Embodied carbon savings of co-living and implications for metrics

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ABSTRACT

In light of the climate crisis and conflicting political ambitions in many countries to rapidly increase the number of dwellings, what housing strategies could reduce emissions? Co-living is one strategy sometimes highlighted but rarely implemented in mainstream construction practices. Using two Swedish case studies, the potential embodied carbon savings are explored for co-living designs. When comparing building designs, normalisation of impacts or energy use per floor area is unequivocally the norm. The present comparison between co-living and traditional apartment design indicates an embodied carbon savings at the building level of 10–20% depending on whether embodied carbon is normalised per gross or residential floor area. However, normalisation per capita (inhabitant) shows substantially higher savings of 21–36% depending on the case studied. The effect of different metrics is illustrated to quantify potential embodied carbon savings of non-mainstream building design solutions such as co-living. Even more substantial embodied carbon savings can be achieved by avoiding new construction through the ability of enabling a more efficient use of indoor space. The need for rethinking carbon and space metrics will help the building sector meet emission targets.

PRACTICE RELEVANCE

Evidence is provided to show that design for co-living could be one way to offer a climate-efficient and qualitative housing alternative for single households in many countries. However, to visualise such potentials, developers are recommended to use additional metrics when evaluating how resource or climate-efficient are alternative designs. Traditional metrics such as kWh or kg CO₂e/m² of gross or heated floor area ought to be complemented by displaying resource use or embodied carbon per designed number of building user and per accessible floor area for each user. Up-to-date generic values are provided for the embodied carbon of different types of space. These can be used in early planning to display the consequences of the number of kitchens and bathrooms and their space occupation in client decisions and early architectural design.
1. INTRODUCTION

The building sector is a major contributor to problems such as climate change and resource depletion. In the European Union, energy-related greenhouse gas (GHG) emissions of residential and non-residential buildings account for approximately 36% of all yearly GHG emissions (EASAC 2021). Significant emissions are caused by the construction of new buildings and the renovation of existing buildings, so-called embodied carbon or embodied GHG emissions in buildings which primarily emanate from the production of the large volumes of materials needed (Birgisdottir et al. 2017). Climate mitigation in the building sector has largely focused on reducing operational emissions, mainly through decarbonisation of the energy supply as well as improvements in operational energy efficiency. With the more recent concern for embodied emissions, mitigation strategies such as the decarbonisation of material production, primarily cement, concrete and steel, and material substitution, such as increasing construction in timber, are increasingly highlighted (Favier et al. 2018; Karlsson et al. 2021; Malmqvist et al. 2018; Röck et al. 2020). Still, to reach net-zero climate targets, these strategies need to be complemented with other strategies as to reduce the amount of new construction and the more efficient use of building space (Francart et al. 2018; Ness 2022; Xue 2015). The promotion of such strategies could be seen as part of the sufficiency discourse, which has become more accentuated the last decade (Callmer 2020; IPCC 2022). Sufficiency in relation to the building sector has in the academic community primarily targeted dwelling areas per person in the Western context (Cohen 2021; Hagbert 2016; Lorek & Spangenberg 2019; Ness 2020; Sandberg 2018; Stephan & Crawford 2016; Stieß et al. 2019; Viggers et al. 2017), and the need for reducing these, with the environmental debate in mind.

Co-housing or designs for co-living materialise a sufficiency ideal in building design. Co-living is a way of sharing resources, in this context building space and appliances, resulting in lower emissions and resource use (Chatterton 2013; Cohen 2021; Francart et al. 2018; Tummers 2017). Another possible reason for the renascent interest for co-living options is the critics against the streamlined housing production of today, and misfit to current preferences. For example, in 2016 single households constituted 40–50% of all households on the German market, which, on the other hand, was dominated by three- to four-room apartments (Lorek & Spangenberg 2019). The situation is similar in Sweden where more than 50% of the households in apartment buildings are currently single-person households (Statistics Sweden 2021), but increasing preferences for co-living are evident when younger people are surveyed (Akademiska hus 2020).

Although co-living has long been suggested as a resource and emission-saving strategy, few studies actually quantify and explore the savings potentials of co-living compared with contemporary modern housing. Primarily such studies encompass quantifications of the level of energy savings due to reduced dwelling areas per person (e.g. Lorek & Spangenberg 2019; Stephan & Crawford 2016; Viggers et al. 2017). Cohen (2017) even explored what a sustainable, sufficient dwelling area per person could constitute in quantitative terms. These studies mainly explored the resource savings due to less space to be heated and ventilated if dwelling areas per person decreased. Proponents for co-housing also often argue that there may be positive effects on resource use connected to co-living practices through enabling and promoting sharing habits (Hagbert et al. 2020). Several studies aimed at evaluating potential environmental savings due to co-living practices, some of which are reviewed by Daly (2017). Most studies conveyed lower ecological or carbon footprints of co-housing communities compared with reference points. However, the review also covered cases with higher carbon footprints (Daly 2017). Some scholars further argue that the most important energy savings due to co-housing relate to the pro-environmental values of many initiators of collaborative housing projects, leading to a selection of innovative operational energy solutions, such as photovoltaics (Marckmann et al. 2012; Tummers 2017; Vestbro 2012).

As seen above, studies on potential resource savings through different forms of co-living primarily target operational energy savings through the reduced need for heating spaces or more pro-environmental lifestyles with respect to food and transportation choices. However, to our knowledge, no study has explored the potential embodied carbon savings through co-living design compared with apartment design. Stephan & Crawford (2016) studied potential life-cycle energy
savings due to reduced house sizes, but focused on embodied energy and did not investigate the effect with respect to co-living design as a way to reduce space needs in housing.

