs for the A4 archetype were created by urban planners for the design options ('Typical' and 'Preserve-Existing') and each densification strategy (S0, S2 and S3). The typical scenario for the N1 neighbourhood was sourced from a project by BS + EMI Architektenpartner AG. The typical scenario for the N2 neighbourhood was sourced from a project by Graber Pulver Architekten. The difference between the two example neighbourhoods, N1 and N2, is the architectural approach to designing the new structures based on the available plot. The N1 plot has a high aspect ratio which allows the buildings to be aligned in a regular sequence. The triangular plot of N2 means that the buildings need to be arranged irregularly to make the most of the available space. The A4 archetype was considered to have the greatest flexibility regarding the construction of new buildings and modification of existing structures. The two reference neighbourhoods of this study are representative of the A4 archetype [16]. The A4 archetype accommodates an estimated 30% of the occupants in the post-war neighbourhoods in Switzerland and was shown to have the highest densification potential of the archetypes. In the 'Preserve-Existing' design option, the population quota for each densification strategy was first accommodated by extending the existing buildings by one floor, as this was deemed structurally feasible for the reference designs. New buildings were then constructed in between the existing buildings. The 'Preserve-Existing' design option is generally not favourable in practice due to the additional costs and complexity of extending and building around the existing structures, which could also cause disturbance to the existing occupants. On the other hand, preserving existing structures may be favourable for occupants, which could increase project acceptability and consideration of heritage values [48]. A visualization of the densification strategies and the design options for the reference design case studies is shown in Fig. 1.

In the 'Preserve existing' option, the creation of multiple small and fragmented buildings was necessary. This is not favourable due to losses in economies of scale that are possible in the 'Typical' option. The widespread infilling of existing neighbourhoods will also reduce the number of unsealed surfaces and urban green spaces, which increases urban runoff [24] and reduces other ecosystem services such as using trees for heat-adapted design. The 'Preserve-Existing' option was hypothesized as a less material-intensive alternative to the typical approaches to urban densification.

2.5. Energy and emissions modelling

Densification provides the opportunity to renovate the existing building stock to current building standards to reduce the amount of energy they consume. CESAR-P is an urban building energy modelling simulation software for assessing the energy performance of buildings and retrofitting strategies at a district scale. The software was released as an open-source Python package [18]. The predecessor software was used in previous studies to assess the retrofitting scenarios in districts across Switzerland [56] and to evaluate the feasibility of decentralised energy storage [35]. At the core of CESAR-P is a set of construction and building usage archetypes, based on statistical data about the Swiss building stock and national construction standards. These data resources are used to parameterize individual building models in EnergyPlus. EnergyPlus is a whole-building simulation software that uses mass and heat balance equations to model the energy flows across the thermal zones of a building [11]. CESAR-P assigns internal conditions and occupancy profiles for each building type based on the Swiss SIA 2024 standard, which provides typical conditions for different categories of buildings [46]. All the scenarios were simulated using a Zurich weather file based on a 2015 reference year. CESAR-P extrudes each polygon uniformly using the building height to generate the building volume. The energy

