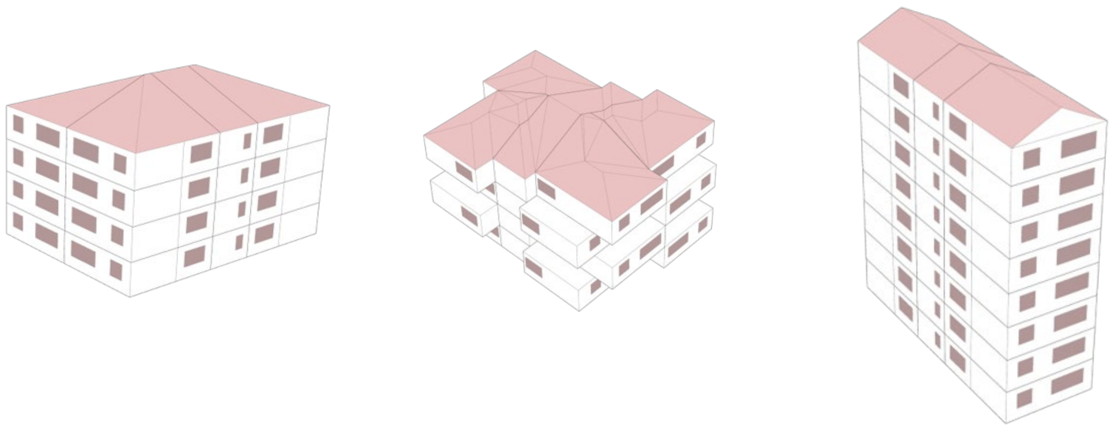
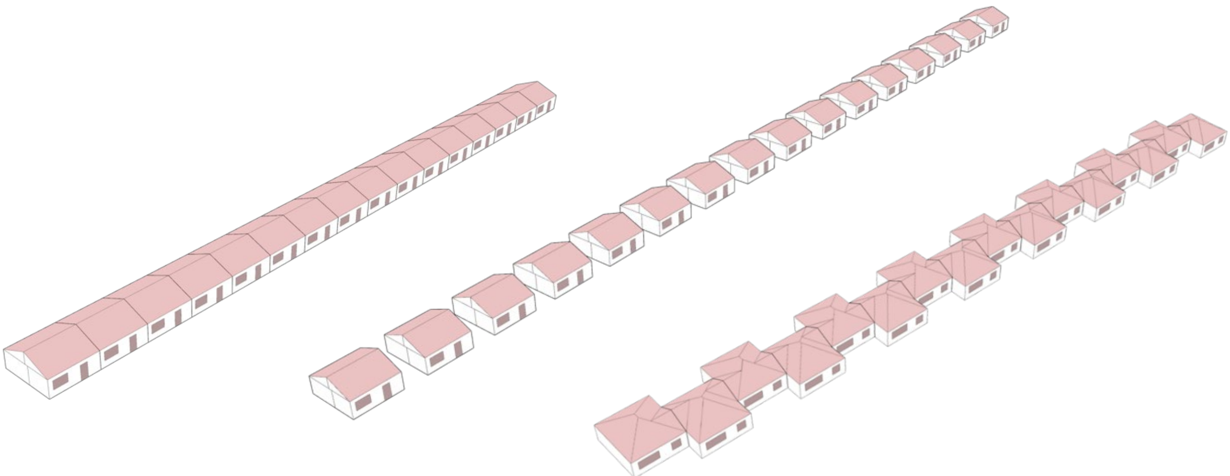


Evaluation of Building Forms

An analytical study on environmental impact and energy performance

Marianna Ciepiela & Shivani Mutatkar

Master thesis in Energy-efficient and Environmental Buildings
Faculty of Engineering | Lund University



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.

Master Programme in Energy-efficient and Environmental Building Design

This international programme provides knowledge, skills and competencies within the area of energy-efficient and environmental building design in cold climates. The goal is to train highly skilled professionals, who will significantly contribute to and influence the design, building or renovation of energy-efficient buildings, taking into consideration the architecture and environment, the inhabitants' behaviour and needs, their health and comfort as well as the overall economy.

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.

Examiner: Dennis Johansson (Division of Building Services)

Supervisors: Ulla Janson (Division of Building Services), Karin Farsäter (Division of Building Services), Michael Englund (Competence leader sustainability, ARKITEMA, Stockholm), Aija Baumane (Sustainability specialist, ARKITEMA, Stockholm)

Keywords: Building form, Form factor, Energy demand, Environmental impact, Global warming potential

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Abstract

The study consisted of an analysis of buildings with different forms, based on residential archetypes, and an assessment of their energy demand and environmental impact, for Swedish conditions. A *Shoebox Study* was performed, including seven building archetypes, developed by assembling basic units, shaped like a shoebox. A number of form-defining properties was selected based on the literature review, allowing to describe the form of buildings analysed in the study in a clear and consistent way. The energy performance was determined using Climate Studio plug-in in the Rhinoceros software. The environmental impact was assessed using One Click LCA, incorporated into the Revit environment. It was aimed to find a correlation between the building form, energy performance and environmental impact. The correlation was assessed while focusing on a realistic approach to the design of buildings with varying shapes but constant living floor area, referred to as residential space floor area, and when analysing an impact of the scale of buildings with a constant shape but varying living floor area. Subsequently, a *Case Study* was performed, where a form of a building used in a real-life project developed by Arkitema company, was assessed. The objective was to determine if a correlation between the building's form, energy demand and environmental impact, established in the *Shoebox Study*, can allow to predict the performance of a building with a different form. The prediction was carried out by the means of mathematical proportion. Subsequently, simulations of the energy performance and environmental impact calculations were performed for the *Case Study* and the results compared with the predicted values to assess the accuracy of the prediction. Ultimately an assessment of the relationship between the building form, the energy demand and GWP was done for the *Shoebox Study* and *Case Study* together, in order to analyse the correlation in the context of a real-life building form. Two separate assessments were performed with the results expressed per m^2 of the heated floor area and per m^2 of the residential space floor area and the outcomes compared to illustrate the impact of the service spaces, included in the heated floor area, on the energy demand and global warming potential of considered buildings.

Acknowledgements

We would like to thank our supervisor, Ulla Janson and our co-supervisor, Karin Farsäter, for providing us with guidance and constant encouragement during the process of developing the project described in this paper.

Moreover, we would like to express our appreciation towards Aija Baumane and Michael Englund, from the company Arkitema, without whom the broad spectrum of the study could not be covered. Along with granting us access to the real-life project developed by the company Arkitema, which allowed for the *Case Study* to be a part of the research, Aija and Michael provided us with their broad expertise regarding the building design and inspired us to address the topics valuable for the building industry.

Furthermore, we would like to express our gratitude to Danai Petrou, from WSP, Denmark, for her time guiding us through the One Click LCA software and for valuable inspiration during numerous brainstorming sessions.

Finally, we would like to thank our examiner, Dennis Johansson, for constructive feedback on the report and his dedication and patience when answering all of our questions.

Contributions

Creating the models in Rhinoceros along with the energy simulations and verification of results against the BBR was performed by Marianna Ciepiela. Shivani Mutatkar was responsible for generating the detailed models in Revit and carrying out the LCA calculations in One Click LCA. Development of the building forms, as well as research regarding the assumptions made in the study, followed by the analysis and interpretation of results, was conducted by both authors.

Abbreviations and quantities

BBR	Boverket's Building Regulations
SVEBY	Standardisera och verifiera energiprestanda i byggnader
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
U-value	Heat transfer coefficient
U_{mean}	Average value of the heat transfer coefficient values
EPpet	Primary energy demand
A_{temp}	Heated floor area
$A_{residential}$	Residential spaces floor area
Aom	Thermal envelope area
CLT	Cross laminated timber
SFP	Specific fan power
HR	Heat recovery
ACH	Air changes per hour
LCA	Life Cycle Assessment
EPD	Environmental Product Declaration
GWP	Global Warming Potential
WFR	Window to Floor Ratio
HLFF	Heat-loss form factor
FF	Form factor
GHG	Green-house gasses

Glossary

Multi-dwelling building – ”..any building comprising two or more dwelling units, including, but not limited to, apartments, condominiums, co-ops, multiple family houses, townhouses, and attached residences” according to the *Law Insider Dictionary*.

Single-dwelling building – A building consisting of a single-family detached houses or one single-family building

Multi-storey building – A building consisting of more than two storeys.

Single-storey building – A building consisting of the ground storey only.

Residential space – Private living area, excluding any common area in the building

Service area – Area in the building used for corridors, elevator shafts, stairwells, etc.

Unit – A space in the building restricted for a single family/ tenant

Building envelope – Components of the building structure enclosing the building within the heated floor area, according to the BBR.

Global Warming Potential – Environmental impact category, accounting for the emissions of green-house gasses, expressed in kg of CO_2 equivalent.

Heated floor area - Floor area of temperature-controlled spaces heated to more than 10 °C, according to the BBR.

Overheating hours – Time when the operative indoor temperature exceeds 26°C

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1 Introduction

As high energy demand and carbon emissions are pressing issues in all industrial sectors, goals have been set by the European Union in order to increase the energy efficiency and reduce the greenhouse gasses emissions in the upcoming years (European Comission, n.d.). With residential buildings responsible for a major part of the energy use and carbon emissions of the building sector (Takano et al., 2015), (Gustavsson & Joelsson, 2010), it has become crucial to explore different approaches to reducing energy demand and environmental impact of new buildings.

