Evaluating the Embodied Carbon Impact of Modular Construction through the Application of Zero-Loss Yield

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Master Thesis in Energy-Efficient and Environmental Buildings

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Lund University

Lund University, with eight faculties and a number of research centres and specialized institutes, is the largest establishment for research and higher education in Scandinavia. The main part of the University is situated in the small city of Lund which has about 112 000 inhabitants. A number of departments for research and education are, however, located in Malmö. Lund University was founded in 1666 and has today a total staff of 6 000 employees and 47 000 students attending 280 degree programmes and 2 300 subject courses offered by 63 departments.

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The degree project is the final part of the master programme leading to a Master of Science (120 credits) in Energy-efficient and Environmental Buildings.

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Abstract

Modular construction has recently become a renowned method of building. Many studies have been conducted on the benefits of modular construction; however, the available literature on its potential downsides is scarce. This study aims to evaluate the sources of potential embodied carbon inefficiencies of a modular multifamily residential building in San Diego, California. Quantity takeoffs and lifecycle analysis procedures were applied to collect data for the primary case study. Other similar projects were analyzed and compared to the primary case study. The results indicate that modular construction may experience an increase of embodied carbon of up to 10% compared to an identical, conventionally built project. A key driver of this embodied carbon inefficiency is an increase in structural material required to resist transport and placement stresses. Another primary driver is the doubling of walls that comes with the selection of highly standardized unit modules. Finally, the most significant driver of embodied carbon increases in this case study was the inefficiency of transporting fully assembled modules from the modular unit assembly factory to the construction site. If these sources of embodied carbon inefficiency can be mitigated, modular construction companies will be able to offer even more sustainable solutions to clients in addition to possible economic benefits and time savings often attainable from prefabrication.

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1. Introduction

Climate change is an escalating struggle, and substantial efforts must be employed to mitigate its effects. Buildings and construction account for more than 35% of global final energy use and nearly 40% of energy-related CO_2 emissions [1]. Construction industry professionals have been innovating and applying strategies to reduce greenhouse gas emissions through advances in energy efficiency, renewable energy production, and sustainable methods for constructing and operating buildings and infrastructure. While these efforts are decisive to tackling the climate crisis, another source of substantial greenhouse gas emissions is often overlooked [2]. According to the 2017 Global Status Report from the UN Environment Programme, greenhouse gases emitted from the production of materials used in the building sector make up 11% of total global greenhouse gas emissions [1]. These emissions are referred to as embodied carbon.

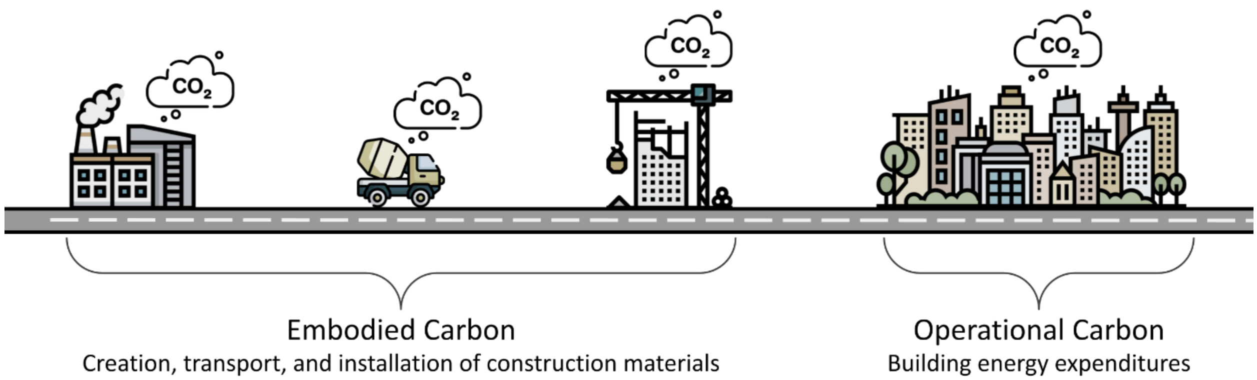

Figure 1 – Embodied Carbon and Operational Carbon

Embodied carbon has been a central element in the United Kingdom Green Building Council's (UK GBC) Net Zero Carbon Building framework. The embodied carbon of buildings varies depending upon the building type and a range of other factors, such as design and material availability [3]. However, the embodied carbon of most buildings will generally fall in the range of 400 – 1,000 $kgCO_2eq$ per m^2 of the gross internal area [4]. As detailed in UK GBC's Renewable Energy Procurement & Carbon Offsetting Guidance [5], mitigating these carbon emissions in the early phases of a project incurs a much lower cost than offsetting them post-construction and during the lifetime of a building. Guides such as the Embodied Carbon Primer [6] take it a step further and push the idea of material circularity. In addition to reducing embodied carbon emissions, resources and materials must be considered a 'store' rather than a 'flow,' and buildings should be thought of as 'material resource banks' [6].

Within the realms of construction innovation, the practice of modular construction has been renowned as a reliable method for improving several areas of the construction process [7]. Modular construction projects involve constructing separate building sections – or modules – in a controlled, off-site manufacturing facility while capitalizing on progressive assembly methods [8]. The benefits of the modular construction approach include safer work environments, decreased site disruption, and the possibility of significantly reducing construction schedules due to the elimination of weather delays and the opportunity for assembling different building sections simultaneously regardless of their permanent placement [8].

Modular construction companies also have a more significant opportunity to focus on standardization, repeatability, and incremental optimization, applying manufacturing methods to reduce development and long-term operation costs [9]. This is imperative as, over the past seventy years, labor productivity in the construction industry has remained stagnant despite significant technological advances. In manufacturing, where technology has been more willingly adopted, labor is almost nine times more productive over the same period [10].