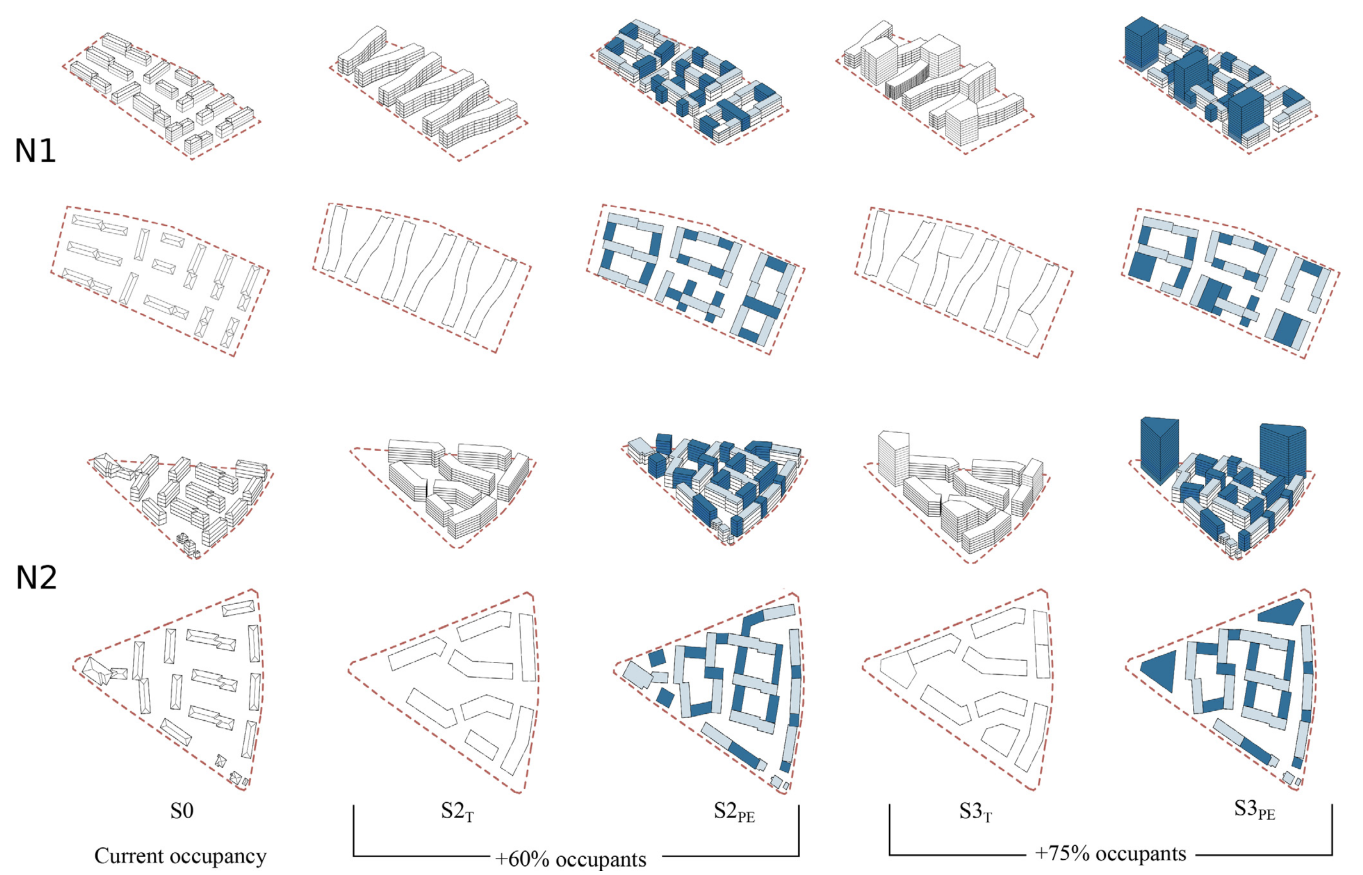

Fig. 1. The urban designs of the example neighbourhoods (N1, N2) to test implications of different densification scenarios and design options. S2 is a densification strategy that increases the resident population by 60%. S3 is a densification strategy that increases the resident population by 75%. Each densification strategy has two design options; Option (T) represents the 'Typical' architectural approach to densification planning; Option (PE) is the 'Preserve-Existing', where the construction of new buildings is minimised and all existing buildings are extended by one floor. The buildings outlined in light blue are extended by one floor and the dark blue polygons represent new buildings. Both neighbourhoods accommodate a similar quantity of people. The average percentage increase in occupants is shown for each densification strategy.

reference area in all cases was assumed to be 100% of the gross floor area to determine internal loads from occupancy and equipment according to the SIA 2024 standard [46]. In this project, the functionality of CESAR-P was extended to include the following features:

- Extension of the archetype database with representative timber and concrete constructions. The intensity of timber versus concrete in newly built buildings or parts of buildings has been previously investigated [2].
- The calculation of embodied emissions incurred by new buildings. Reference values were used from the SIA 2032, which is a standardised approach to calculating the environmental impacts of building construction in Switzerland [52]. This standard was used to determine the embodied emissions associated with each building element (walls, roof, ground, internal floor). The SIA 2032 standard reports an annual embodied emissions value per unit area for each building element assuming an amortisation period specific to that element."