The issue of how resource efficiency is actually measured is increasingly raised as an obstacle to the realisation of co-living projects (Francart et al. 2020; Höjer & Mjörnell 2018). If measuring energy use or embodied carbon per person instead of per m², co-living would be more beneficial compared with most contemporary housing production (Akademiska hus 2020; Francart et al. 2020). This is in line with scholars suggesting additional metrics (other than measuring energy use per m²) to better highlight resource efficiency in buildings (Bastos et al. 2014; Francart et al. 2020; Huovila et al. 2017; O’Brien et al. 2017; Sekki et al. 2017). The added value of co-living is not revealed in contemporary decision-making, which is based on a limited number of indicators. Co-housing and co-living proponents typically highlight that co-living may entail the access to additional functions for its dwellers compared with mainstream apartment buildings. Vestbro (2012), for example, highlights potential access to playrooms for children, hobby rooms, guest rooms, saunas and exercise rooms. In addition, softer values such as reduced loneliness and sharing housework (e.g. cooking) are benefits of co-living that are commonly raised (Hagbert et al. 2020).

In light of the climate crisis and the political ambition in many countries to rapidly increase the number of dwellings, different strategies to reduce emissions deserve exploration. What are some potential carbon savings that a co-living strategy could actually deliver? The aim of this paper is to assess potential embodied carbon savings of implementing co-living designs in buildings. A second aim is to visualise the effect of alternative metrics, as well as the added value of co-living, of relevance to decision-makers in building processes. Two case studies of co-living designs are used to illustrate potential embodied carbon savings and various metrics.

Two notes on the terminology need to be made. First, the studies in this paper focus on design for co-living. This means the design of housing units in which the inhabitants share basic dwelling functions with each other. This is differentiated from co-housing or collaborative housing in which inhabitants normally have their own apartment with basic functions and then share functions with others, such as a large canteen, hobby room, library, etc. Second, the paper uses the term embodied carbon to denote embodied GHG emissions for simplicity in communication, still acknowledging that the latter term is the more correct scientific term for the variable under study.

2. METHODOLOGY

2.1 OVERVIEW OF THE STUDY

This paper is a result of the work performed during the period 2020–21 in two Swedish research and development (R&D) projects: Co-Kitchen¹ and Max4Lax.² Both projects focused on developing co-living unit designs for two different target groups. Co-Kitchen targets students and the studied design has been realised in practice in a living lab environment for student housing at the Royal Institute of Technology (KTH) campus in Stockholm. Max4Lax targets elderly single women. In the latter project, design proposals were developed, but it is yet unclear if the studied design will be realised for the particular development project. The motive for this focus was the perceived need to diversify the contemporary housing market for these two target groups, for whom living alone is not preferred.

The development of detailed research questions as well as ideas on alternative metrics were developed in dialogue with professionals representing designers, urban planners, developers, property owners and other researchers who participated in each project. To examine the potential embodied carbon savings by employing designs for co-living, quantifications were performed on design proposals from the two case studies of the projects. To enable a rich and interesting discussion on the topic, analyses were first performed for co-living designs compared with apartment building designs. In the next step, the detailed results of the case studies were used
to estimate and discuss potential embodied carbon savings if design for co-living was to be implemented at a larger scale.

The architects developing the design proposals were the same in both projects, but the detailed case study methodologies differed slightly with respect to the goals of each R&D project. Apart from stakeholder dialogues, the development of design proposals and quantifications of the embodied carbon, desktop studies compiling existing statistics and data from other studies were used to enrich the discussion.

### 2.2 OVERVIEW OF THE CASE STUDIES AND STUDIED DESIGNS

Table 1 overviews the studied designs where case study 1 (CS1) represents the case with student housing and CS2 that with housing for elderly women.

#### 2.2.1 CS1: Co-Kitchen student co-living in Live-in-Lab

This case study first looks at a full-scale implementation of a design for student co-living compared with a design with individual student units, the so-called testbed assessment. This is made possible through KTH’s Live-in-Lab (LiL), which is a testing and research platform with the goal of increasing collaboration between academia and industry. An important part of the LiL is the physical testbed, in which new designs and services can be tested in real homes. Originally, the testbed was designed as four small apartments (Figure 1a), but during the Co-Kitchen research project it was reconstructed into a co-living unit with four bedrooms, finalised in August 2021 (Figure 1b).

The LiL testbed is situated in a larger student accommodation area called ‘Forskningen’ at KTH campus with a total of 309 student studios with a similar layout to the original testbed apartments (Figure 1a). To analyse potential embodied carbon savings from co-living design also at the building level, the Forskningen student housing unit (Figure 2) was used as the case study building.

Three alternative layout plans for co-living units implemented in the case study building Forskningen were designed by the architects of the project, building upon the design developed for the LiL testbed (Figure 1a). This also enabled a somewhat freer design exploration by the architects, compared with the testbed design. As the physical restrictions of the testbed did not allow for a design with more sleeping units than four, the number of rentable dwellings was the same for both studied layout plans of the testbed (Figure 1). However, the kitchen design of the co-living unit of the testbed is large enough to accommodate more than four residents and the design opportunities of co-living could therefore be better explored when applying them to an entire floor plan (Figure 3). This floor plan is still based on the original geometries, but stretching out the angled floor plan, of the case study building Forskningen. The three co-living interior design alternatives were developed for rectangular floor plans both for simplification and to better accommodate co-living units since the as-built geometry was not feasible for a cost-effective design hosting co-living units.