In an attempt to account for the energy demand and carbon emissions of a building it is important to consider the energy efficiency and environmental performance already at the early design stage. The common way of optimizing the building's performance is through passive or active measures, focusing on decreasing the energy demand, or energy use of the building (Konstantinou & Prieto, 2018), or reducing the environmental impact by applying more environmentally friendly materials to the building's structure (Uzan Sacha, 2019). It is, however, worth noting that the building's shape and geometry can be used early in the design process, as indicators regarding the energy demand and carbon emissions (D'Amico & Pomponi, 2019). Moreover, the building scale is an important factor, when analysing the relative performance of buildings (Lotteau et al., 2017)

The building's shape and geometry, referred to as the building form, are described by correlations between different factors, accounting for the thermal envelope area, heated floor area, volume and other geometrical characteristics. Establishing those correlations allows to determine the amounts of materials used in the building, influencing its environmental footprint. The building form is also known to impact the rate of thermal losses through the envelope (Pacheco R et al., 2012), affecting the building's energy demand. Studies have been performed on the influence of the building's form on the energy demand and on the carbon emissions, however not much research has been done analysing both aspects of the building's performance simultaneously, in relation to the building form.

The study described in this paper, has been conducted in order to find a correlation between the building's form and it's performance in terms of energy and environmental impact. It is hoped that the research will contribute to the field of building design, allowing to visualize the relationship between the building's geometry and its effect on the energy demand and carbon emissions. The drawn conclusions are expected to enable a rough estimation of the building's relative performance when deciding among various residential building forms in the early design stage.

With timber used as the main material of the structure components of the buildings analysed in the study, it was hoped to initiate a further discussion, leading to evaluation of the study findings in relation to other building materials.

1.1 Background

According to the Sweden's Draft Integrated National Energy and Climate Plan, Sweden's goal, aimed to be achieved by the year 2030, is to increase the energy use efficiency by 50%, compared to the country's energy use in 2005 (Ministry of the Environment and Energy, 2018). Moreover, Sweden intends to reach carbon neutrality, with zero net greenhouse gasses emissions into the atmosphere by the year 2045 (Ministry of the Environment and Energy, 2018). According to the report by the French High Council on Climate, published in November 2020, the building sector accounts for more than a third of carbon dioxide emissions in the European Union (Government of France, 2020). It has, therefore, become crucial to increase the energy efficiency of new buildings and reduce the carbon emissions attributed to the building construction, use and dismantling, including further allocation of materials.

Both, the energy use, accounting for heating, cooling and electricity, and materials, including their production, transportation and utilisation at the end of life, contribute to the total carbon emissions of a building. Due to their green sourcing of energy countries like Sweden emphasize the evaluation of embodied impact (Swedish Energy Agency, 2021).

Life cycle assessment method is used to estimate the total emissions associated with the building's energy use and the embodied carbon. LCA allows to assess the environmental impact of a building throughout its entire life cycle. The use of LCA in an early design stage has been said to have a significant potential towards promoting a sustainable design (Brismark et al., 2022).

Although a considerable number of studies has been performed regarding the LCA of buildings, few studies have been conducted to assess the relative relationship of the LCA and different residential building types, (Takano et al., 2015) and limited number of studies considered the building's shape and geometry as a parameter when assessing the environmental performance (Leskovar et al., 2019). Foraboschi et al focused on the building height when analysing the environment impact of different buildings (Foraboschi et al., 2014).

Multiple studies were also conducted to investigate the relationship of the building form and its energy performance, however not a lot of research was found analysing the building's energy demand and carbon footprint simultaneously in relation to the form. Moreover, not many studies have addressed the integration of life-cycle energy together with the life-cycle emissions, in different residential typologies (Adalberth, 2000).

1.1.1 Literature Review

This chapter will focus on defining the form of a building along with the terminologies related to the geometry of the form that were investigated in various studies. Moreover, previous studies on energy performance and the environmental impact correlating to the form of a building, will be discussed. In addition, the chapter will discuss the advantages of timber and cross laminated timber (CLT) as a building material.

1.1.1.1 Building form

The definition of a building form is described below and different building forms in the residential typologies will be discussed. Additionally, studies relating to different characteristics of a form and their role in establishing form-defining properties, will be addressed.

What is a form of a building?

Form of a building in architecture refers to its spatial configuration as positioned in any open space. This is a three-dimensional object and can be characterized in accordance with its geometry, size, shape, mass and scale amongst other factors. One study refers to it as a combination of elements such as a point, a line, a plane and a volume that influences the geometry of a form (STANKOVIC et al., 2018). The primary elements that constitute a form are a point which is a dimensionless element, a line which is a one-dimensional element, a plane which is a two-dimensional element and volume which is a three-dimensional element (*Ching-Architecture_form_space_order*, n.d.). The primary elements that constitute a form are: a point, which is a dimensionless element, a line, which is a one-dimensional element, a plane which is a two-dimensional element and volume which is a three-dimensional element (*Ching-Architecture_form_space_order*, n.d.).

Residential buildings archetypes

Residential building typologies vary in relation to the form, allowing to determine residential building archetypes. These archetypes have been categorized below (Smith, 2014).

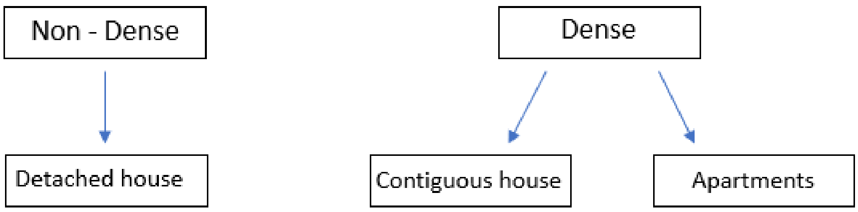


Figure 1: Depiction of the various housing archetypes

The housing archetypes can be divided into two categories, the non-dense and the dense type of housing, as seen in Figure 1. The non-dense category consists of the detached house archetype whereas in the dense category the contiguous archetype and the apartment archetype are included.

Non-dense type of housing

The detached house can be termed as an individual type of a form that is not spatially connected with other residential units (Smith, 2014). A chain-house form or an individual house form can be thought of as a detached house archetype as seen in Figure 2. This type is generally very predominant in low density cities.

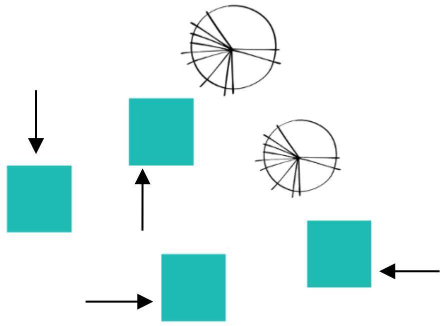


Figure 2: Conceptual sketch of multiple detached houses

Dense type of housing

The contiguous house as seen in Figure 3 (left), consists of 1 or more units that share a wall with the other units either in a linear pattern or a nonlinear and a more ambiguous pattern (Smith, 2014). These archetypes were seen to have their own entrance with the presence of an adjoining street. A rowhouse form can be thought of as a contiguous house archetype. An apartment, as seen in the Figure 3 (right), consists of multiple units grouped together in a single building block that has a single doorway leading to the outside. It can also be defined as a building that meets the dwelling needs for several or multiple families (Smith, 2014).

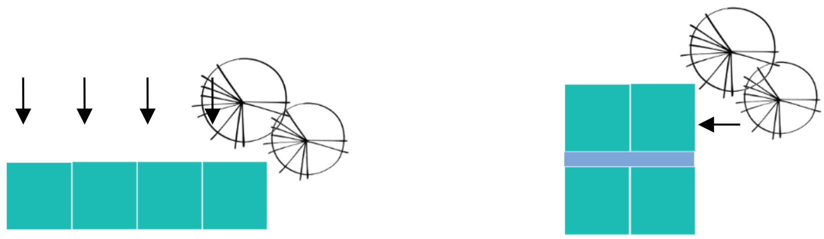


Figure 3: Conceptual sketch of a row-house (left) and an apartment block (right)

Role of the form-defining properties

The form-based ratios help to determine clear relationships between the different characteristics of a building form. These can be used to then draw conclusions on the energy and even environmental performance of the building since the ratio between the properties of the form, such as the volume and the external surface area, are characterized by energy and carbon-intensive supply chains (D'Amico & Pomponi, 2019). The form-based ratios can also help to determine the compactness factor of a building which is an important indicator towards reducing the energy demand (Catalina et al., n.d.). Additionally, a study by Hong Soo Lim and Gon Kim described that, when the surface area of the building envelope is smaller than the volume they occupy, the heat losses through convection or radiation are reduced (Lim & Kim, 2018). The study also describes the possibility of predicting the heat loss with the knowledge of the ratio. Another study on the form factor, described below, indicates that in order to achieve lower carbon emissions, designers and housing developers should aim for lower values of the form factor (NHBC Foundation, 2016).

The ratios defining the building form

Various ratios that help describe the form of a building were studied and are described below.