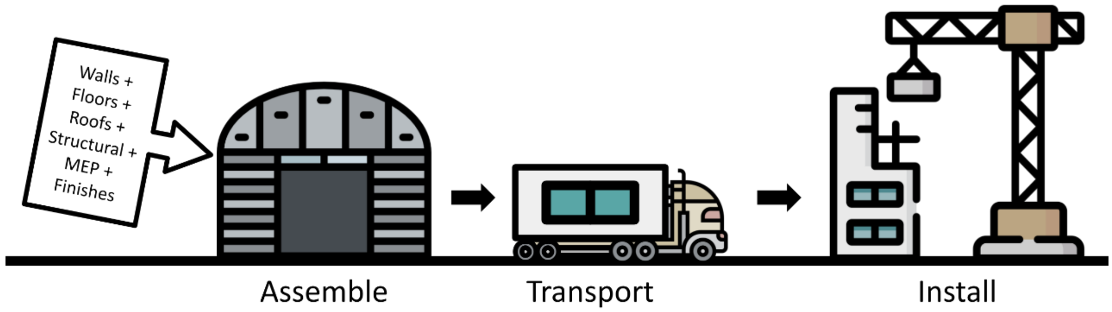

Figure 2 – Process Flow of Modular Construction

In regards to embodied carbon, modular construction may offer some positives. Construction waste may be significantly reduced in modular construction compared with conventional construction [9][11]. The standardization of modules allows for less material waste while the factory setting protects materials from accidental damage typical in conventional construction sites [12]. Additionally, modular buildings can be more easily disassembled, and the modules may be relocated or retrofitted for reuse [8]. This reduces both the demand for raw materials and the amount of energy expended to create a new building or renovate an existing structure [8]. These impacts are significant as estimates indicate that around 40% of landfill waste comes from construction [11].

In contrast, modular buildings may require more material than identical, conventionally built projects [13]. Modular units likely require a higher degree of structural fortitude due to stresses experienced during transport and placement [13][7]. Additionally, the drive towards standardization and repeatability could require each individual module to be fully insulated and structurally independent despite not requiring [7]. Said standardization of units might also lead to a decrease in space efficiency as the livable spaces are not entirely flexible. Similarly, the transport of individual units most likely leads to decreased transport efficiency as the built-up modules are largely empty space [14].

1.1. Project Aims

This study aims to explore the possible sources of embodied carbon increases in modular construction. These sources of potential improvements will be evaluated by magnitude and mitigation difficulty. Along with the necessary future work, the goal of this study is to create a guide for modular construction companies to follow in order to keep their embodied carbon emissions in check.

This study applies the philosophy of zero-loss yield, defined as comparing the current state of a manufacturing or construction process to a 'perfect' state based on first principles or hard physical limits. The difference between these two states is considered opportunity for improvement unless conclusively proved otherwise. The size of this opportunity is then used as a metric by which to prioritize improvement efforts [15]. This analysis approach was selected as it was used by other related research projects at the Cambridge Centre for Smart Infrastructure and Construction (CSIC). Additionally, it provides an easily applicable framework for both construction and manufacturing, which is relevant given the manufacturing solicitations of modular construction [16].

1.2. Scope

Table 1 - Scope

This project is about:	This project does not consider:
Embodied carbon emissions	Operational or end-of-life carbon
Material carbon efficiency	Economics or legal regulations associated with carbon
Carbon efficiency of usable living space	Construction waste variability
Transport carbon efficiency	Onsite / factory machinery emissions
Carbon implications of modular construction	Other benefits or drawbacks of modular building

1.2.1. Definitions

Construction Waste – The project defines "construction waste" as any quantity of material that does not contribute to the project's final structure and services as defined by the contract drawings. This definition includes, but is not limited to:

- Discarded material
- Temporary structures
- Rework
- Overdesign

Embodied Carbon – The project defines "embodied carbon" as the measured carbon dioxide equivalent of all greenhouse gas emissions from the point of extraction to the point of use or installation of construction materials. Reuse or end-of-life carbon will not be considered part of the definition.

1.2.2. Assumptions

The study operates based on the assumption that all drawings, data, and project information used in calculations are finalized.

1.3. Previous Works

A significant number of studies have been conducted on construction and building carbon. The studies vary in scope, methodology, and purpose. Much of the research up to date has focused heavily on operational carbon [17][18][19]. That said, plenty of studies have been carried which cover a range of life cycle phases. Gustavsson et al. [20][21] studied the carbon emissions of a wood-framed apartment building, considering the material production, construction, building operations, and end-of-life phases of the project. They found that wood-structured buildings generate fewer carbon emissions than concrete. Dodoo [22] analyzed the carbon implications of building with a complete life cycle perspective, including energy supply systems.

The subject of circularity has also been widely examined. Kanters et al. [23] studied how circular building design could reduce pressures on natural resources. Building upon previous literature on lifecycle analysis and innovative materials [24][25], the study conducted by Kanters explored the design process of circularity in buildings and the challenges of applying circularity principles to the construction industry. The study found the conservativeness of the construction industry and the lack of political urgency as the principal barrier to furthering circularity in buildings.

Modular construction has become a more popular research topic in recent years. However, the research on modular construction and carbon emissions is minimal. Pervez et al. [26] studied the carbon emissions of two Pakistani, single-family, single-story houses of similar design. However, much of their data was obtained through a series of questionnaire surveys aimed at local homebuilders. Kamali et al. [27] examined the environmental impacts of three conventional and prefabricated homes in Canada. This study was heavily reliant on surveyed data and struggled to compare individual impacts of the lifecycle analyses. Aye et al. [28]

aimed to quantify the embodied energy of modular prefabricated steel and timber multi-residential buildings to determine if prefabrication improved environmental performance compared to conventional concrete construction.

Measuring material waste is an essential strategy for improving carbon efficiency across the board, and a variety of tools exist to measure the material efficiency of a project [15]. Among these methods, comparing construction material estimates with actual site delivery quantities was determined to be the most accurate way of analyzing waste. However, gathering accurate data for measuring material quantities proved to be incredibly complicated. According to several employees at an unnamed American construction company, material deliveries are not always recorded, and when they are, they may only invoice the cost and not the quantity [7]. Over-design of specifications or onsite over-installation is usually not indictable and may even be seen as a plus; therefore, it is not typically tracked [7]. Additionally, as-built drawings are usually generated for liability and financial purposes; consequently, project managers may be reluctant to label material quantities as "waste" [7]. These problems are further compounded by the range of ways in which different companies measure material quantities and in their varying definitions of and attitudes towards waste [7].

2. Methods

The analyses and calculations compare the different sources of embodied carbon emissions across various modular and conventional multifamily residential buildings.