To allow for a just a comparison, the following modelling was performed. First, building components affected by the co-living design were singled out from the original building information model (BIM) model of Forskningen and replaced with the components in each co-living design alternative from the digital architectural Revit models. The components affected by co-living designs include interior walls, floors, ceilings, internal doors, interior furnishing, and appliances in kitchens and bathrooms. Finally, it was assumed that the embodied carbon per gross floor area of the building components which were not affected by the co-living designs stayed the same as for the original design of the Forskningen case study building. This is a simplification; however, it means that the calculations are based on the same type and amounts of large, load-bearing structural materials per gross floor area, for all studied alternatives. Thus, the analysis is focused on the parts affected by apartment versus co-living design. For further details about this modeling, see the supplemental data online.
### Table 1: Key facts about the three case studies (CS)

<table>
<thead>
<tr>
<th>CS1: TESTBED ASSESSMENT (Figures 1 and 2)</th>
<th>CS1: BUILDING-LEVEL ASSESSMENT (Figure 3)</th>
<th>CS2: BUILDING-LEVEL ASSESSMENT (Figure 4)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>AS-BUILT DESIGN WITH FOUR STUDIOS</strong></td>
<td><strong>AS-BUILT DESIGN WITH ONE CO-LIVING UNIT</strong></td>
<td><strong>CO-LIVING DESIGN A</strong></td>
</tr>
<tr>
<td>Grass floor area (m²)</td>
<td>114</td>
<td>114</td>
</tr>
<tr>
<td>Residential floor area (RFA) (m²)</td>
<td>86</td>
<td>104</td>
</tr>
<tr>
<td>Main structural material and structural solution</td>
<td>n.a.</td>
<td>• External load-bearing sandwich walls</td>
</tr>
<tr>
<td>Number of floors</td>
<td>One</td>
<td>Three buildings: six to seven floors each with one floor underground</td>
</tr>
<tr>
<td>System boundary for the building inventory</td>
<td>All building components that were subject to changes due to the co-living design in the interior of the testbed, i.e. interior walls and wall coverings, floor coverings, interior roof materials, doors, fixed furnishing and appliances including, e.g., whitegoods and sanitary goods. Other technical installations are excluded</td>
<td>All building components covered in the testbed assessment plus the rest of the building elements and components. The only components not covered include potential materials for soil stabilisation and groundwork preparations. This system boundary corresponds to the proposed system boundary for limit values in the climate declaration regulation in Sweden (Boverket 2023)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• If some building components, such as furnishing for kitchens and bathrooms, were missing in the model quantifications, these were manually added based on layout plans and typical kitchen and bathroom compositions</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Technical installations were included based on the standard value on embodied carbon for multifamily dwellings of 17.3 kg CO₂e/m² heated area from Malmqvist et al. (2021)</td>
</tr>
</tbody>
</table>
Figure 1: Original apartment layout (CS1) (a) and layout with a co-living unit (CS1) (b).
Source: Figures and co-living design by Theory Into Practice (TIP), https://www.theoryintopractice.se/.
Reproduced with permission.

Figure 2: CS1: One of the three buildings of Forskningen, including the KTH’s Live-in-Lab (LiL) testbed.
Source: Theory Into Practice (TIP). Reproduced with permission.

Figure 3: Layout plans of the studied co-living designs applied to the case study building Forskningen in CS1.
Source: Figures and co-living design by Theory Into Practice (TIP). Reproduced with permission.
2.2.2 CS2: Max4Lax co-living for elderly women

Max4Lax is a concept developed by the architectural firm Theory Into Practice (TIP). Its goal is to create a new alternative in the housing market adapted to the economic constraints and life situation of female senior citizens by offering co-living with a rent of SEK4000/month. This case study concerns a planned housing project developed by the municipal housing company in the city of Uppsala, Sweden. The drawn original ‘Takryttaren’ building project design was done to host 47 apartments of different sizes, 30–74 m² (Figure 4a). This project provided TIP with an opportunity to showcase for the developer how the implementation of the Max4Lax concept of this building could be done. The resulting design, developed within the original building geometry, thus hosts 12 co-living units (11 units of 222 m² and 1 unit of 159 m²), with 81 bedrooms in total (Figure 4b).

2.3 EMBODIED CARBON ASSESSMENT

All embodied carbon assessments in this paper include building life cycle modules A1–A3 (product stages, i.e. cradle to gate) according to the European Standard EN 15978 (European Standards 2011). The motivation for this system boundary is that it covers the majority of the embodied carbon of a building in a life-cycle perspective (e.g. Moncaster et al. 2019; Nygaard Rasmussen et al. 2018; Röck et al. 2020), and that it thus also represents the central emissions of interest in relation to current policy developments to regulate embodied emissions (e.g. Danish Building Regulations 2023; European Commission 2021; Ministère de la Transition Écologique 2020). Full building inventories, following the proposed system boundary for limit values in the climate declaration regulation in Sweden in 2025–2027 (Boverket 2020, 2023; Malmqvist et al. 2021), of the case study buildings were used as the basis for the embodied carbon assessments. These were erected based on quantifications in Revit or BIM models and product information in construction drawings and additional information for the respective buildings. If some building components (e.g. furnishing for kitchens and bathrooms) were missing in the model quantifications, then these were added manually based on layout plans and typical kitchen and bathroom compositions. Once this had been done, the quantified embodied carbon was deemed to constitute 95% of the real impact.
of the full building inventory according to the system boundary given in Table 1. To compensate for this, the result was divided by 0.95 to better represent a complete building inventory. This procedure corresponds to the recommendations issued by the national authority Boverket for the erection of climate declarations according to the Swedish regulation (Finansdepartementet 2021). Finally, it was not possible to quantify technical installations of the case study buildings. Therefore, the embodied carbon for these was calculated based on the heated floor area, using a standard value for multifamily dwellings of 17.3 kg CO$_2$e/m$^2$ heated area from Malmqvist et al. (2021).