Form Factor (FF)

A form factor (F.F) is calculated as the ratio of the surface area, A (m^2), of the total thermal envelope to the total heated volume of the form, V (m^3). The unit of the ratio is expressed as 1/m (Ivanova & Ivanova Chief-Asst Arch, 2016). In another study, the form factor is described as a shape factor (A/V) and states that the shape factor for a single-family house is between 0.8 – 1 m^2/m^3 and that of a passive house is less than or equal to 0.8

m^2/m^3 (Lylykangas, n.d.). Another study also states that the form factor can be used to determine the compactness of the building and states that the energy demand bears proportion to the compactness ratio (Depecker et al., 2001). Depecker also states that, the outdoor climate is a significant influencer in assessing the energy demand of a building. It is noted that the compactness is more relatable when the climate is rigorous, while on the other hand, the compactness becomes insignificant when the outdoor climate is mild.

Heat-loss Form Factor (HLFF)

The heat-loss form factor (HLFF) is a term used to denote the ratio between the surface area of the thermal envelope, A (m^2), to the treated floor area, A (m^2) (Ivanova & Ivanova Chief-Asst Arch, 2016). Another study by Lylykangas mentioned that the Swedish passive house experts have termed HLFF as a shape factor (A_{om}/A_{temp}) wherein, the A_{om} represents the thermal envelope area while the "A_{temp}" represents the heated floor area (Lylykangas, n.d.). Lylykangas also mentions that the high thermal heat losses through the building envelope could be accounted for by the high shape factor ratio, referring to a case study of Alingsås, Gothenburg, Sweden (Lylykangas, n.d.). Additionally, Lylykangas also mentioned that the HLFF was a better ratio than the FF to compare the energy efficiency of the buildings.

Aspect Ratio

The aspect ratio is defined in one study as the ratio between the building's length to the width (McKeen & Fung, 2014).The paper also states that the total surface area subject to thermal transfer is a function of its dimensions or so-called aspect ratio. McKeen and Fung made a conclusion that designs that require more surface area of the walls will exhibit a higher amount of thermal heat transfer (McKeen & Fung, 2014). From their study, it is evident that with a lower aspect ratio and same height for two building forms, the form with a lower aspect ratio is noted to be more efficient than the form with a higher aspect ratio.

A study performed by Hemsath and Alagheband Bandhosseini described the relationship between aspect ratio, building height and number of storeys and the energy demand which is depicted as 'loads' and expressed in kWh (Hemsath & Alagheband Bandhosseini, 2015).

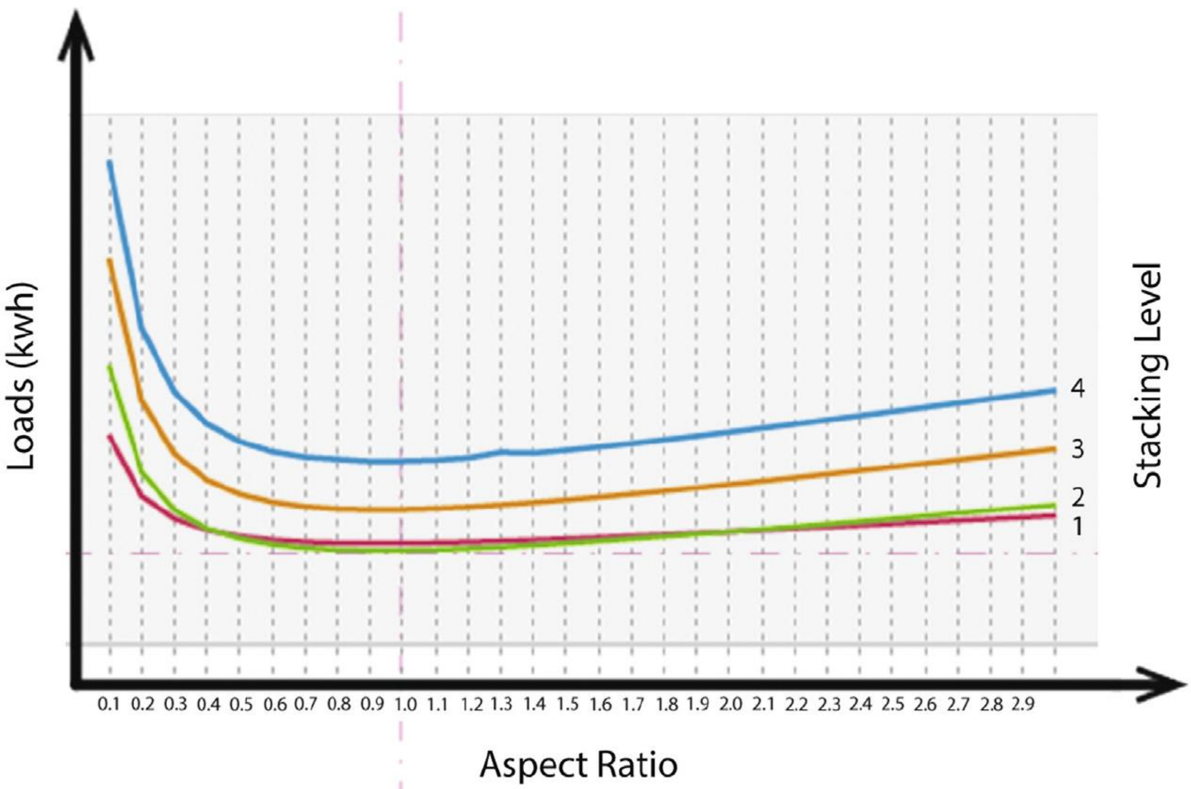


Figure 4: Relationship between the aspect ratio and energy demand with respect to the height (Hemsath & Alagheband Bandhosseini, 2015)

As seen in the Figure 4, the duo stated that the pink vertical dashed line has the same aspect ratios for the different forms and the pink horizontal dashed line demonstrates the range of aspect ratios along the x-axis. From their analysis, it is evident that, for the same aspect ratio, as the stacking effect or the number of storeys increase, the energy demand also increases. An observation was made in the paper that the stacking level 2 was seen to be optimal between the aspect ratio range of 0.5 to 2.1 as it yielded the lowest energy demand.

Other geometric ratios

Another geometric ratio impacting the energy efficiency of a building addressed the relative compactness (R_{cd}) index of a building form (Koźniewski et al., 2022). Koźniewski stated that this index can be used to evaluate the energy demand of a building during an early design phase. He opined that the R_{cd} is greater than 1 when the building plan is rectangular, non-square polygon or any shape other than a square (reference building of a square plan is considered for evaluation) or equal to 1 for an optimal performing building with a square plan. A percentage deviation is achieved from the reference dimensions of the building when the result is multiplied by 100. This informs the designer about the percent deviation and makes it easier to compare the results. A study by Ferdous and Gorgolewski states that the compactness of a building form is the ratio between its volume (V) to the area of the external thermal envelope A_{om} (S) (Ferdous & Gorgolewski, n.d.). They also determined that higher compactness ratios determine the compactness of the form.

1.1.1.2 Co-relation between the building form, energy performance and environmental impact of buildings

The focus towards reducing the operational energy for a building form has been quite dominant in the recent past. However, increasingly, calculations over the past decade inform that more attention should be paid towards calculating and reducing the embodied impacts o buildings (Pomponi & Moncaster, 2018).

Building form and energy demand of buildings

As no sufficient research was found on the influence of the building's form on its energy performance in relation to residential typologies, literature addressing the correlation in office buildings typologies was included in the review. Fedous and Gorgolewski put forth the compactness ratio as an indicator towards energy performance (Ferdous & Gorgolewski, n.d.). Within this study, the energy demand (kWh) was determined in relation to different building geometries, based on typologies of office buildings located in Toronto. The study showed as the compactness ratio increased, the total energy demand for space heating decreased.

As seen in the Figure 5, this holds true, and the total energy was seen to decrease with an increase in the compactness (V/S). The study also stated that another ratio could be utilised to measure compactness, namely, the floor area "A_{temp}" denoted as "F" to the envelope area A_{om} denoted as "E". The same trend was observed for comparing assessing the energy demand to the forementioned ratio.

Archetype	F/E	V/S	S_{south}/S_{west}	Total energy, MWh/yr
Sq	1.5	4.6	1	1111–1289
RecEW	1.3	4.1	4	1122–1324
RecNS	1.3	4.1	0.3	1138–1373
Cross	1.2	3.9	1.3	1138–1380
H	1.2	3.9	0.8	1135–1385

F/E increasing
V/S increasing
Total energy increasing

Figure 5: Co-relation between the form-defining properties and the energy demand for space heating (Ferdous & Gorgolewski, n.d.)

The study also concluded that, the space heating demand is significantly impacted by the aspect ratio. Gratia and de Herde described that the compactness of the building was important as compactness is inversely proportional to the surface area of the total thermal envelope (Gratia & de Herde, 2003). The study further concluded that a compact form not only reduces the energy demand but is also a determinant factor in reducing the total construction costs.

The relation between the building's space heating demand and the compactness ratio is presented in the Figure 6, and it is evident that the building with the most compact form yielded the lowest heating energy demand. The study was conducted to test different forms for an office building category.

Another study pointed out that the energy performance of the building was related to the geometric efficiency (A/S) which was a ratio of the area of the building's thermal envelope (A) to the heated floor area of the building (S) (Parasonis Josifas et al., 2012).