2.1. Case Studies and Data Collection

Two primary case studies – one modular and one conventional – were analyzed and compared. While these two cases are not identical, they provided valuable and comparable data as they are both multifamily residential buildings with multiple floors. Additionally, obtaining material quantities from these cases was relatively simple. The main focus of this study was the modular case, while the conventional case was used as a grounding and sizing reference. Details on how the conventional case study was used to feed information into the modular case study can be found on section 2.2.

2.1.1 Modular Case Study – The Quilt Project

The Quilt Group is an American modular building developer currently designing a modular residential building in San Diego, California. The building will consist of fifty units covering five residential levels and a ground floor comprised of amenity, parking, and retail spaces [13]. The gross internal area of the building is 36 420 square feet / 3 383,5 square meters [13]. Quilt provided schematic drawings, bills of material, and wall, floor, and ceiling schedules of their San Diego project, which is expected to break ground in September of 2021 (Figure 3). This project case study was selected as the developer made all of their preconstruction data available for academic scrutiny. This case study is limited by the accuracy of the data from the schematic drawings compared to actual onsite conditions when the project is built. These limitations are further explored in section 4.1.

Figure 3 – San Diego Quilt Project, Modular Case Study (Source: The Quilt Group)

Calculations were supported by the most recent drawings and documents provided by Quilt. A worst-case scenario approach was selected in situations where a design or execution decision had not yet been made. The purpose of this approach is to estimate the greatest amount of improvement that exists between the current plan of the Quilt project and a 'perfect' plan.

2.1.2. Conventional Case Study – The Wälludden Project

The Wälludden building is a conventionally built, multifamily residential building located in Växjö, Sweden. Like the Quilt project, the Wälludden project is supported by a wood structure. Its sixteen units span across four floors, and the gross internal area is 1,190 square meters [29]. The building does not contain any amenities, parking, or retail spaces. Data from this building was obtained from a 2014 Uppsala University report [29]. It was selected due to its similarity to the Quilt project as it also a multifamily residential building spanning multiple floors. Additionally, complete embodied carbon data was readily available for comparison. However, it is recognized that the differences in geographical location and building size may lead to skewed data and results. These limitations are further explored in section 4.1.

Figure 4 – Wälludden Project, Conventional Case Study (Source: Booli.se)

2.2. Material Efficiency

Quantity estimates for the structural materials of the Quilt project were taken off using Bluebeam Revu (Figure 5). The quantities obtained directly from the drawings pertained to the modularly-built project (Quilt M). A second estimate relating to an identical, conventionally built project (Quilt C) was calculated by removing the doubling of the P3 walls (Appendix 1) and removing the additional structural elements required for modular transport. Determining the amount of structural material needed to be removed to obtain a quantity consistent with conventional construction was achieved by conversing with the Quilt Group and their architect [14].

These estimates were converted into separate material weight quantities in Microsoft Excel and compared to an early-phase bill of materials, provided by Quilt for verification. Specific product data and material densities were found from several distributors and retailers (Appendix 2). The amount of carbon emissions per kilogram for these materials were obtained using the ICE carbon database [30]. With the total weights per material and values of embodied carbon per kilogram of material, the structure's total embodied carbon was calculated.

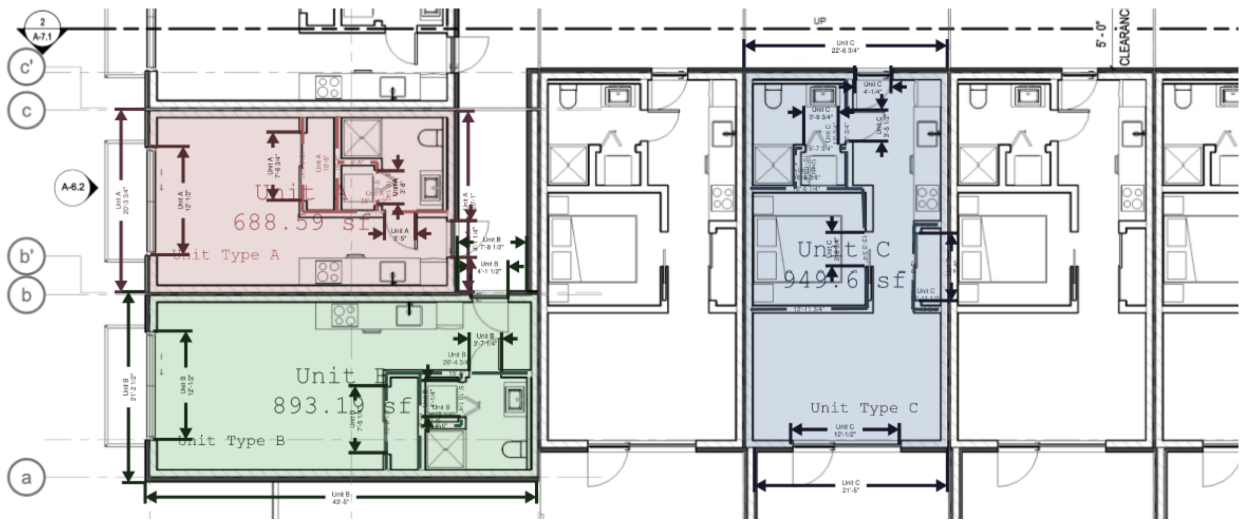

Figure 5 - San Diego Quilt Project Quantity Takeoffs on Bluebeam Revu

The total embodied carbon quantities of the building were estimated using existing data from a case study on the Wälludden project [29]. The total embodied carbon of the Wälludden building served as a base number and was sized in ratio to the number of units between the two projects. Sizing in ratio to total floor area was also conducted. The data from this case study was imperative for establishing a base number and estimate for the total embodied carbon of the Quilt project, not just the structural materials. The limitations of this case study and the use of its data for sizing are explored in section 4.1.