Mostly generic, average climate data for construction products were taken from the national database in Sweden, complemented with data from the Finnish national database, which includes data for interior finishes and fixed furniture to a higher extent than the Swedish database. Climate data for white goods were taken from Femenías et al. (2016). Generic data were used, as the main objective of the study was to examine the embodied carbon of alternative designs rather than the preferences of architects and developers concerning product choices. Climate data for products represent emissions of GHGs given as global warming potential (GWP) according to the EN 15804 standard, using GWP 100 as the characterisation method. Note that the data used do not consider any biogenic emissions. Further details regarding calculation methodologies for each case and analysis is found in the next section.

By studying two different but complementary cases, as well as several alternative layouts for co-living, the results of this study are novel and contribute to a rich discussion about the potential embodied carbon impact and savings of co-living designs compared with contemporary apartment design.

3. RESULTS

Section 3.1 presents the results from the testbed assessment. The focus is on providing more detailed knowledge on which building elements and their embodied carbon are affected by the interior layouts when co-living is compared with apartment design. The subsequent sections presents the results from the building-level assessments.

3.1 EMBODIED CARBON: COMPARING CO-LIVING WITH STANDARD APARTMENT LAYOUTS

CS1 offered an opportunity to study the embodied carbon of the relevant building components when shifting from a layout with four apartments (Figure 1a) to a co-living unit with four bedrooms (Figure 1b). The embodied carbon of the latter is 67% of the original apartment design. This reduction is primarily due to differences regarding doors, interior walls, and furnishing and appliances of kitchen and bathrooms (Figure 5). For doors, the reason is that apartment doors are made of steel to be compatible with fire safety requirements, whereas for bedrooms in the co-living unit wooden doors are used. The production of steel involves a large amount of embodied carbon and thus considerably affects the result (Table 2).

![Figure 5: Embodied carbon (modules A1–A3) of the original apartment layout compared with the co-living layout of the KTH's Live-in-Lab (LiL) in CS1.](image-url)
The embodied carbon of interior walls differs due to the distribution of different wall types, and subsequent material content. Most significant is the reduced amount of bathroom walls and their tiled surfaces as a result of halving the number of bathrooms in the co-living unit compared with apartments that host one bathroom each. Finally, the embodied carbon of the co-living kitchen corresponds to that of three original studio kitchens (Table 2).

<table>
<thead>
<tr>
<th>ROOM AND LAYOUT TYPE</th>
<th>SPECIFICATION OF INVENTORY</th>
<th>EMBODIED CARBON FOR MODULES A1–A3 (kg CO₂e)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS1</td>
<td>Kitchen fittings, furnishing and appliances for one kitchen—co-living layout</td>
<td>Cabinet fittings, two sinks with water taps, and appliances in the form of two large fridge/freezers, two ovens, one stove with two hobs, one stove with four hobs, two fans, one dishwasher. Adapted for four to six students</td>
</tr>
<tr>
<td></td>
<td>Kitchen fittings, furnishing and appliances for one kitchen—apartment layout</td>
<td>Cabinet fittings, one sink with water tap, and appliances in the form of one small fridge, one oven, one stove with two hobs, one fan</td>
</tr>
<tr>
<td></td>
<td>Bathroom fittings furnishing and appliances for one bathroom—both co-living and apartment layout</td>
<td>Toilet, sink with water tap, bathroom cabinet, mirror, shower faucet with shower set and glass shower wall</td>
</tr>
<tr>
<td>CS2</td>
<td>Kitchen fittings, furnishing and appliances for one kitchen—large apartment of the original apartment layout</td>
<td>Cabinet fittings, one double sink with water taps, laminate countertop, and appliances in the form of two large fridge/freezers, one combined oven/stove with four hobs, one fan, one dishwasher</td>
</tr>
<tr>
<td></td>
<td>Kitchen fittings, furnishing and appliances for one kitchen—small apartment of the original apartment layout</td>
<td>Cabinet fittings, one sink with water taps, laminate countertop, and appliances in the form of one large fridge/freezer, one combined oven/stove with four hobs, one fan, one small dishwasher</td>
</tr>
<tr>
<td></td>
<td>Kitchen fittings, furnishing and appliances for one co-living unit—co-living layout</td>
<td>A bigger one plus a kitchenette with similar appliances as the apartment kitchen</td>
</tr>
<tr>
<td></td>
<td>Bathroom fittings, furnishing and appliances for one bathroom—large apartment of the original apartment layout</td>
<td>Toilet, sink with water tap, two bathroom cabinets, shower faucet with shower set and glass shower wall, one laundry machine, one dryer</td>
</tr>
<tr>
<td></td>
<td>Bathroom fittings, furnishing and appliances for one bathroom—small apartment of the original apartment layout</td>
<td>Toilet, sink with water tap, two bathroom cabinets, shower faucet with shower set and glass shower wall, one combined laundry machine/dryer</td>
</tr>
<tr>
<td></td>
<td>Bathroom fittings, furnishing and appliances for one co-living unit—co-living layout</td>
<td>Toilet, sink with water tap, two bathroom cabinets, shower faucet with shower set and glass shower wall</td>
</tr>
<tr>
<td>Both CS</td>
<td>Apartment door</td>
<td>Steel</td>
</tr>
<tr>
<td></td>
<td>Bathroom door</td>
<td>Wood</td>
</tr>
<tr>
<td></td>
<td>Bedroom door</td>
<td>Wood (higher quality/classified for acoustics and fire)</td>
</tr>
</tbody>
</table>

Table 2: Overview of the fittings, furnishing and appliances included in embodied carbon assessments of bathrooms and kitchens of the case studies (CS), and the resulting embodied carbon.
Tables 2 and 3 present additional quantifications concerning the internal building components of relevance for the layout plans. These data provide indicative values to designers when considering embodied carbon in the design process. In both cases, the embodied carbon of co-living kitchens is higher than for apartments. The higher value for the co-living kitchen in CS2 compared with CS1 is due to the commonly lower standard applied to student housing. In addition, the co-living kitchen design in CS2, adapted for the target group of elderly women, includes additional storage, workspace and appliances than that for students. The higher embodied carbon of bathrooms in large apartments (CS2) is a result of additional personal laundry equipment.