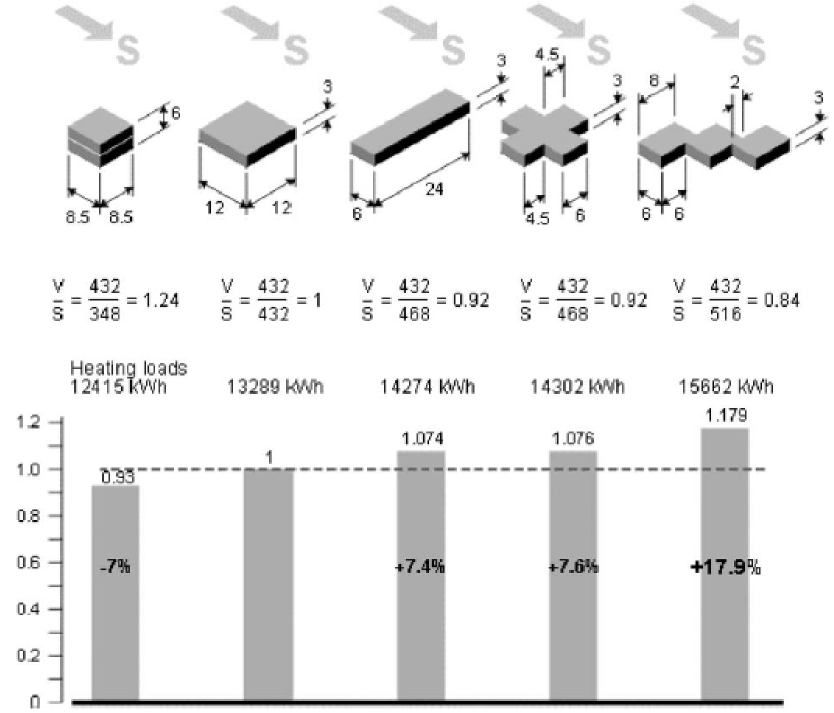


Figure 6: Influence of the compactness ratio on the space heating demand (Gratia & de Herde, 2003)

Furthermore, a study conducted by Pacheco, Ordonez and Martinez stated that the best compact building is the one with a very high compactness ratio which suggested that the possible thermal heat losses were minimal (Pacheco R et al., 2012). The study also suggested that factors that affected the energy demand significantly were: the building orientation, the building shape and the form factor of the building which is the ratio of the building's external envelope to the volume of the building. In addition, the study conducted by Danielski, Fröling and Joelsson for residential buildings suggested that buildings with a higher shape factor are less compact and are prone to higher thermal heat losses (Danielski et al., n.d.).

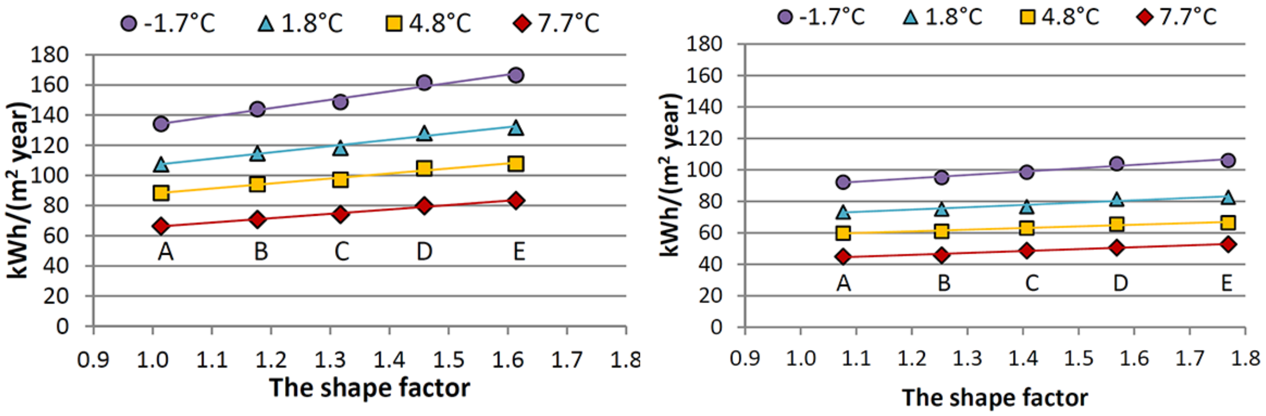


Figure 7: Influence of the shape factor with thinner envelope (left) and thicker envelope (right) on the space heating demand (Danielski et al.*, n.d.)*

The results obtained in this study indicated that the space heating energy demand for the buildings with various forms A to E that were studied, increased with an increase in the shape factor as seen in Figure 7. The study further delves deeper in the analysis regarding a thinner thermal envelope versus a thicker thermal envelope. Figure 7 (left) further informed that, the difference between the slopes of the lines in relation to different temperatures and different shape factors varied more for a building with a thinner thermal envelope than for a building with a thicker thermal envelope as seen in Figure 7 (right) (Danielski et al., n.d.).

A study by Parasonis concluded that, the facades of a building form that are uneven and have protruded elements, such as walls or slabs that stick out of the building, increase the risk of thermal bridges. Thus, even though the volume of the building is thought of as compact, the energy losses increase, and the heating demand increases for such buildings with such forms (Parasonis, 2010).

Research performed by Wei for residential buildings in China proposed relating the number of floors and the building scale to the heating energy demand. The research concluded that, the number of floors directly impact the heating energy while the scale factor plays an important role in the cooling and electricity demand of buildings (Wei et al., 2016). In addition, a study conducted by the NHBC foundation (NHBC Foundation, 2016) studied the impact of the form factor on the space heating demand of a building by testing a few archetypes, such as a bungalow, a detached house, a semi-detached house, a mid-terrace and an end mid floor apartment as seen in Figure 8 (right).

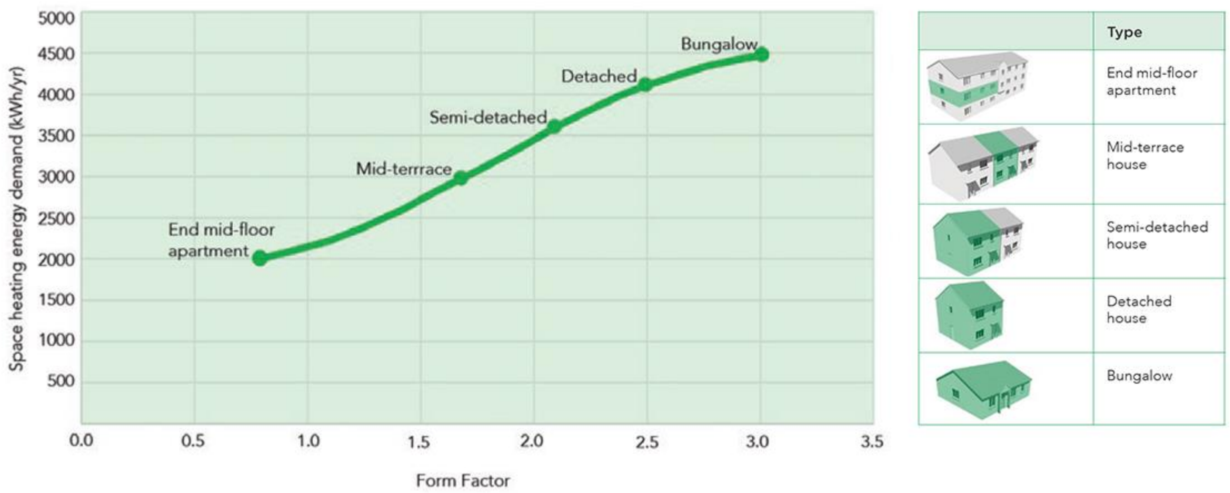


Figure 8: Form factor versus the space heating demand for various building archetypes (left) and housing archetypes (right) (NHBC Foundation, 2016)

While analysing the result of the study conducted by the NHBC foundation, it is evident that, the space heating demand increases with an increase in the form factor. The detached house ranked the highest and the worst while, the end mid-floor apartment ranked the lowest and the best in terms of space heating demand as seen in Figure 8 (left).

Building form and environmental impact of buildings

Demand for LCA studies in the residential sector is fairly small. it's not yet compulsory but a voluntary thing to do (Beemsterboer, 2019). Demand for LCA studies in the residential sector is fairly small. The reason may be that it's not yet compulsory but a voluntary thing to do (Beemsterboer, 2019).

What is LCA and why is it used?

Life-cycle assessment (LCA) is a method of evaluating the environmental impacts of a product or a system during all of its life cycle stages (Astrup et al., n.d.). The life cycle stages entail the product's-system's manufacturing (A1-A3), transportation (A4), the installation phase of the product (A5), the use stage of the product (B) which includes, maintenance, repair and the actual use stage, the disposition of the product known as end of life (C) and the reuse or recycle, which has added benefits, stage (D).

According to the European Commission, the LCA serves as one of the finest frameworks and structures for evaluating the potential environmental impacts of a product (Schlanbusch et al., 2016). Moreover, it can be used as a tool to further analyse the environmental impacts connected to the lifecycle stages of a product, a building, a building component, materials, or even an entire neighbourhood of an urban environment (Schlanbusch et al., 2016).

What is Global warming potential and what is the global warming potential (GWP) impact category?