Equation 1 and Equation 2 were used to find the total embodied carbon emissions for Quilt C, while Equation 3 was used to find the total embodied carbon emissions for Quilt M. The equations were generated as part of the calculations.

$$kgCO_2eq_{(Quilt\ C)} = \left[\left(\frac{\#\ of\ units_{(Quilt\ C)}}{\#\ of\ units_{(wälludden)}}\right) \times kgCO_2eq_{(wälludden)}\right] \qquad (eq.\ 1)$$

$$kgCO_2eq_{(Quilt\ C)} = \left[\left(\frac{total\ m^2{}_{(Quilt\ C)}}{total\ m^2{}_{(wälludden)}}\right) \times kgCO_2eq_{(wälludden)}\right] \qquad (eq.\ 2)$$

$$kgCO_2eq_{(Quilt\ M)} = kgCO_2eq_{(Quilt\ C)} + \left(kgCO_2eq_{(Quilt\ M\ structural)} - kgCO_2eq_{(Quilt\ C\ structural)}\right) \qquad (eq.\ 3)$$

2.3. Transport Efficiency

Modular projects differ when it comes to the extent of off-site prefabrication. The Quilt project will transport fully assembled modules from their prefabrication factory near Loma Linda to the site in San Diego, a distance of about 100 miles/161 kilometers. Transporting fully assembled modules is less carbon-efficient, as trucks will be limited by volume capacity rather than weight capacity. The material quantity discrepancies between the two projects were disregarded in order to isolate the implications of the transport inefficiencies. The study operated under the assumption that the distance of all materials from source to site (for Quilt C) and source to factory (for Quilt M) was fifty miles.

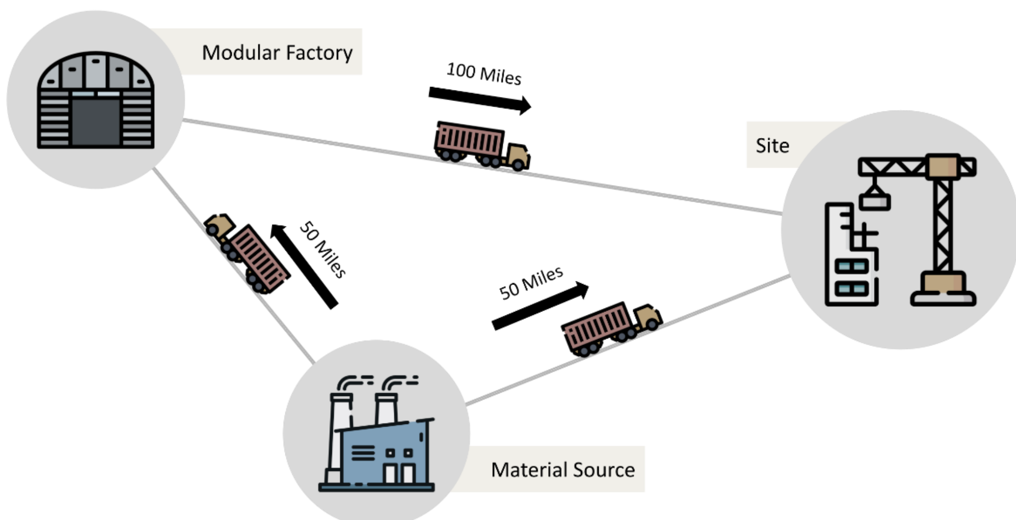

Figure 6 – Transport Visualisation

The first step in determining the impact of this efficiency decrease was to calculate the number of truck hauls required to transport all material for Quilt C. This was accomplished by finding the weight capacity of the average low-loader truck – which, per communication with Quilt, is the standard for transporting construction equipment and prefabricated modules. The total material weight had been obtained from the material efficiency calculations. By dividing the total material weight of the building by the truck capacity, the number of hauls was found. This method assumed total transport efficiency for Quilt C.

The number of truck hauls required to transport all material for Quilt M was calculated by assuming one haul per module. This assumption was comfirmed by the Quilt Group [14]. Next, the weight of all individual modules was subtracted from the total material weight. This residual material was assumed to be transported in fully efficient hauls, like the material for Quilt C. The modular hauls plus the fully efficient hauls equaled the total number of hauls required for Quilt M.

The quantity of carbon emissions produced by hauling all material from the source to the site/factory was found using Equation 4. This value equals the total transport emissions for Quilt C. The value of average US truck emissions per ton-mile was taken from The Green Freight Handbook [31].

$$kgCO_2eq_{(Quilt\ C)} = total\ material\ weight \times avg.truck\ emissions\ per\ ton \cdot mile \times distance \qquad (eq.\ 4)$$

The number of emissions from the transport of material from the factory to the site was found using Equation 5. The number of total transport emissions for Quilt M was found using Equation 6.

The number of modular hauls required per conventional haul was found to be (115 ÷ 77) = 1.49

$$kgCO_2eq_{(factory\ to\ site)} = 1.49 \times material\ weight \times avg\ truck\ emissions\ per\ tonmile \times distance \qquad (eq.\ 5)$$

$$kgCO_2eq_{(Quilt\ M)} = \ transport\ kgCO_2eq_{(Quilt\ C)} + kgCO_2eq_{(factory\ to\ site)} \qquad (eq.\ 6)$$

2.4. Space Efficiency

The space efficiency of the Quilt project was determined by examining livable floor space and circulation areas, which comprised of corridors and stairwells. This calculation was carried out by measuring floor spaces in Bluebeam Revu. Amenity spaces and parking areas were not considered as these areas are highly impacted by cultural and geographical factors. The study also included corridor widths in front of each unit entrance.