Table 3 illustrates the embodied carbon of different room types in CS2, including some additional variations, per floor area or linear metre. As shown, there are significant differences between various room types. Tiled bathroom walls have a higher embodied carbon than bathroom type 3, which has painted walls. Table 3 reports embodied carbon per linear metre for kitchens, as the floor plan is often open in contemporary apartments. The differences for kitchen types are due to the apartment kitchens, especially the smaller ones, mainly consisting of appliances for which the embodied carbon is high. The kitchen for co-living instead houses more workspace and storage as the appliances are shared between several households and the kitchens are larger.

<table>
<thead>
<tr>
<th>ROOM TYPE</th>
<th>SPECIFICATION OF INVENTORY</th>
<th>FLOOR AREA OR LINEAR MEASURE</th>
<th>EMBODIED CARBON FOR MODULE A1–A3 (kg CO₂e/m² FLOOR AREA OR RUNNING METRE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ordinary apartment room, e.g. bedroom</td>
<td>Parquet floor, gypsum boards on walls, painted walls. No fittings and furnishing</td>
<td>13 m²</td>
<td>19</td>
</tr>
<tr>
<td>Bathroom 1</td>
<td>Completely tiled floor and walls, plywood and wet room gypsum boards, fittings according to small apartment in Table 2</td>
<td>4.2 m²</td>
<td>190</td>
</tr>
<tr>
<td>Bathroom 2</td>
<td>Completely tiled floor and walls, plywood and wet room gypsum boards, fittings according to large apartment in Table 2</td>
<td>5 m²</td>
<td>200</td>
</tr>
<tr>
<td>Bathroom 3</td>
<td>Tiled floor, painted walls, plywood and wet room gypsum boards, toilet, sink with water tap, bathroom cabinet, mirror</td>
<td>2 m²</td>
<td>140</td>
</tr>
<tr>
<td>Bathroom 4</td>
<td>Completely tiled floor and walls, plywood and wet room gypsum boards, fittings according to co-living unit in Table 2</td>
<td>3.9 m²</td>
<td>170</td>
</tr>
<tr>
<td>Bathroom 4, timber slabs</td>
<td>Completely tiled floor and walls, plywood and wet room gypsum boards, fittings according to co-living unit in Table 2, additional floor work due to timber slab</td>
<td>3.9 m²</td>
<td>180</td>
</tr>
<tr>
<td>Large apartment kitchen</td>
<td>PVC floor under and tiling above countertop, and kitchen fittings and furnishing according to large apartment in Table 2</td>
<td>5.2 m</td>
<td>220</td>
</tr>
<tr>
<td>Small apartment kitchen</td>
<td>PVC floor under and tiling above countertop, and kitchen fittings and furnishing according to small apartment in Table 2</td>
<td>3.1 m</td>
<td>240</td>
</tr>
<tr>
<td>Co-living kitchen</td>
<td>PVC floor under and tiling above countertop, and kitchen fittings and furnishing according to co-living unit in Table 2</td>
<td>13 m</td>
<td>180</td>
</tr>
</tbody>
</table>

Table 3: Embodied carbon (per floor area or running metre) for the internal fittings, furnishing and surface materials for different types of rooms, developed in CS2

Note: PVC = polyvinyl chloride.
3.2 EMBODIED CARBON SAVING POTENTIALS AT BUILDING LEVEL

The embodied carbon of the entire buildings was also studied for co-living design compared with standard apartment design implemented in the two case study buildings. Figure 6 shows the embodied carbon per gross floor area and residential floor area, respectively, for the two cases.

According to the Swedish regulation for the climate declaration of buildings (Finansdepartementet 2021), the reference unit gross floor area should be used for the declared values. However, Figure 6 also presents the results per residential floor area. The results display that the embodied carbon of the two alternative building designs resulted in a reduction of 6–7% for CS1 and 9% for CS2 for the co-living design compared with the apartment design when gross floor area is used as the reference unit. When residential floor area is used, the reduction is instead 23–24% for CS1 and 16% for CS2. This is because the co-living designs have higher space efficiencies (residential floor area/gross floor area) than the apartment building designs. The reduction of embodied carbon in the co-living design in CS2 is primarily a result of a lower amount of interior concrete walls, which separate the apartments in the original design. In the co-living proposal, these are replaced by stud walls as each floor plan holds two larger co-living units instead of eight separate apartments. The fire safety requirements might influence the choice of wall types. Nevertheless, for CS2, the architects argued that fire safety requirements were solved in other ways.

3.3 EMBODIED CARBON SAVINGS USING ALTERNATIVE METRICS

One primary rationale with co-living is the sharing of space, and thus the potential of hosting a higher number of residents in the same space compared with individual apartments. Figure 7 shows this effect on the cases studied in this paper.

Figure 6: Embodied carbon of the entire buildings (modules A1–A3) with a co-living respective apartment design, using two different reference units.