Global warming is a global phenomenon and accounts for the rise in global temperature of the earth's climate (Ibrahim Dincer & Azzam Abu-Rayash, 2020). The rise in temperature is due to the emissions of certain gases into the atmosphere, known as the greenhouse gases (GHG's). These greenhouse gases usually comprise of carbon dioxide (CO_2), Methane (CH_4), Chlorofluorocarbons (CFC's) and Nitrous oxide (N_2O). Ozone is considered as another greenhouse gas but is not accounted for in the phenomenon of global warming (B. John Garrick, 2008). GWP was generated as a metric to evaluate the impact of each of the gases that trap the heat and affect the global warming. Carbon dioxide was chosen as a reference gas and the impact was calculated as kilograms (kg) of CO_2 equivalent (eq) to combine the influence of all the GHG's, in line with the Inter-governmental Panel on Climate Change (IPCC) (John Durkee, 2006). According to the Paris Agreement, the goal of restricting global warming to below 1.5 degrees Celcius is crucial to combat climate change (*United Nations Framework Convention on Climate Change*, n.d.). Additionally, every nation signing the Agreement is encouraged to set national goals to reduce greenhouse gases (GHGs). In this regard, Sweden aims to achieve zero net emissions of GHG by 2045 (Swedish Ministry of the Environment, 2020).

Previous work on the form impact on LCA

Very few studies have been carried out on the subject related to the building form on its embodied carbon or even embodied energy (Lotteau et al., 2017). A recent study compared two building forms that 'varied only in their gross floor area', and it was concluded that, the building with a higher volume and more surface area performed worse than the building with the smaller volume and the smaller surface area (Budig et al., 2020). Another study investigated the influence of different forms of residential buildings, such as a detached house form, a semi-detached house form, a terraced house form and an apartment form. The results from the study indicate that the building with the detached form had the highest environmental impact. The building with the terraced form performed better than the building with the apartment form, which in turn was seen to perform better than the detached and the semi-detached buildings (Trigaux et al., 2014). A paper by Lotteau, Loubet and Sonnemann, mentioned that the embodied energy was seen to be lower for low rise buildings and higher for high rise buildings. Additionally, it stated that as the number of storeys approached 10, the impact was quite evident (Lotteau et al., 2017).

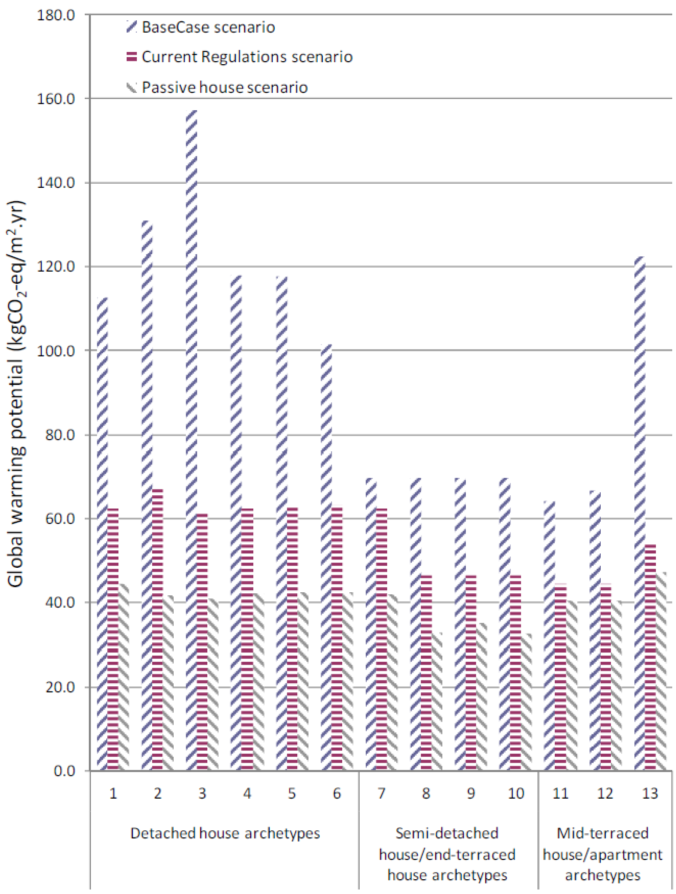


Figure 9: Relationship between the GWP and the different housing archetypes (Famuyibo et al., 2013)

A study by Famuyibo et al. addressed the different form archetypes of the residential buildings. As seen in Figure 9, it was observed that, the performance of the detached houses was the worst in terms of total GWP while the mid-terraced house/apartment archetype seemed to perform the best out of all the three archetypes. However, the archetypes. no 13 of the above Figure 9, representing the mid-terraced house/apartment was seen as an outlier with respect to environmental performance (Famuyibo et al., 2013).

Influence of the building form on the energy performance and environmental impact of buildings

Studies indicate that, although life cycle assessment has been performed for different buildings, there have been fewer studies investigating the environmental profile between different housing archetypes (Takano et al., 2015). Furthermore, there is only a handful of studies integrating lifecycle assessment with the energy performance analysis in relation to different forms of residential buildings. A report by NHBC foundation stated that, an optimal shape and form has clear benefits to residents of the housing units, associated with space distribution, and also reduces the energy demand and the environmental impact in terms of the total greenhouse gas emissions (NHBC Foundation, 2016).

Another study investigated the relationship between the different housing types in the UK and the total life cycle energy and emissions. It was concluded that, the detached house has the highest space heating and domestic hot water energy demand followed by the semi-detached and the terraced house. Moreover, the same trend was observed while examining the results for total GWP (Cuéllar-Franca & Azapagic, 2012). An observation was made in the study that the use stage contributed more to the total emissions than the product stage and construction-installation stage, which indicated that the source of the energy system was not renewable and significantly impacted the result of life cycle assessment of the building. In another study, undertaken for a detached house, a rowhouse, a townhouse and an apartment block in Finland, it was opined that the detached house had the highest impact in the total life cycle energy balance of the housing typologies, as seen in Figure 10, followed by the rowhouse, townhouse and then the apartment block (Takano et al., 2015).

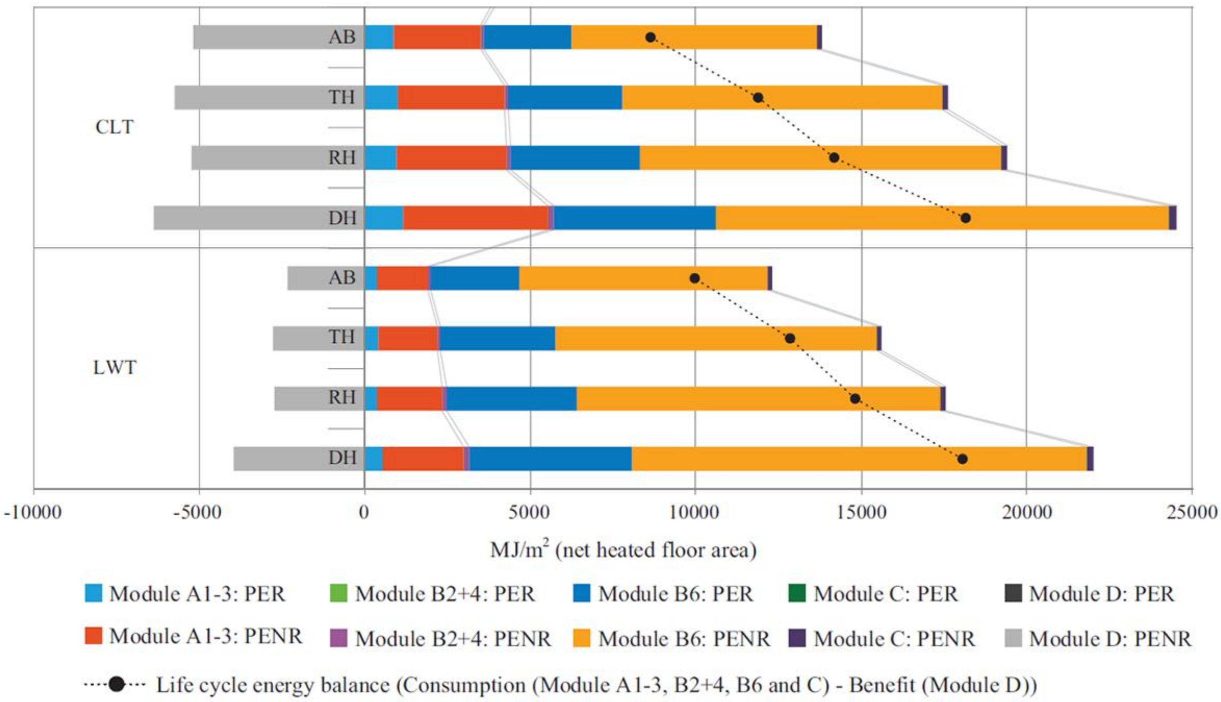


Figure 10: Comparison of environmental impact in life cycle stages for different building archetypes with light-weight timber and CLT (Takano et al., 2015)

Serrano and Alvarez, in their study, scrutinised different typologies of housing in terms of their volume, compactness and area, and evaluated the difference between single family dwellings and multi-family dwellings. They concluded that, even though the multi-family dwellings accounts for 10% more built up area, the associated energy and emissions are much smaller as compared to a single-family dwelling (Serrano & Álvarez, 2016). Furthermore, the study compared the terrace shaped semi-detached houses with slab shaped compact apartment buildings, as the compactness ratios were relatively close, and it was noted that the former consumed 2.69 times more energy and accounted for 2.72 times more CO_2 emissions than the latter.