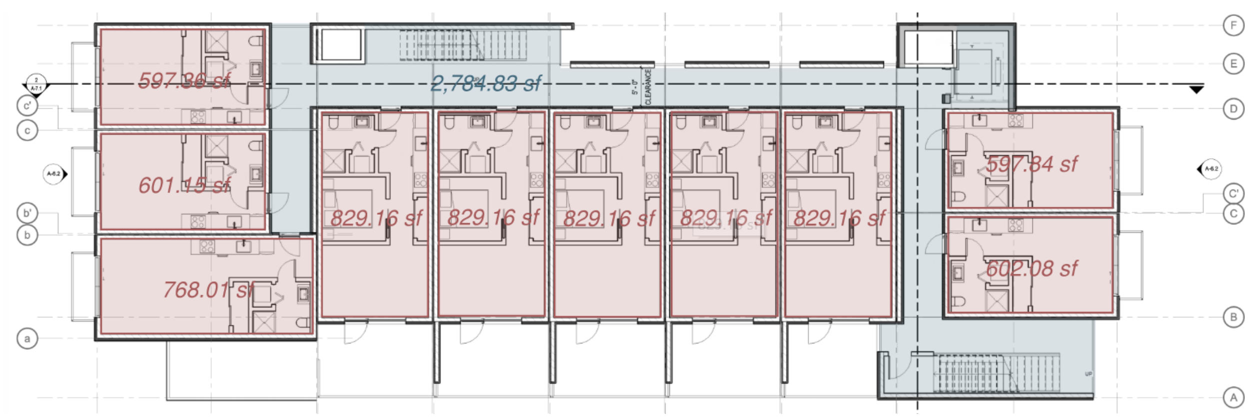

Figure 7 – Measurements of Usable Living Space on Bluebeam Revu

Additional modular and conventionally built project drawings were also measured to obtain a more comprehensive idea of the space efficiencies between modular and conventional projects. The data of these projects was obtained from private company websites. The names of these companies and projects have been omitted from the report as explicit permission to name them was not acquired. Average space efficiency in the Los Angeles area was obtained from a reputable blog [32].

Equation 1 was used to estimate the embodied carbon of the private industry projects. Embodied carbon per square meter of usable living space was used as the functional unit to compare all measured projects.

3. Results

The material efficiency calculations demonstrate that the wall doubling and structural reinforcement in the Quilt project could yield an increase in embodied carbon of 34,926 kgCO_2eq, which is almost 5% more than an identical, conventionally built project. Additionally, the inefficiency of transporting the built-up modules and the extra step in the supply chain could increase the embodied carbon emissions another 40,891 kgCO_2eq. Assuming space efficiency is a design issue rather than a modular versus conventional construction issue, the total increase in embodied carbon emissions due to opting for a modular construction approach could be up to 75,817 kgCO_2eq; a 9.85% increase.

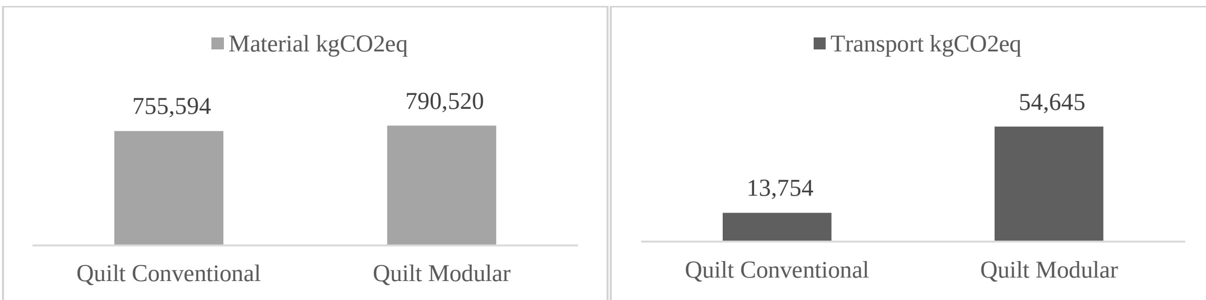

Figure 8 – Material and Transport Carbon Emissions, Modular vs. Conventional

3.1. Material Efficiency

Detailed material efficiency calculations can be seen in

Appendix 3. The discrepancy in material quantities between Quilt C and Quilt M is due to the doubling of the interior walls between units (Appendix 1) and the additional structural material required due to stresses experienced during transport and crane placement [14]. By utilizing the worst-case scenario of the sizing method, it was determined that Quilt M could generate up to 4.86% more embodied carbon for this scenario than Quilt C. The results of these calculations are illustrated in Figure 9.

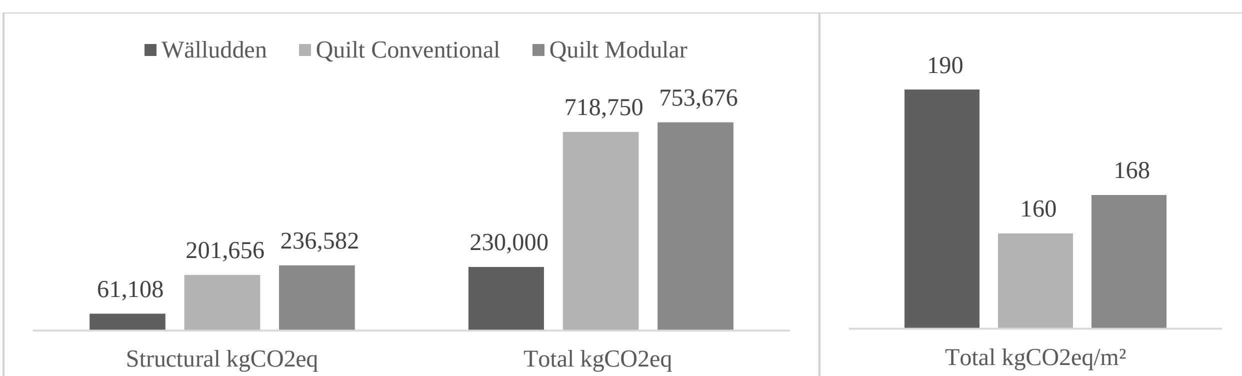

Figure 9 – Material Carbon Efficiency Results

3.2. Transport Efficiency

The transport efficiency calculations (Appendix 4) show that 49% more haul trips were required for Quilt M than for Quilt C.

The Quilt M project, employing a factory approximately 100 miles away from the site, would produce transport emissions accounting for up to 8% of the total embodied carbon emissions of the project. Quilt C would produce about one-fourth of that. The results of the transport efficiency calculations are detailed in Table 2.

Table 2 – Transport Carbon Efficiency Results

	Quilt Conventional	*Quilt Modular*
# Trips Required:	77	115
Total Transport $kgCO_2eq$:	13,754	54,645
% of Total $kgCO_2eq$	2%	8%

3.3. Space Efficiency

The space efficiency calculations (Appendix 5) show that while the Quilt project's space efficiency is relatively low, a clear difference in space efficacy between modular and conventional projects cannot be proven. The average space efficiency in Los Angeles projects is 83% [32]. Both modular and conventional case studies obtained efficiencies around this number.