As part of the early-stage design analysis, the SIA 2032 standard was used to calculate the embodied energy and emissions of new building constructions [52]. The SIA 2032 provides amortised (i.e. considering the life expectancy of different components) annual values of embodied energy and emissions across the economic lifetime for different building elements. Each element and the chosen option for analysis are listed in Table A.1.

To quantify the impact of the construction choice on the neighbourhood archetype, the embodied and operational energy totals were calculated across each neighbourhood and divided by the number of occupants. A constant value of 46 m^2/occupant [20] was assumed for this calculation.

To calculate the embodied energy of the extended buildings, it was assumed that the original parts of the building are retrofitted as standard. It was assumed that the extensions of the existing buildings by one additional floor on the top of the building are always constructed in timber. The embodied emissions from constructing the additional timber walls and roofs for the extension are identical to the typical constructions for the timber construction strategy. Total emissions are comprised of the following components:

- **Construction material choice**: The construction of the building elements (wall, roof, ground floor, internal floors) of new buildings in timber or concrete
- **New build baseline**: The construction of all other building elements that are not specifically linked to the choice of construction material choice according to the assumptions in the SIA 2032 e.g. excavation. The field selection is constant for all buildings but the value is calculated based on the building geometry, see Table A.1.
- **Extension**: The extension of the buildings by one floor using timber walls and roofs
- **Heating emissions**: The emissions incurred from heating the building. In the absence of data about the heating system for the reference designs, emissions for heating the reference urban design with a gas boiler and a heat pump are assumed. To determine the carbon emissions produced by supplying the thermal energy demand to the building, we multiply the ideal energy calculated by CESAR-P to heat the building by a carbon emission factor of 0.054 kg CO_2-eq for the heat pump and 0.234 kg CO_2-eq for the gas boiler. These emission factors are taken from life cycle assessment data in the construction sector [28].

2.6. Concrete and timber building elements

Two material choices, concrete or timber, were investigated for each densification strategy and design option per urban design. The material layers for each building element (roof, ground floor, external wall and internal floor) were selected from the Lesosai 2020 standard construction library [13]. Lesosai software is used to certify compliance of a construction design to Swiss building standards, more details are provided in Section 2.7. The different construction strategies investigated in this work are concrete and timber scenarios. These construction strategies only apply to the new buildings required in each densification strategy. In both strategies, concrete was used for the ground floor. The different construction material choices and their assignment to each individual building element are shown in Fig. 2.

2.7. Evaluating construction strategies

For each urban design, the footprint polygons for the new and extended buildings were labelled for each design and scenario. It was assumed that all existing buildings are renovated to the required heat transfer coefficients of the Swiss SIA380 standard [45]. The construction characteristics of the existing buildings were assigned using the CESAR-P default library for the building age category 1949–1978 [56]. All buildings were assigned as multi-family residential in all reference designs.

3. Results

3.1. Total emissions

The total emissions for each urban design, densification and construction strategy are shown in Fig. 3. This shows the emissions attributed to each of the building components listed in cf. Section 2.5. Each component will be discussed separately relative to its contribution to the total emissions in the following sections.

3.1.1. Choice of construction material

Fig. 3 shows that the timber scenario generates less emissions than the concrete scenario. This can be seen across all densification strategies. Only focusing on the emissions from the choice of construction material reveals that the average embodied emissions for building timber elements are less than half those for concrete, namely 105 kg CO_2 per occupant, per year for the all concrete scenario and 43 kg CO_2 per occupant, per year for the timber scenario.