1.1.1.3 Use of timber as a structural material with a study on Cross laminated timber (CLT)

Several studies have confirmed the relation between the choice of building construction materials with the carbon footprint of a building. In this context, Gustavsson and Joelsson put forth that the wood framed buildings require less energy and emit less CO_2 during their life cycle than any other materials used in a building (Gustavsson & Joelsson, 2010). In addition, using wood-based products compared to concrete products, allows to avoid the process-related CO_2 emissions from the calcination of cement. Wood is seen to be used extensively as a building material for the construction of single-family dwellings in Sweden and its use in other housing typologies, such as apartment buildings, has grown (Sathre, 2007). While comparing the various structural building materials, wooden buildings were seen to perform better and emit the least amount of GHG over their entire life cycle compared to masonry, steel or concrete buildings (Amiri et al., 2020). Moreover, a recent study states that CLT can be used in place of reinforced concrete, as the main load bearing component in a building structure (Andersen et al., 2022). Furthermore, it was suggested that CLT has a lower impact on the global warming compared to concrete, when used as a building material.

1.1.2 Building Standards

In this chapter general information and requirements stated in the building standards and used in this paper, are introduced. Mainly the Swedish standard, Boverket - "The National Board of Housing, Building and Planning's building regulations (2011: 6)", referred to as BBR, and SVEBY 2012, along with other standards such as ASHRAE 90.1, and a European standard SS-EN15978:2011.

1.1.2.1 Energy use – guidelines and requirements

The BBR is used as used in Sweden as a main indicator regarding energy calculations, complemented by the industry's interpretation of the functional requirements for energy management – SVEBY. Guidelines regarding features, not described in the BBR or Sveby, can be found in the ASHRAE 55 standard.

BBR

The BBR contains guidelines regarding the building design, accounting for the building envelope and systems used in the building, and requirements concerning the building's energy demand, expressed by the Primary Energy demand value.

U_{mean}

According to the BBR, the building envelope should be designed accounting for the heat-transfer coefficient value. The average value of the heat-transfer coefficient, U_{mean}, of the building envelope components, is not to exceed a value of 0.4 W/(m^{2}K). Average heat transfer coefficient, for building components and thermal cold bridges, established according to SS-EN ISO 13789: 2017 and SS 24230 (2), is calculated following the formula (1):

$$U_m = \frac{\sum_{i=1}^{n} U_i A_i + \sum_{k=1}^{m} l_k \Psi_k + \sum_{j=1}^{p} \chi_j}{A_{om}} \qquad (1)$$

Where:
U_m – average heat transfer coefficient, W/(m^{2}K)
U_i – heat transfer coefficient of a building component i, W/(m^{2}K)
Ψ_k – heat transfer coefficient of a linear thermal bridge k, W/(mK)
χ_j – heat transfer coefficient of a point-shaped thermal bridge j, W/K
A_{om} – the thermal envelope area, m^2

HVAC design

Requirements regarding the design of the HVAC system, accounting for heating, cooling and ventilation, are stated in the BBR and indicate a maximum value of the specific fan power, i.e., SFP, equal to 1.5 kW/(m³/s), accounting for heat recovery in the system. Minimal amount of external air used for mechanical ventilation is stated as 0.35 l/s per m^2 of the floor area. The setpoint for the heating system is specified as 21°C.

Primary Energy

The value that describes the building's energy performance is expressed as the primary energy number. The figure consists of the building's energy use, where energy for heating has been corrected by the geographical adjustment factor (*Fgeo*). The building's energy use is then multiplied by the weighting factors for energy carriers and divided by the heated floor area (A_{temp}). The geographical factor is assigned based on the building's location in Sweden. The primary energy number, EPpet is calculated according to the formula (2):

$$EP_{pet} = \frac{\sum_{i=1}^{6} \left(\frac{E_{uppv,i}}{F_{geo}} + E_{kyl,i} + E_{tvv,i} + E_{f,i} \right) \cdot VF_i}{A_{temp}} \qquad (2)$$

Where:
EP_{pet} – primary energy number, kWh/(m^2·year)
$E_{uppv,i}$ – space heating energy use, kWh/ year
F_{geo} – geographical adjustment factor, -
$E_{kyl,i}$ – space cooling energy use, kWh/ year
$E_{tvv,i}$ – energy for domestic hot water, kWh/ year
$E_{f,i}$ – property electricity use, kWh/ year
VF_i – weighing factor for each energy carrier, -
A_{om} – the thermal envelope area, m^2

The weighing factors for electricity and district heating are presented in the Table 1.

Table 1: Weighting factors for electricity and district heating

Energy carrier	Weighing factor, VF_i
Electricity	1.8
District heating	0.7

The primary energy number, EPpet should not exceed the 75 kWh/m^2 of heated floor area for apartment buildings and 100 kWh/m^2 for detached houses with the heated floor area between 50 and 90 m^2 and 90 kWh/m^2 for detached houses with the heated floor area exceeding 130 m^2, accounting to the BBR.

SVEBY

Sveby is used along the BBR as a complementing document and defines values, that should be followed in the building design process.

Infiltration rates are determined according to the building type, specified as 0.5 l/s per m^2 of the envelope area for a multi-dwelling building, and 0.3 l/s per m^2 of the envelope area for a single-dwelling building, i.e. small house.

Annual domestic hot water energy is defined as 25 kWh/m$^2_{Atemp}$ for a multi-dwelling building and 20 kWh/m$^2_{Atemp}$ for a single-dwelling building, and 10% heat recovery is accounted for with each value, equal to 2.5 kWh/m$^2_{Atemp}$ and 2.0 kWh/m$^2_{Atemp}$ respectively.

Annual residential electricity use is determined:

- For multi-dwelling buildings: 2000 kWh/household and 800 kWh/person
- For single-dwelling buildings: 2500 kWh/household and 800 kWh/person

According to Sveby, 70% of the electricity use can be utilized in the building in the form of heat, recovered during the heating season. The lighting electricity accounts for 21% of the residential electricity use in the multi-dwelling buildings and 25% in the single-dwelling buildings.
Annual residential electricity use should not exceed 30 kWh/m^2.

Annual energy surcharge is considered due to manual opening of the windows, equal to 4 kWh/m$^2_{Atemp}$

ASHRAE

Metabolic rate of people according to ASHRAE 55 is defined based on an activity. The value for "standing-relaxed" is specified as 1.2 met.

1.1.2.2 LCA – guidelines and requirements

Boverket has recently declared a mandatory climate declaration to be followed so that life cycle assessment (LCA) can be performed to address the climate impact.

BBR

The BBR takes into account the life cycle stages to be followed while performing an LCA. It also considers the building components to be included in the stages A1- A3 stages while performing an LCA. In addition, it includes the values to be used for the calculations in the A4 stage if not mentioned in the Environmental product declaration (EPD).

Life Cycle Stages

According to Boverket, the climate declaration should account for the stages A1 – A5, which are determined according to the European standard SS-EN15978:2011 as seen in the Table 2.

Table 2: Description of the various lifecycle stages included in the climate declaration

Life cycle stages and modules for a building's life cycle according to the European standard SS-EN15978:2011		
A1 – A3	A1	Raw material supply
	A2	Transport
	A3	Manufacturing
A4 – A5	A4	Transport
	A5	Construction, installation process

Building components in the building

According to Boverket, the climate declaration is limited to certain building components, that include, the building's envelope, load bearing structures and interior walls. An overview of the components included is presented in Table 3.

Table 3: Description of the various categories of building components included and not included in the climate declaration

Category	To be included in the climate declaration	Shall not be included in the climate declaration
Load-bearing structural parts - Foundation	Basic construction, insulation underground	Interior finishes, such as parquet floors and linoleum carpet
Load-bearing structural parts -other	Frame (beam, floor, pillars, wall), Wall to ground, Stairs (part of frame), Interior stairs, Exterior roof construction, Ceilings and suspended ceilings, Ramps, Balconies and attic corridors, Castings and raised subfloor	
Climate-Screen	Exterior wall, even building board on the inside, Roofs and floors, Integrated solar cells, façade cladding, Plaster and painting on exterior wall, Window, Exterior doors, Glass sections and glazing	Internal surface layers, Putty on interior wall, Canopy, façade blinds and sun protection, Roof safety, Façade ladders
Interior walls	Interior walls, even building board, glass sections, interior doors	Interior finishes, such as putty, paint and wallpaper, ceiling and floor mouldings, windowsills

Transport stage (A4) and construction and installation stage (A5) guidelines

For stage A4 of the LCA, the impact accounts for the building components used in the building as mentioned in the climate declaration, including the load-bearing structural parts, climate screen and the interior walls as described in Table 4.

Table 4: Description of the lifecycle stage A4, parts included and not included in the climate declaration

Life cycle stage	To be included in the climate declaration	Shall not be included in the climate declaration
A4	Climate impact for the building components of the building as mentioned previously from the manufacturer/factory to the construction site	Transport of other construction products. Other transports, for example transport of sheds and work machines to and from the workplace and transport of consumables.

Stage A5 accounts for the emissions produced in the processes of generation of waste and energy during the construction stage. According to Boverket, the energy intensive processes linked to the construction of the building, include the use of electricity, fuel and heat on site. An overview of the stages is presented in Table 5.

Table 5: Description of lifecycle stage A5, parts included and not included in the climate declaration

Life cycle stage	To be included in the climate declaration	Shall not be included in the climate declaration
A5 construction stage waste	Climate impact from product stage and transport to the construction site of the construction products that are wasted at the construction site. This applies to the construction building components as mentioned previously in the section.	Climate impact from any packaging and other construction product waste that arises at the construction site.
A5 construction stage energy	Climate impact from the use of electricity, heat and fuels at the construction site for all construction products included when the building is constructed.	Energy and fuel for earthworks, Processes relate to the temporary shed and installations are not included.