One factor that seems to yield space inefficiency is asymmetry. Corridor widths are fairly similar across all cases, yet the Quilt Project and Project C only utilize one side of the corridor for entrances to the units. This effectively halves the efficiency of these corridor areas. Consequently, these two projects yield the lowest space efficiency and the highest amount of carbon emissions per area of usable living space. The results of the space efficiency calculations are detailed in Table 3.

Table 3 - Space Carbon Efficiency Results

	Quilt	*Project A*	*Project B*	*Wälludden*	*Project C*	*Project D*
Construction Method:		Modular			Conventional	
# Residential Floors:	5	1	7	4	5	6
# of Units:	50	9	74	16	40	78
Living Space Efficiency:	71%	81%	83%	87%	74%	82%
		Average = 78%			Average = 81%	
$kgCO_2eq/m^2$ of Usable Living Space:	248	217	213	193	227	207
		Average = 225.81			Average = 209.13	

4. Discussion

Modular construction can potentially make up for said carbon increases by providing savings in other areas of the construction process. Figure 10 shows the zero-loss path and areas that cause deviation from zero-loss due to instances of human error, safety, and hard physical limits. Areas that could provide carbon savings by switching to modular include temporary works and over-order guidance. The controlled factory setting of a modular assembly center allows for a significant reduction in over-ordering. Additionally, temporary works are not required in these factories [14].

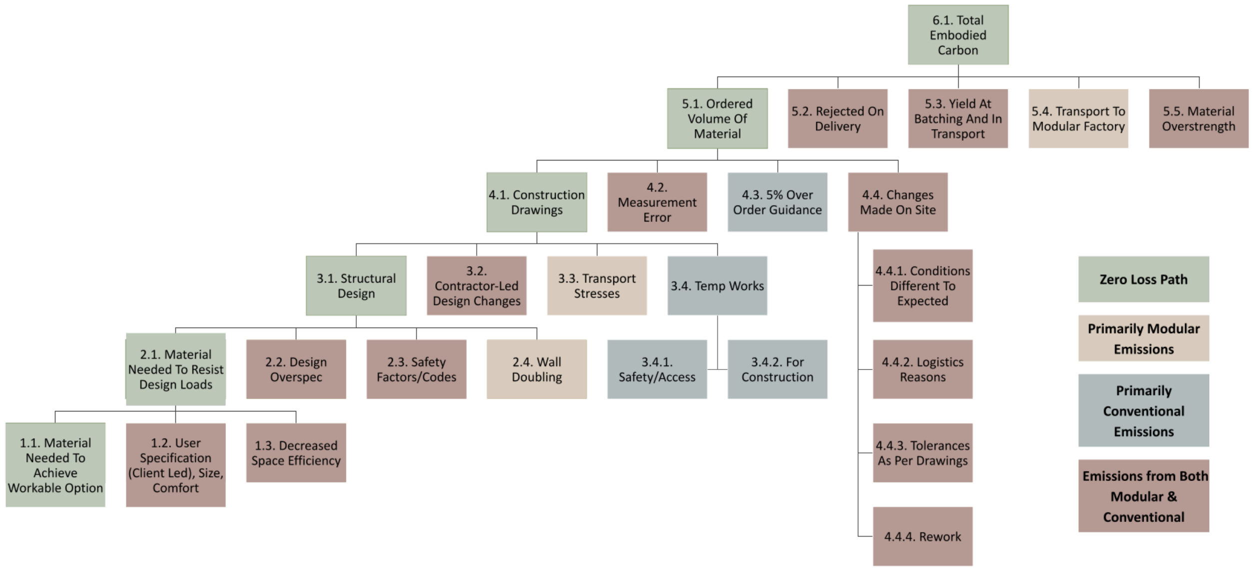

Figure 10 – Zero-Loss Path and Areas of Improvement (Source: Bennett, 2021 [Adapted][33])

In order to competently procure the benefits of modular construction, it is essential to mitigate potential sources of embodied carbon inefficiency. A stakeholder in a modular construction project should consider these carbon inefficiency sources in different orders depending on various conditions, including the distance from factory to site, size of the building, and the extent of wall doubling and additional structural reinforcement.

In the Quilt project, the increased transport emissions are slightly higher than the emissions generated by the additional material. If the distance between the modular factory and site increased to more than 100 miles / 161 kilometers, the increased transport emissions would outweigh the material inefficiency emissions at an increasing rate. Upon such an occurrence, mitigating the increased transport emissions would continue to outweigh the importance of mitigating the increased material emissions. If the distance between the modular factory and site were to be decreased, the increased material emissions would gradually catch up to and eventually overtake the increased emissions generated by the transport.

If the size of the build were to increase, the increased material emissions would eventually become more substantial than the increased transport emissions as the increase in material emissions per module is about eight times as much as the increased transport emissions per module. If the project size decreased, the increased material emissions would become smaller than the increased transport emissions.

In any situation, early involvement by all stakeholders in the design and logistics plan is key to lowering carbon emissions as both economic and carbon costs are more aligned during the early phases of a project [34]. Early involvement and recognition of the sources of carbon inefficiency can produce a modular project that is fiscally profitable without sacrificing carbon efficiency. If a construction method makes sense from both an economic and sustainability perspective, it becomes a more attractive option to implement. Eventually, these are the type of solutions the construction industry requires as large corporations are more likely to support climate solutions if they also provide an economic incentive.

4.1. Limitations

The use of the Wälludden project as a scaling tool for estimating the total embodied carbon of the Quilt project has various limitations. The amount of material actually delivered to the Wälludden construction site is unknown. Also, the buildings are different in size and layout. The difference in geographical location could affect many design elements such as thermal regulation provisions and energy systems. Furthermore, the Quilt project is in a densely urban setting while the Wälludden project sits in a suburb of a small city which is something to consider as retail and underground parking areas are more likely to be found in the city. Different countries also have vastly different cultural and legal reasoning behind design motivations, such as amenity spaces, circulation areas, building codes, and noise standards [32]. This case study was selected as the availability of such data is scarce and difficult to acquire.

The calculations of transport efficiency are based on broad figures, which may undermine several variables. Loading factors are not uniform and are largely affected by the characteristics of the route that the trucks will take. Moreover, routes may be changed due to road closures or other unforeseen conditions. The type of truck will probably differ between projects, and fuel efficiency was not considered in the calculations.