Figure 7: Embodied carbon of the entire buildings (modules A1–A3) with a co-living respective apartment design, presented per designed number of residents.
When using the designed number of residents as the reference unit, the embodied carbon saving is 26–36% in CS1, depending on the co-living design alternative, and 21% in CS2. For the co-living design in CS2, the designated number of persons equals the number of bedrooms in the unit since these are adapted for one person. For the apartment design the designated number of residents is based on the standards normally employed by the developer in question. This entails one resident in one- to two-room apartments and two residents in three-room apartments. Table 4 summarises the areas and number of residents in the studied examples shown in Figure 7.

### 3.4 EMBODIED CARBON IN RELATION TO DWELLING FUNCTIONS

What are the functional differences between single-household apartment and co-living designs? Eco-efficiency metrics can help to identify these. These indicators can inform discussions about the value created from building-related emissions or energy use. For co-living design, accessible floor area per resident could be one way to highlight the ‘value’ side in an eco-efficiency metric since the residents can access a larger accessible floor area through the shared areas of the unit. For example, in the design developed for the co-living in CS2, the residential area is approximately 32 m² per person, while the actual accessible floor area to which each person has access is 109 m² (Table 4). Figure 8 shows the eco-efficiency metric for relevant comparisons of the two case studies. It shows that the co-living design only performs slightly better concerning embodied carbon per gross floor area compared with the apartment designs. However, Figure 8 adds the additional function provided by the co-living design in the form of considerable higher accessible floor area per person for a considerably lower embodied carbon.

<table>
<thead>
<tr>
<th>CASE STUDY</th>
<th>DESIGN ALTERNATIVE</th>
<th>AVERAGE RESIDENTIAL FLOOR AREA PER PERSON IN TYPICAL FLOOR PLAN (m²)</th>
<th>RESIDENTS PER TYPICAL FLOOR PLAN (n)</th>
<th>ACCESSIBLE FLOOR AREA PER PERSON IN A TYPICAL FLOOR PLAN (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS1</td>
<td>Co-living A</td>
<td>19.0</td>
<td>24</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>Co-living B</td>
<td>22.5</td>
<td>24</td>
<td>57</td>
</tr>
<tr>
<td></td>
<td>Co-living C</td>
<td>20.5</td>
<td>20</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>Forskningen (apartment design)</td>
<td>21.5</td>
<td>19</td>
<td>22</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CASE STUDY</th>
<th>AVERAGE RESIDENTIAL FLOOR AREA PER PERSON (m²)</th>
<th>RESIDENTS IN THE BUILDING (n)</th>
<th>ACCESSIBLE FLOOR AREA PER PERSON (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS2</td>
<td>Co-living</td>
<td>32</td>
<td>81</td>
</tr>
<tr>
<td></td>
<td>Original apartment design</td>
<td>34</td>
<td>70</td>
</tr>
</tbody>
</table>

**Table 4:** Floor areas and numbers of residents in the two case studies

**Figure 8:** Conceptual illustration of the eco-efficiency of different home designs applied to the case studies in the study.
3.5 POTENTIAL EMBODIED CARBON SAVINGS AT A LARGER SCALE

Section 3.4 illustrated the link to space efficiency when understanding the potential embodied carbon savings of co-living design. This also pinpoints whether further savings could potentially be reached due to avoiding new construction. For an indication of these implications, the results of the case studies theoretically could be up-scaled. For CS1, the developer in the project is expected to construct a large number of new student housing in the coming years. In this theoretical example, 1000 new dwellings are assumed to be constructed. For a simple illustration, these dwellings are either constructed as traditional studios (as in Forskningen and which has been the dominating discourse the last 20 years in Sweden) or as co-living units (as designed in co-living B in CS1). If each building has five floors for residential use, one building could in the apartment case house 95 students, while 120 students could be housed in the co-living case. This results in 11 buildings needed for 1000 students for the apartment design, but only nine buildings with the co-living design. The resulting embodied carbon saving for the initial construction then approximates to over 2000 tonnes CO₂.

For CS2, the project group reasoned about how a low-cost co-living offer for elderly women, currently unavailable on the housing market, could create opportunities for moving home. A well-known pattern in the Swedish housing market is that elderly people tend to stay in their single-family homes or large apartments due to the low cost, since their mortgage has already been paid, instead of moving to a more suitable and accessible housing solution. When this moving chain is not working appropriately, the supply of homes for young families is affected and consequently the need for new construction. Therefore, an attempt was made to illustrate the potential embodied carbon savings by adding such a housing offer to the market.

Two hypothetical scenarios, here called ‘business-as-usual’ (BAU) and ‘co-living’, for the need of new construction were thus created based on today’s housing statistics for elderly single women in Uppsala county (Table 5). According to the statistics, five of seven single women over 65 years of age live in an apartment of average size 70 m² and the other two women in single-family houses of, on average, 109 m² (Statistics Sweden 2021). In the BAU scenario, it is assumed that the elderly stay in their homes due to the lack of reasonable options, and therefore five apartments and two single-family homes are ‘released’ to the young family market and new construction of these dwellings is avoided. One co-living unit is 222 m² and has room for seven people, following the co-living design of CS2 (Figure 4b). The embodied carbon associated with the new construction was, in both scenarios, calculated based on existing reference values for embodied carbon for new construction (Malmqvist et al. 2021), using the same system boundaries as the rest of the calculations in this paper.

Based on this theoretical exercise, the embodied carbon reduction due to the reduced need for new construction is approximately 50% (Table 5).