3.1.2. Heating emissions

Fig. 3 shows the calculated emissions from the strategies for each reference neighbourhood. The left graph shows the overall

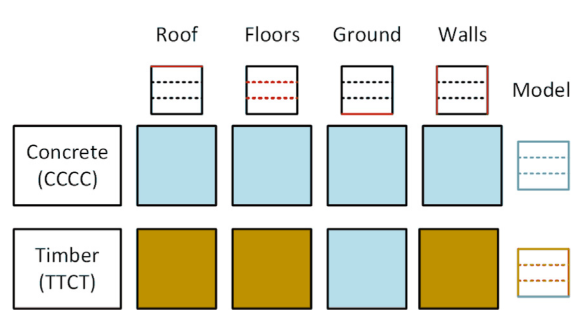

Fig. 2. The assignment of timber (brown) and concrete (blue) to the building elements of the simulation of new buildings for the concrete and timber scenario.

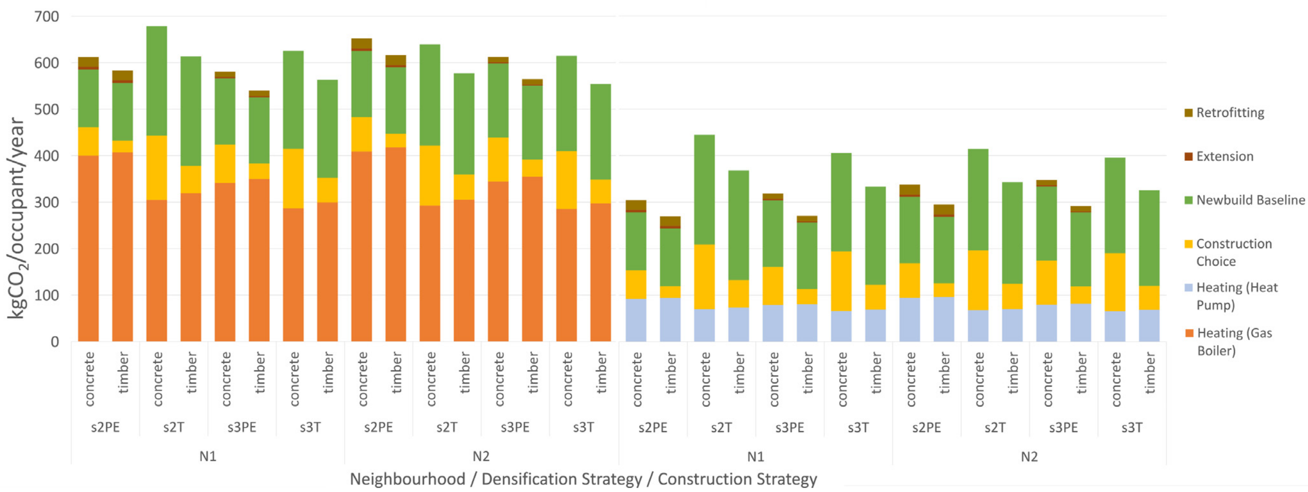

Fig. 3. The total operational and embodied equivalent carbon emissions per occupant, per year for each urban design (N1, N2) and each densification (S2, S3) and the Typical (T) and Preserve-existing (PE) construction strategy. The graphs on the left and right show the operational and embodied emissions when a gas boiler and electric heat pump are assumed respectively.

emissions from gas boilers and the right graph shows when an electric-powered heat pump is assumed to provide the same quantity of heat to the buildings. These two options were chosen as their carbon emission factors represent the range of efficiencies of energy systems encountered in buildings. The left graph of Fig. 3 shows that when gas boilers are assumed, the emissions from heating the building account for the majority of the total emissions. When an electric heat pump is assumed, the heating fraction drops considerably and the total emission is reduced by approximately 50% across all scenarios. The reason for this difference is due to the electric-powered heat pump producing less than a quarter of the emissions of the gas boiler. This analysis highlights the importance of considering the operational aspects that contribute to the total emissions produced throughout a building's lifetime.