The order of magnitude in which the carbon emissions from material and transport inefficiencies would increase and decrease is difficult to quantify as the amount of material and the number of hauls required do not change linearly. Additionally, other projects may have different sized modules which would also decrease the accuracy of the results found in this project.

4.2. Future Works

Further studies to quantify and mitigate carbon inefficiency in modular construction could be helpful to better understand their order-of-magnitude impact. A follow-up, post-construction study on the Quilt project could determine the accuracy of the embodied carbon estimates of this study by comparing the estimated material quantities to the as-built quantities.

Data collection on construction waste on modular and conventional sites may provide new evidence supporting modular construction as a sustainable method of building. While current studies on this subject exist [35][12][36], the data collection methods and definitions of 'construction waste' are inconsistent.

A study on the emissions produced by the different equipment and machinery involved in modular and conventional projects could help produce more accurate data on how modular construction impacts embodied carbon.

Other supplementary research efforts should be directed at finding solutions to help minimize the sources of carbon inefficiency found in this study. Finding a way of avoiding double walls or figuring out what drives symmetrical versus asymmetrical design choices are some worthy options. An analysis of how to minimize additional structural reinforcement required due to transport and crane placement stresses may also provide worthwhile carbon reduction possibilities.

Another valuable research work would be to examine the feasibility of transporting the individual modules at a slightly lower degree of completion and waiting to fully assemble them closer to the site. This may increase the maximum number of modules transported per haul.

Finally, a study to determine the practicability of offsetting additional carbon emissions that may stem from modular construction using the economic savings modular construction may provide. Assigning shadow costs to embodied carbon incursions due to the application of modular construction methods may indicate that compensating these additional emissions by funding an equivalent carbon saving elsewhere is a viable option.

5. Conclusions

- A modular building may generate up to 10% more embodied carbon than an identical, conventionally built building.
- The main drivers of this possible increase of embodied carbon are:
  - The increase in structural material required by individual modules.
  - The doubling of walls occurring from standardization of modules.
  - The inefficiency of transporting fully assembled modules.
- These conclusions are based on the data selected and may not be accurate for all modular projects.

6. Scientific Summary

Modular construction has been extensively regarded as an innovative and green method of building. Numerous studies have been conducted on the benefits of modular construction; however, the available literature on its potential downsides is quite limited. This project evaluates the sources of potential embodied carbon inefficiencies of a modular multifamily residential building in San Diego, California – The Quilt Project. Quantity takeoffs and lifecycle analysis procedures were applied to collect data for the primary case study. Other similar projects were analyzed and compared to the primary case study.

The analyses and methods involved evaluations of the material, transport, and space efficiencies of the Quilt building compared to other similar case studies. The comparison of these efficiencies focused on discrepancies that existed due to the nature of modular construction and its requirements. For example, modular construction requires an increase in structural material quantity due to the stresses the modules experience during transport and crane placement. Another example that was studied is the inherent decrease in transport efficiency due to the fact that built-up modules yield a lower truck loading factor when hauled. Limitations of these comparison methods were also deliberated.

The results indicate that modular construction may experience an increase of embodied carbon of up to 10% compared to an identical, conventionally built project. A key driver of this embodied carbon inefficiency is an increase in structural material required to resist transport and placement stresses. Another primary driver is the doubling of walls that comes with the selection of highly standardized unit modules. Finally, the most significant driver of embodied carbon increases in this case study was the inefficiency of transporting fully assembled modules from the modular unit assembly factory to the construction site.

Discussions and potential future works to supplement this project should be geared towards amplifying and deepening our understanding of these sources of carbon inefficiencies along with other sources that were not included in this project, such as fuel efficiency and differing machinery. Among these recommendations, a follow-up and post-construction audit of the Quilt Project is of chief importance as it will clarify the degree to which the estimates of this study were accurate and dependable. Collaboration with industry partners will be vital in obtaining the information needed for insightful academic studies.

If these sources of embodied carbon inefficiency can be mitigated, modular construction companies will be able to offer even more sustainable solutions to clients in addition to possible economic benefits and time savings often attainable from prefabrication.

This project was conducted in cooperation with The Quilt Group and under the supervision of the Centre for Smart Infrastructure and Construction at the University of Cambridge.

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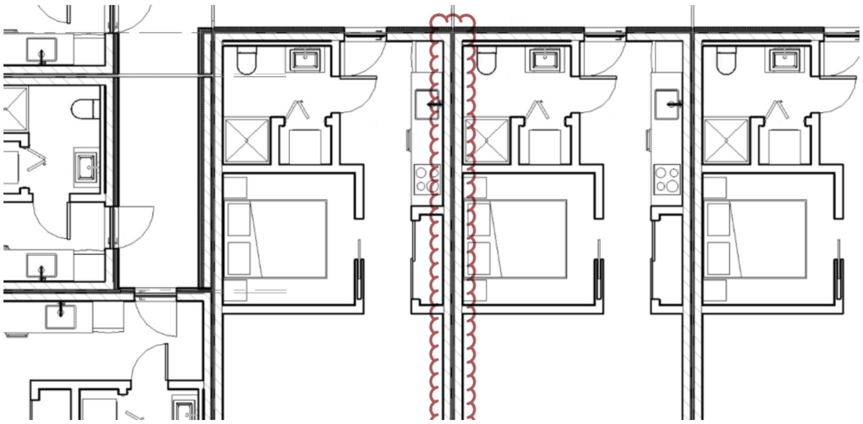
8. Appendices

Appendix 1- Doubling of Interior P3 Walls



Appendix 2 – Product Data Source List (Accessed March 2021)