SS-EN15978:2011

Life cycle assessment follows the EN15978:2011 standard which includes the stages as described below in the Figure 11. The stages A1 – A5 that are mandatory and need to be followed. The assessment of the other stages is voluntary.

Indicators for environmental impacts	Unit Indicator	Modules A1 to A5		Modules B1 to B7							Modules C1 to C4				Module D
		Product stage (A1-3)	Construction Stage (A4-5)	Use stage							End of life stage				Benefits and loads beyond the system boundary
				Building in use					Energy use B6	Water use B7	Deconstruction / demolition	Transportation	Waste processing	disposal	Re-use Recycling Recovery potential
				Use of products B1	Maintenance B2	Repair B3	Replacement B4	Refurbishment B5							
Global warming potential, GWP	kg CO_2 equiv														

Figure 11: Life cycle stages mentioned in the standard EN15978:2011

1.1.2.3 Other requirements

The BBR states, that the window to floor ratio, defining the percentage of glazing area in the floor area of the residential space, should be a minimum of 10% accounting for the necessary daylight level in the rooms.

1.2 Aim and Objectives

The aim of the study was to enhance the knowledge of how the building's form impacts the energy demand and environmental performance of a building and to recognize the constraints that will influence the relationship. The aim was accomplished by a number of objectives:

The first objective of the study was to find a correlation between the building's form, based on a typical residential archetype, described by form-defining properties and designed in accordance with the BBR, and the building's performance in terms of energy demand and environmental impact.

The second objective was to use the established correlation to predict the energy demand and carbon footprint of a building with a different form, used in a real-life project.

The final objective of the study entailed comparing the energy performance and environmental impact of the buildings developed in the study and the building derived from the real-life project, in relation to established form-defining properties when different units, representing the heated floor area and the residential space floor area, are considered.

1.3 Scope

A total of seven residential building types, with varying forms, were modelled in the study, called the *Shoebox Study*, and the values of form-defining properties were calculated for each building form. The "Shoebox Study" referred to the basic design of a unit, in a shape of a shoebox, used in the development of building models. The models were used to simulate the energy demand of the buildings, aimed to comply with the BBR requirements. Simultaneously, the LCA calculations were performed.

The *Shoebox Study* was divided into two assessments, focusing on different aspects. In the first assessment, referred to as *Sub-study 1*, performance of six buildings with different forms was analysed and compared to one another. The focus was put on assessing energy demand and carbon footprint per m^2 of the heated floor area of the buildings, with the same residential space, but varying shapes and aspects of the design, corresponding to a realistic design approach for different building types. In the second analysis, referred to as *Sub-study 2*, performance of two buildings with the same shape was compared, with the focal point being the building scale. The forementioned analyses were carried out to answer the first research question, aiming to establish the correlation between the building's form, its energy demand and environmental impact.

In order to answer the second research question, which aimed to determine if the study findings could be used to predict the relative energy demand and environmental impact of a building, a *Case Study,* was introduced. The form of a building considered in the *Case Study,* was based on a real-life project of a Nordic company, Arkitema. Based on the calculated properties defining the building form, and the findings from *Sub-study 1*, an attempt was made to predict the performance of the building. In order to assess the accuracy of the prediction, the energy demand of the building was simulated and the carbon emissions calculated, and the results were compared with the predicted values.

In order to analyse the correlation between the building's form and it's performance, in reference to a real-life project, the comparison of *Sub-study 1* and *Case Study* buildings was carried out. The energy demand and the GWP was compared for the buildings described in the *Sub-study 1* and *Case Study*, in relation to their form-defining properties. The results were expressed per m^2 of the heated floor area and per m^2 of the residential space floor area were compared against each other.

The study was performed for Swedish conditions, localized in the city of Malmö.

The research and analysis was conducted over a period of 4,5 months.

1.4 General limitations

A number of general limitations of the study is presented in this section and listed below.

1) Having incorporated reliably sourced structural details into the models developed in the study, no detailed structural analysis of the buildings was conducted.
2) No detailed assessment of the daylight conditions in the rooms was carried out beyond maintaining the value of window to floor ratio above the 10% required by the BBR.
3) The analysis was done only for the Malmö location.
4) No detailed moisture assessment in the building structure was performed.
5) The energy performance of the building models was analysed only in one orientation, and no further analysis on the impact of the building's rotation was carried out.
6) The building services system was not dimensioned and no detailed analysis of the system's energy use was performed.
7) No life cycle costing analysis was incorporated into the study.

2 Methodology

The *Methodology* chapter begins with an overall methodology description. Subsequently the *Shoebox Study* is described in detail, including the assumptions made about the design and energy performance of the analysed buildings. The selected form-properties are presented and an approach to the energy simulations, and LCA calculations is explained. Next, the *Case Study* is described, with the assumptions regarding the building design and energy performance explained. The approach to the energy simulations and LCA calculations is presented. Simplifications regarding the energy simulations and LCA calculations are stated. The method of presenting the results of energy demand and LCA calculations is introduced in corresponding sections.

2.1 Overall methodology description

The seven building archetypes, considered as a part of the *Shoebox Study* were divided into the *Sub-study 1* and *Sub-study 2* and further analysed. The building models were developed simultaneously in Rhinoceros, 3D modelling software and Revit design software and the values of their form-defining properties were calculated. The Rhinoceros models were used for further simulations using Climate Studio, a Rhino plug-in based on the Energy+ engine. The simulations results were used for the analysis of the buildings' energy demand, including the energy for space heating, domestic hot water and property electricity. All results were further assessed and performance of the buildings' was evaluated using Microsoft Excel. Primary energy, corresponding with BBR's EP_{pet}, as well as the mean value of the envelope's heat transfer coefficient, U_{mean}, were calculated for each model to ensure the values don't exceed the numbers specified by the standard. The Revit models were incorporated into One Click LCA environment, and the results were used for the life cycle assessment. The LCA was performed for the A1-A3, A4, A5, B6 and C1-C4 stages and the global warming potential was analysed. The carbon footprint was assessed according to the life cycle stages as well as per each considered category. Furthermore, the volume of materials assembled in the models was calculated to allow for an in-depth analysis of the emissions origin. Based on the results of the energy demand and GWP obtained for the different building archetypes, the relationship of the form, energy performance and environmental impact, was established and the first research question was answered. A graphical overview of the method described above is presented below in Figure 12.

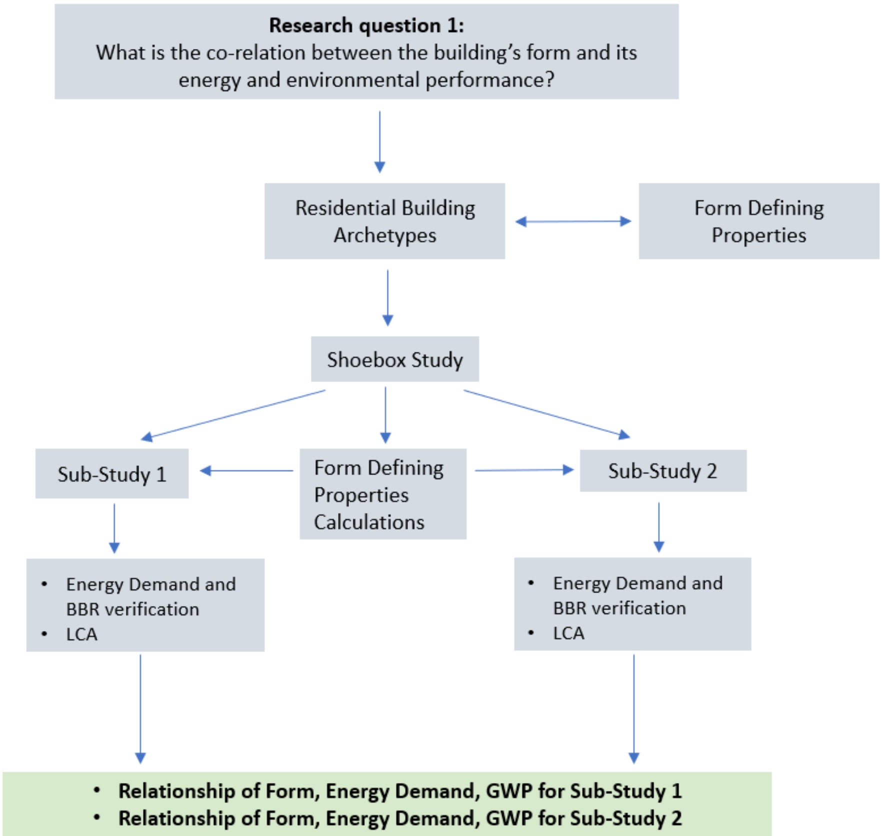


Figure 12: Graphical overview of the methodology part covering research question 1

In order to answer the second research question, the process illustrated in the Figure 13 was carried out.