In both graphs displayed in Fig. 3 it can be seen that the reduction in the emissions, due to construction material choice, is partly offset by a difference in heating emissions, between construction material choice (concrete vs timber) and densification approach (T vs PE). There was a negligible difference between the timber and concrete strategies for all densification strategies (2%) whereas the difference between the S2T and S2PE is 25% and between S2T and S2PE is 16%. The reason for this difference is due to the poorer performance of older, retrofitted buildings relative to new ones. This occurs due to assumptions made by the energy simulation, which assumes older buildings have higher air infiltration compared to their newer counterparts. Fig. 3 shows that this difference offsets the benefits achieved through using construction materials with lower carbon intensity. In the case of N2, a greater reliance on existing buildings offsets the reduction in savings due to reduced construction and the PE scenario has an increase in total emissions per occupant.

3.1.3. Baseline embodied emissions vs extension

The SIA 2032 standard also contains various building elements that were beyond the scope of this study. To put emissions from the choice of construction material into the context of the overall performance of the building, an assumed baseline was calculated for new buildings, Appendix Table A.1 details the assumptions for the other elements included in this baseline that were outside the scope of this study. The baseline and embodied energy incurred by retrofitting and extending existing buildings are shown in Fig. 4. Because the baseline is the same for both timber and concrete the graph only shows the results from the different densification strategies.

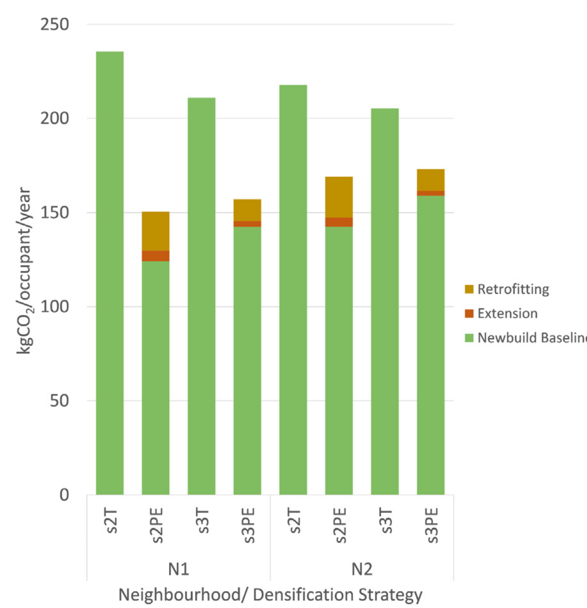

Fig. 4. The embodied emissions associated with retrofitting, extending and constructing the buildings in each strategy (PE: Preserve-Existing, T: Typical).

The N1 reference design has a greater reduction in the number of new buildings which achieved a reduction in new build emissions per occupant compared to N2. This result also shows a reduction in per occupant emissions between the S2T and the S3T densification scenarios, this is because embodied emissions for the new buildings are shared by a greater number of people. As the typical approach to construction, S2T and S3T, only contain new buildings, see Fig. 1, they only contain the newbuild baseline component. In all cases, the energy required per occupant to construct these buildings is greater than retrofitting and extending the existing buildings in S2PE and S3PE. There is also a slight increase between the S2PE and S3PE for both urban designs. This is because it is limited how much an existing building can be extended before a new building is required to house the additional occupants in the S2PE scenarios. This is why a reduction in extension emissions and an increase in new build emissions are observed.

4. Discussion

Fig. 3 presents the full results of this study by combining all the different scenarios and design approaches. The main findings are:

1. Using timber instead of concrete achieves a 60% reduction in the embodied emissions of the considered construction elements; however, these construction elements only make up approximately 30% of the total embodied emissions of the new buildings.
2. The 'Preserve Existing' construction option has higher operational emissions (due to the relatively poor performance of retrofitted buildings compared to new ones). In the N2 urban design with gas heating, this results in a higher overall emission intensity per occupant, as shown in the left half of Fig. 3.
3. In the urban designs considered in this study, the preservation and extension of existing buildings achieved on average a 30% reduction in embodied per capita emissions compared to the 'Typical' approach. The difference is less in the 'Concentrated' densification strategy because the existing buildings can only be extended to a certain point before additional buildings are required to house the additional occupants. In case of the need to achieve high-density values, there is, therefore, a limit to how much the existing buildings and supporting infrastructure can be extended.