AIR/WATER BARRIER - PROSOCO - JOINT & SEAM	https://prosoco.com/product/joint-seam-filler/
AIR/WATER BARRIER - PROSOCO - SPRAY WRAP MVP	https://prosoco.com/product/spray-wrap-mvp/
FINISHES - EXTERIOR - METAL SIDING	https://custompartnet.com/sheet-metal-gauge
FINISHES - EXTERIOR - T&G SIDING	https://ekvintagewood.com/pages/siding-specifications
FINISHES - INTERIOR - DRYWALL	https://certainteed.com/drywall/products/type-x-drywall/
GLASS	https://onlinelibrary.wiley.com/doi/pdf/10.1002/9780470259795.app1
INSULATION - KINGSPAN KOOLTHERM R-17	https://www.kingspan.com/us/en-us/product-groups/insulation/insulation-boards/kooltherm-k9-internal-insulation-board
INSULATION - STUD LAYER - ROCKWOOL	https://rockwool.com/north-america/products-and-applications/products/comfortbatt/
WOOD - RAINSCREEN - FURRING STRIPS 1X4	https://cor-a-vent.com/sturdi-strips.cfm
WOOD - SHEATHING - PLYWOOD	https://soundproofingcompany.com/soundproofing_101/building-materials-weights-guide
WOOD - STUD LAYER - UNINSULATED 2X6, 24" OC.	https://onlinelibrary.wiley.com/doi/pdf/10.1002/9780470259795.app1
#DV_STRUCTURAL_WOOD_SOFTWOOD-LUMBER	https://onlinelibrary.wiley.com/doi/pdf/10.1002/9780470259795.app1
CONCRETE - CAST-IN-PLACE	https://onlinelibrary.wiley.com/doi/pdf/10.1002/9780470259795.app1
FINISHES - INTERIOR - DRYWALL	https://certainteed.com/drywall/products/type-x-drywall/
SITE - GRAVEL - COMPACTED	https://onlinelibrary.wiley.com/doi/pdf/10.1002/9780470259795.app1
WOOD - SHEATHING - PLYWOOD	https://soundproofingcompany.com/soundproofing_101/building-materials-weights-guide
WOOD - TRUSSES - FLOOR/ROOF (2X8, 16' OC.)	https://onlinelibrary.wiley.com/doi/pdf/10.1002/9780470259795.app1
INSULATION/THERMAL BARRIER - SIP PANEL	https://plastifab.com/usa/products/building-systems/insulspan-structural-insulating-panels.html
WALL SHEATHING - DENSDECK ROOF BOARD	https://buildgp.com/product/densdeck-roof-board/
WOOD - SHEATHING - OSB	https://soundproofingcompany.com/soundproofing_101/building-materials-weights-guide

Appendix 3 – Material Efficiency Calculations

Project:	Wälludden	Quilt	Quilt			
Construction Method:	Conventional	Conventional	Modular			
Location:	Växjö	San Diego	San Diego			
Levels:	4	6	6			
Total Floor Area (m^2):	1364	4481	4481			
# of Units:	16	50	50			
				Difference ↓	*Difference per Module ↓*	*Average ↓*
Structural kgCO2eq:	*61108*	201656	236582	34926	699	219119
Structural kgCO2eq/m^2:	*14*	45	53	8		
					Conventional to Modular % Increase in kgCO2eq	
		3.3	*← Multiplier*			
Total kgCO2eq:	230000	*755594*	*790520*	*← Sized by m^2*	4.62%	
Total kgCO2eq/m^2:	190	*169*	*176*	*← Sized by m^2*	4.62%	
		3.125	*← Multiplier*			
Total kgCO2eq:	230000	*718750*	*753676*	*← Sized by # of Units*	4.86%	
Total kgCO2eq/m^2:	190	*160*	*168*	*← Sized by # of Units*	4.86%	

Appendix 4 – Transport Efficiency Calculations

Project:	Quilt	Quilt			
Transportation Method:	Conventional	Modular			
Truck Capacity (tons):	22	22	1.49	*← Number of modular trips required per conventional trip*	
# Trips Required:	77	115	49%	*← Percent increase*	
Structural Material (kg):	469486	469486	247568.00	kg	
Structural Material (tons):	518	518	272.90	tons	*← Weight of all modules*
Est. Total Material (tons):	1700	1700	1427.26	tons	*← Total material weight minus weight of modules*
Structural kgCO2eq:	219119	219119	5.5	tons	*← Weight of one module*
Est. Total Material kgCO2eq:	719847	719847	88.3	kgCO2eq	*← kgCO2eq of one module if D=100 miles*
			161.80	g of CO^2/ton-mile	*← Average truck CO2 emissions per (US) ton-mile*
1% of Est. Total Material kgCO2eq:	7198	7198	0.16	kg of CO^2/ton-mile	**Green Freight Handbook*
5% of Est. Total Material kgCO2eq:	35992	35992			
Ton-Miles; Transport = 1% of Total Material CO2eq:	44490	44490	907.18	kg/ton	
Ton-Miles; Transport = 5% of Total Material CO2eq:	222450	222450	2000.00	lbs/ton	
Miles; Transport = 1% of Total Material CO2eq:	26	18			
Miles; Transport = 5% of Total Material CO2eq:	131	88			
kgCO2eq if Distance of Source to Site/Factory = 50 Miles:	13754	13754	*← Source to site (conventional) = source to factory (modular)*		
kgCO2eq if Distance of Factory to Site = 100 Miles:		40891	*← Factory to Site (modular only)*		
Total Transport kgCO2eq:	13754	54645			
% of Total Material CO2eq	2%	8%			

Appendix 5 – Space Efficiency Calculations

Project:	Quilt	Project A	Project B	Wälludden	Project C	Project D	
Construction Method:	Modular	Modular	Modular	Conventional	Conventional	Conventional	
Location:	San Diego	Los Angeles	San Diego	Växjö	San Diego	San Diego	
# Residential Floors:	5	1	7	4	5	6	
# of Units:	50	9	74	16	40	78	
Total Floor Area (m^2):	4481	842	5400	1364	2435	4125	***← Does not include balconies***
Circulation Areas (m^2):	1294	156	924	174	630	759	
Circulation Space Per Unit (m^2):	25.9	17.3	12.5	10.9	15.8	9.7	
Usable Living Space (m^2):	3187	685.5	4476	1190	1805	3366	
Living Space Efficiency:	71%	81%	83%	87%	74%	82%	***← Los Angeles Average = 83.1%***
	Average = 78%			***Average = 81%***			
Total kgCO2eq:	790520	*148454*	*952646*	230000	*410594*	*695541*	
kgCO2eq/m^2 of Usable Living Space:	248	*217*	*213*	193	*227*	*207*	
Corridor Width Per Unit (ft):	5'	3'	2.5'	N/A	5'	3'	

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