<table>
<thead>
<tr>
<th>NEW CONSTRUCTION</th>
<th>RESIDENTIAL FLOOR AREA (m²)</th>
<th>EMBODIED CARBON (kg CO₂e)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base scenario</td>
<td></td>
<td></td>
</tr>
<tr>
<td>New construction of two single-family buildings</td>
<td>218</td>
<td>37,900</td>
</tr>
<tr>
<td>New construction of five apartments in multifamily buildings</td>
<td>350</td>
<td>152,500</td>
</tr>
<tr>
<td>Sum</td>
<td>568</td>
<td>190,400</td>
</tr>
<tr>
<td>Co-living scenario</td>
<td></td>
<td></td>
</tr>
<tr>
<td>New production of a co-living unit with seven bedrooms</td>
<td>222</td>
<td>96,700</td>
</tr>
<tr>
<td>Sum</td>
<td>222</td>
<td>96,700</td>
</tr>
</tbody>
</table>

Table 5: Embodied carbon savings when one co-living unit for seven elderly women in CS2 is constructed instead of the new construction of buildings that it is assumed that the co-living unit can replace.
4. DISCUSSION

4.1 IS CO-LIVING A STRATEGY FOR REDUCING EMBODIED CARBON IN CONSTRUCTION?

Two cases of co-living unit designs were compared with more conventional apartment designs. Both cases displayed embodied carbon savings for the co-living designs despite being different with respect to dwelling types and target groups. In CS1, the original building hosts many small studios for students, whilst the original design of CS2 is a contemporary multifamily building with apartments of mixed sizes. The original building designs differ, for example, regarding how room division is done and fire issues are resolved, which cause constraints for implementing a co-living design on the geometries of the original buildings. Thus, the study provides evidence of opportunities for embodied carbon savings through co-living design under different conditions. The results demonstrate the potentials for embodied carbon savings. This is due to the sharing of kitchens and bathrooms in co-living since their embodied carbon is higher than bedroom units. The reduced number and space for kitchens and bathrooms potentially also implies a further embodied carbon reduction for building services. However, in the present study, specific bills-of-quantities for building services were not obtained and this effect could thus not be demonstrated. Instead, the embodied carbon for building services in the co-living designs can be understood as overestimated since standard values derived from contemporary apartment designs were used for all alternatives studied.

The origin of the embodied carbon savings in the two case studies varied. Apartment dividing walls were constructed as stud walls between the student studios in CS1, but as concrete walls between the apartments in CS2. As a consequence, the embodied carbon savings from the reduced need of internal walls was smaller for CS1 compared with CS2. On the other hand, the savings due to a reduced number of apartment entrance doors were higher in CS1 compared with CS2. The reason is the larger amount of apartment doors in a building with many small apartments. However, a critical issue for realising such savings is that the building authorities do not consider bedrooms in co-living units as separate living units. If they did, higher fire safety requirements would introduce the use of doors with higher embodied carbon.

Despite the differences between CS1 and CS2, the percentage savings are similar in both cases. One plausible explanation could be that both buildings studied have structural designs in concrete to a high degree representative of contemporary construction of multifamily buildings in Sweden. For such buildings, the structure dominates the total embodied carbon. However, for buildings designed with a low-carbon structure (e.g. timber), other components of the building will comprise a more significant proportion of the total embodied carbon. For example, in a comparison using the average reference value for timber frame apartment buildings in Sweden, 150 kg CO₂e/m² gross floor area (Malmqvist et al. 2021), the embodied carbon savings of the co-living design of CS1 would be more than 12%, compared with the 7% reported in Section 3.2. With more low-carbon structural designs, on which current regulatory frameworks (Regeringskansliet 2021) focus, the effect of co-living design as a low-carbon solution would thus become more noticeable. Nevertheless, the saving potentials in general for other structural solutions come with uncertainties that deserve further calculation. For example, timber frame buildings require more plaster for interior walls to provide fire resistance.

When evaluating embodied carbon savings with other metrics than per gross floor area, the case studies clearly display more substantial savings due to co-living designs, as discussed in Section 4.2. It needs to be emphasised that co-living in itself is not synonymous with embodied carbon savings. This is exemplified by the Akademiska hus (2020) that evaluated several student dwellings with varying degree of co-living designs. The embodied carbon per resident varied substantially from 10 to 27 tonnes CO₂e, and there were examples of large common areas for the residents or larger private spaces with individual bathrooms.

The potential exists to reduce the need for new construction as a consequence of implementing more co-living designs for the target groups of the studies: students (CS1) and elderly women (CS2). This would create considerable carbon savings. The upscaling exercise of CS2 approximately halved emissions, to be made at the community level for the change in needs for new construction through implementing co-living designs.
Student housing would probably not affect societal moving patterns much. For this target group, the need is for new construction with low-carbon solutions. The theoretical example in this study showed that embodied carbon savings can be substantial by meeting goals more efficiently by constructing fewer buildings due to efficiency gains in spatial use.

4.2 IMPLICATIONS FOR METRICS

The case studies’ results clearly demonstrate that there is a need for additional metrics when assessing embodied carbon savings of co-living designs. In the studied cases, the co-living alternatives displayed more prominent saving potentials when measured per residential floor area and per designated number of resident, compared with per gross floor area. In CS2, the original apartment design was already rather space efficient in terms of residential floor area/gross floor area, and thus the choice of reference area unit was less significant when comparing co-living designs with ordinary apartment designs. But for CS1, co-living design provided an opportunity for more space-efficient floor planning whilst the reference norm (i.e. many small studios) is more difficult to plan in a space-efficient way because of the corridors needed. In this case, the choice of reference unit plays a more important role.