4.1. Environmental performance of densification

This study focused on the embodied and operational emissions resulting from the choice of using timber versus concrete in new constructions and the number of new buildings required to meet densification quotas. We show that it is possible to achieve savings in embodied emissions by reducing reliance on new buildings.

In this study, we presented an analysis for gas boilers and heat pumps, Fig. 3 shows that heating systems with fewer carbon emissions have a large impact on the total emissions of a building. In this study, we found that using an electric-powered heat pump reduces total emissions by approximately 50% in all the scenarios considered. This also means that if buildings are equipped with low-emission heating systems, the construction strategy and material choice account for a greater relative portion of the total building emissions. This means there will be an increase in the relative benefit of densifying using the 'Preserve-Existing' strategy.

The values of embodied energy and embodied carbon were taken from the SIA 2032 standard to investigate the impact of material choice in each of the densification strategies. These values are assumed to represent the average impact of using timber and concrete in the construction of buildings. The authors acknowledge that there are many different forms of concrete and some may even have a better environmental footprint than timber [39]. There is also the potential to recycle and reuse materials that will reduce the reported embodied energy and emissions [5]. The purpose of this study is to indicate the impact of the choice of using concrete versus timber for the different building elements. A detailed life cycle assessment of the building products should be considered on a project basis.

4.2. Importance of assessment boundaries

To conclude that densification has lower embodied emissions than not densifying, a more explicit definition of the alternatives is needed. For a deeper comparison, a more detailed assessment would need to include an alternative scenario that detailed where the occupant would reside if not in the densified location. This would further necessitate considering additional influencing factors, such as mobility and socioeconomic factors, that could be also affected by densification. However, structural densification might be the only option to accommodate a large increase of inhabitants if alternatives are constrained (e.g. by land or regulations). This work provides a means to assess and identify some of the key aspects a planner must consider when deciding on densification approaches.

4.3. Limitations, data availability and research opportunities

Densification is a complex process involving multiple, interlinked sectors and factors e.g. mobility, socio-economic, construction, environmental etc. Data was not available in this study for a detailed analysis of the impact of densification on emissions beyond the construction materials. Additional studies that extend the methodology to include additional indicators, such as quality of life or economic costs, are also recommended. Several studies have investigated the impact of densification on indicators beyond the scope of this study [17,7,54]. Further areas of research could be the impact of reduced open space in the 'Preserve-existing' design option concerning sustainable drainage and urban runoff management [24] or the challenge of urban heat-adapted design with blue-green infrastructure for heat mitigation [37,31] or how to improve biodiversity within neighbourhoods undergoing densification [12].

In this study, the assumptions made regarding building lifetime were already integrated into the carbon intensity values published in the SIA standard. New research however shows that information models could provide deeper reasoning into why buildings are constructed and demolished and provide a quantitative assessment of the demolition rate [3]. This could be useful to compare the growing population and identify the most suitable locations to densify based on the upcoming areas for demolition.

This study made assumptions about the construction elements and their properties using statistics about typical buildings and building regulations in Switzerland. We also assumed that all buildings in the reference designs were extended by one floor. In reality, this might not be possible and it may also be possible to extend by a greater number of floors. A more detailed assessment of the different requirements and construction practices for tall buildings might also be necessary. One study showed that the slenderness (H/B) ratio is an important consideration for tall buildings due to the additional thickness to support the walls in long, thin buildings [4]. In this study, we assumed that all walls were of equal thickness regardless of building height. To carry out such a study would require more detailed designs of the reference cases and the buildings within.

Our findings are in good agreement with the previously published embodied performance of timber versus concrete [9]. However, there is now a wide range of timber and concrete-based materials that vary considerably in their characteristics and their carbon/energy intensity [39]. This variability could have a significant impact on the findings.

This study used regional standards and statistics to obtain values of the carbon intensity and the thermal-physical properties required for simulation. This is considered the best available approach for the scope of this study. As more data become available regarding the prevalence of types of timber and concrete used in the industry, their spatial availability relative to each neighbourhood and their embodied energy, it could be used to provide a more accurate picture of the impact of not only densification strategies but also the implications of other urban planning studies.

By considering emissions per occupant for different densification scenarios, this research also considers how many occupants are within the building, rather than only considering the physical characteristics of the building. In this study, we assumed that all buildings in each reference design contained the same floor area per occupant. If it is possible to house more people within buildings to achieve less floor area per capita (e.g. by reducing the number of empty nesters) [49], this will also reduce the per capita emissions. In this study we did not consider the economic implications of each design; however, this is a key determining factor in the success of a design. From a social perspective, many occupants may also not wish to move into densified locations due to a reduction in personal space. Requiring a population to live in a densified environment may have societal implications beyond those considered in this study.

5. Conclusions

This paper presented an approach to modelling the embodied and operational emissions associated with the construction of buildings for densification. We found lower embodied emissions are possible when the densification strategies prioritise the preservation of the existing buildings rather than rebuilding. However, the reduction in embodied emissions was offset in some cases due to the poorer performing retrofitted buildings when gas heating is assumed. When a heating system with a lower carbon intensity is considered, in this case an electric heat pump, the value of total emissions is reduced across all strategies that preserve the existing buildings rather than rebuilding them.

It is important to note that the purpose of this study was to demonstrate an approach to evaluate densification strategies where both operational and embodied emissions are considered. A more comprehensive and detailed set of reference urban designs are required to fully understand the impact of densification on the resulting emissions. Based on the identified limitations and shortcomings of our analysis, important considerations for a more comprehensive future research agenda on sustainable densification can be planned. With this in mind, we recommend addressing the following points in future research:

- Focus the analysis around the additional occupants of population projections that are driving the need for densification. Also, increase the boundaries of analysis to include where the occupants will be placed if not in densified regions. This will help quantify the true impact of densification across Switzerland.
- Define a set of densification archetypes that are representative of the locations where densification is possible. These archetypes should be characterised in terms of their supporting infrastructure, densification capacity, construction restrictions and socio-economic factors.
- Provide a deeper analysis of the social, environmental and economic aspects of densification.

To this end, not only more detailed simulation approaches are required but also interdisciplinary collaborations between practitioners from the field and the building energy simulation community.

Declaration of Competing Interest

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

Acknowledgements

This work was supported by the Swiss Federal Office of Energy under the project StaVerdi (SI/501894–01). We would like to thank BS + EMI Architektenpartner AG and Graber Pulver Architekten who allowed us to use their designs in our reference cases.

Appendix A

A.1. Calculating the embodied emissions using SIA 2032

Table A.1
This table shows how the SIA 2032 was used to calculated the embodied emissions in this study. The elements: external wall construction, ceiling construction and roof construction were set as concrete or timber depending on the construction scenario shown in Fig. 2. The remaining elements were set as constant for all new buildings.

Building Element	Calculation Method	Assumption
Excavation	10% Building Volume	Without groundwater
Floor slab, foundations	Footprint Area	Insulated
Outer wall below terrain	Perimeter*Excavation Depth	Insulated
Roof above terrain	NA	Insulated
External wall construction above terrain	Outer wall area	Timber/Concrete
Outer wall covering above terrain	Outer wall area	Light cladding, rear-ventilated
Window	Window Area	0 for full glazing, average value 2-fold/3-fold
Inner wall	Gross Area	Mean value load-bearing and non-load bearing
Ceiling construction (including ceiling covering)	Footprint Area*number of floors	Timber/Concrete
Insulation against unheated surface	Roof Area	
Ceiling construction	Footprint Area	Finished floor covering (without substructure)
Balcony	NA	
Roof construction	Roof Area	Concrete ceiling/wooden ceiling
Roof structure	Roof Area	Insulated (flat roof)
Electric system	Gross Area	Residential
Heating system	Gross Area	Heat generation and distribution
Ventilation system	NA	Ventilation system
Water system	Gross Area	Residential

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