The differences in quality for design alternatives need to be accounted for and made visible. For example, the co-living kitchen proposal entails a substantial improvement in cooking conditions compared with small studio kitchenettes in CS1. In addition, shared bathrooms in co-living creates space for additional qualities and functions. Inhabitants benefit from a consequently larger accessible floor area. In the co-living student design of CS1 it is, for example, possible to invite a larger party home for dinner, watch a large screen television together with friends or have fellow students over for group work. All these activities are hard to perform in the small studios of 21 m² in the comparative design in CS1.

The current state-of-the-art reference units for energy use and embodied carbon of buildings have several shortcomings. The common way to measure embodied carbon (and energy use/demand) per m² does not reflect the resource saving potential, neither in general (Norman et al. 2006; Prasad et al. 2023: 79–117; Rasmussen et al. 2022) nor for co-living (e.g. Francart et al. 2020; Huovila et al. 2017; O’Brien et al. 2017; Sekki et al. 2017). This implies that even though climate concerns are integrated into investment decisions for new housing, the additional climate benefits of co-living design are not quantified and typically omitted from the decision process. Therefore, the use of alternative metrics is recommended to provide a fairer comparison between apartment and co-living designs. Such metrics would present the amount of embodied carbon/accessible floor area per capita. Additional metrics to highlight the enabling of various functions and activities through design would also be valuable to complement ‘traditional’ metrics. This could include, for example, several functions such as indoor cycle storage, a re-use room, a workshop and gathering facilities, or in-dwelling activities such as inviting more than four people for dinner or having fellow students at home for group work activities.

The theoretical upscaling of CS2 also provides an illustration about the potential role of embodied carbon savings through co-living design at a larger scale. Although moving patterns are hard to predict, it illustrates potential savings through optimising new construction and the use of already built assets. This type of decision support could be valuable for urban planners with the responsibility to meet housing needs and climate goals simultaneously. As argued by various scholars (e.g. Lorek & Spangenberg 2019; Stephan & Crawford 2016; Xue 2015), more space-efficient, but still qualitative, housing is an important strategy to meet climate goals. Current building practices in Western countries are far from achieving this. In the Swedish context, the size and type of housing being built does not reflect the household composition in today’s Sweden. The recommended alternative and complementary metrics could be used to ensure that contemporary housing construction is aligned with household composition needs and climate goals, whilst ensuring that aspects such as quality and potential negative side effects are not neglected.

Other approaches than these types of ‘eco-efficiency metrics’ could also be explored. An expansion of the system boundaries for the embodied carbon assessment might include the public space that a person needs in their everyday life. For example, someone living in a student dorm would
normally be expected to use more public space and facilities than if residing in co-living student units, as exemplified in CS1. The reference unit in such a calculation would then be ‘the area that a person needs to be able to sleep, eat, socialise with friends, study together, exercise, etc.’ instead of a conventional one such as ‘1 m² of a building’.

5. CONCLUSIONS

In affluent contexts where the contemporary household composition is dominated by single households, more space-efficient designs can be a part of a strategy to meet climate targets. Well-planned co-living can offer a climate-efficient and qualitative housing alternative for single households in many Western countries. It is recommended that ‘traditional’ metrics based on floor area are complemented by displaying embodied carbon/accessible floor area for the designed number of users.

This study explored potential embodied carbon savings (modules A1–A3 according to EN 15978; European Standards 2011) in co-living design, compared with contemporary apartment design. The study is therefore unique since environmental savings of co-housing and co-living previously have focused operational energy savings and lifestyle changes. The studied concrete building cases display a potential saving at the building level of nearly 10%, when the unit kg CO₂e per gross floor area is used, and around 20% when the unit kg CO₂e per residential floor area is used. The savings in percentage increase if low-carbon structural solutions are applied, which is expected due to policies for embodied carbon reduction of buildings. But more importantly, using m² of gross or residential floor area as the reference unit does not fully display the climate benefits of co-living design. A per capita reference unit, based on the designated number of residents, reveals co-living designs have the potential to drive the larger embodied carbon savings through a decreased need for new buildings to be constructed.

Moreover, the functional differences between co-living and contemporary apartment designs is a key issue. The study exemplifies eco-efficiency metrics to better highlight such differences, which could be significant complementary metrics for planning and building actors to use when taking the decisions. The embodied carbon per accessible floor area for each resident provided an example of an eco-efficiency metric that can be used to better consider co-living design in housing developments. This type of metric is also important to display potential non-space efficient co-living designs. That is, embodied carbon assessment is important also for ensuring smart co-living design to really deliver climate-efficient and qualitative complements for the contemporary housing market.

The embodied carbon savings due to co-living design results from reduced amounts of heavy materials used for the separation of apartments (walls and apartment doors) and the number of and space occupied by kitchens and bathrooms. The study provides up-to-date generic values on the embodied carbon of different types of space. This can inform and assist decisions made by planners, architects and clients. Nevertheless, the more substantial embodied carbon savings of well-planned co-living designs are the potential for avoiding new construction through the ability of enabling a more efficient use of indoor space. This study offers two examples of indicative quantifications of such embodied carbon savings.

NOTES

1 See https://www.liveinlab.kth.se/projekt/r-d-projects/co-kitchen/co-kitchen-1.967437/.
2 See https://www.max4lax.se/.
3 See https://www.liveinlab.kth.se/.
4 See https://www.boverket.se/sv/klimatdeklaration/klimatdatabas/.
5 See https://co2data.fi/.
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COMPETING INTERESTS

The authors have no competing interests to declare.

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SUPPLEMENTAL DATA

Supplemental data for this article can be accessed at: https://doi.org/10.5334/bc.347.s1

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