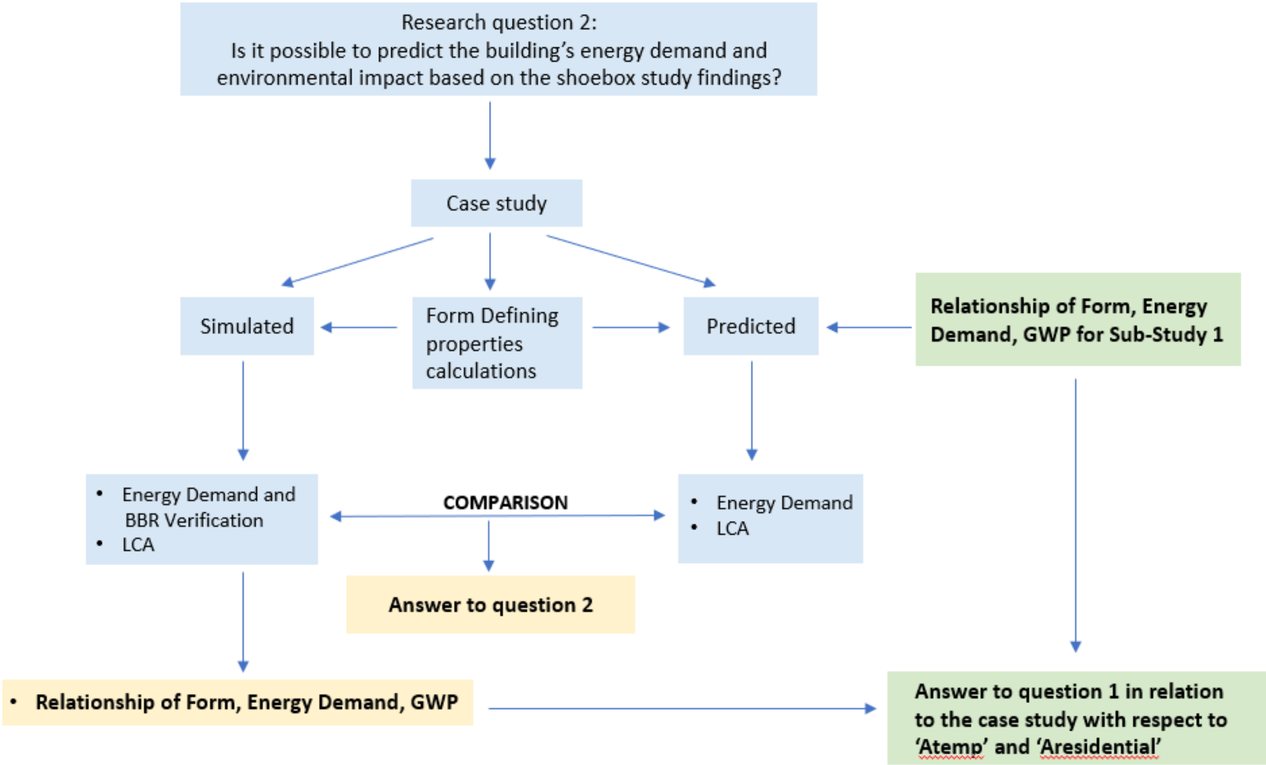


Figure 13: Graphical overview of the methodology part covering research question 2

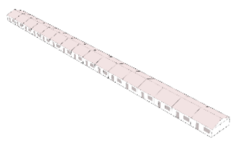
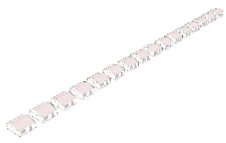
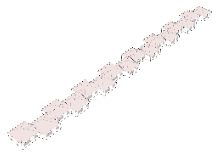
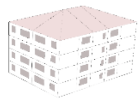
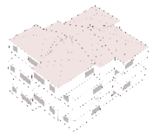
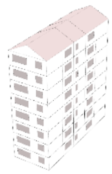
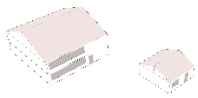
The *Case study* comprised an analysis of a building, used in a project by the Arkitema company, with the same inputs and assumptions about the design as applied in the *Sub-study 1*. Using the findings obtained in the *Sub-study 1* as well as the calculated values of the form-defining properties, an attempt was made to predict the energy demand and the environmental impact of the building. Simultaneously, the actual energy performance of the building was simulated and the LCA carried out in the same manner as in the *Sheobox Study*. The results were compared with the predicted values to assess the accuracy of the prediction and answer the second research question.

A relationship between the energy demand, the GWP, and the form of the building, was assessed together for the *Sub-study 1* and *Case Study* archetypes, to examine the relationship in the context of a real-life project, in relation to the heated floor area and residential space floor area.

2.2 Shoebox study

The *Shoebox Study* consisted of *Sub-study 1* and *Sub-study 2*. The two studies were conducted separately in order to distinguish different aspects of the evaluation. *Sub-study 1* comprised of an analysis of energy performance and environmental impact of six different buildings with constant residential space, but different shapes and varying assumptions made about their design and performance, described further in subsection. In *Sub-study 2*, two buildings were analysed and their performance compared, allowing to evaluate the relationship between proportionally increasing the building volume, impacting the energy and resources demand, and enlarging the heated floor area by adding another storey, influencing the value of the results presented per m^2 of the heated floor area. Performance of the buildings in relation to one another other, was referred to the calculated values of corresponding form-defining properties of each building. The graphical overview of the forms is presented as images in the Table 6.

Table 6: Graphical overview of the different forms of the residential archetypes

Sub-Sub-study 1					
Row-house	Chain-house	Staggered row-house	Mid-rise compact	Mid-rise staggered	High-rise
					
Sub-Sub-study 2					
Scaled unit and small unit					
					

Sub-study 1

Six models of residential buildings were created as a result of assembling sixteen units, where each unit represents a living space of a single-family villa, in various ways. The six assemblies were chosen in order to put focus on different aspects of building design:

1) Row-house – to represent an extreme case of a long building, 1-storey high,
2) Chain-house – to represent a frequent architectural choice with significant area exposed and potentially higher thermal losses in relation to the case where some of the walls are tangent to each other,
3) Staggered row-house – to represent a complex shape of a 1-storey high building, with an increased external envelope and more thermal bridges, when compared to the more compact "Row house", and potentially higher thermal energy losses,
4) Mid-rise compact – to represent a case of a 4-storey- building, with a typical design approach of four apartments at each floor and a service area in the middle,
5) Mid-rise staggered – to represent a complex shape of a 4-storey building, with potentially higher thermal energy losses due to increased external envelope area and higher amount of thermal bridges in relation to the compact case,
6) High-rise – to represent an extreme case of a tall building, with only two apartments on each floor, not corresponding to the Swedish design custom.

Sub-study 2

Two models were included in the study, in order to illustrate the impact of the scaling factor when comparing the performance of otherwise similar forms:

1) Small unit – modelled after the "Chain-house", a base for the "Scaled unit",
2) Scaled unit – modelled by increasing the size of the "Small unit" by a factor of 2 and introducing additional storey.

2.2.1 Basic unit design

The design of the unit was based on a typical habitable space that consists of a bathroom, living room, kitchen, dining, and a bedroom for 2 people. Such habitable space identified as a 'unit' was designed for an area of 56.88 m^2. The entire assembly of the construction except the ground slab was made in timber. More details about the structure are described in section 2.2.2.

The layout of the rooms in the unit was designed to maximize the passive solar gains (Lechner Norbert, 1991) for the most used spaces. The living room and the bedroom were placed towards the south and the kitchen and bathroom were placed towards the north. Additionally, the entrance door was added on the northern façade of the unit. The dining area was considered between the south- and north-facing rooms.

Windows were placed on the south and north façade, with more window to wall ratio on the south façade. The total window to floor ratio was 12%, well in line with the minimum of 10% required by the BBR. A triple glazing was selected for the windows, considering the Swedish Energy Agency recommendation for energy-efficient windows (Swedish Energy Agency, 2015). The windows placed on the South façade consisted of the glazing with a U-value of 0.89 W/(m^2·K), whereas the glazing of the windows placed on the North façade amounted to 0.75 W/(m^2·K). A wooden frame with the thermal conductivity of 0.13 W/(m·K) (Bülow-Hübe, n.d.) was selected for all the windows. A thickness of 100 mm for the frame was chosen, considering the maximum value of 140 mm established by NUTEK (Bülow-Hübe, n.d.). Each window was insulated and *Chromatech* spacers (*Rolltech Windows*, n.d.) were considered in the frame.

2.2.2 Building Structure

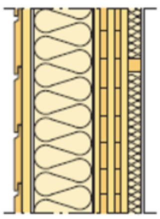
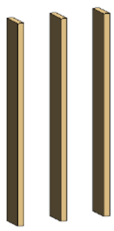
The structure of the forms was designed in accordance with (*The CLT Handbook CLT Structures-Facts and Planning*, n.d.), (*TräGuiden - En Digital Handbok För Trä Och Träbyggande*, n.d.) and (*Martinsons Handbok i KL-Trä*, n.d.). The assembly and characteristics of different building elements was described below.

Exterior Wall

The assembly of the exterior wall was created as seen in

Table 7. The spacing of the timber structural columns within the insulation was 580 mm C/C. The columns were dimensioned to 80 mm by 300 mm.

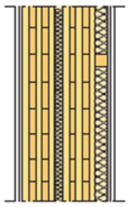
Table 7: Structural details for exterior wall and structural framing in the wall

External Wall construction	**Wall layers from outside to inside**	**Total thickness/ mm**	**U-value/ (W/(m^{2}K))**
	22 mm External Wooden Cladding 34 mm Wind Protection Vapour retarder 300 mm Rockwool insulation 100 CLT panels 45 Batt insulation 13 Gypsum wall board	514	0.10
Structural framing inside the wall: 	**Timber Columns within the 300 mm insulation layer** 80 X 300 mm 580 mm C/C	80	

Internal Load-Bearing Wall

The assembly of the interior load bearing wall was created as seen in Table 8. The described assembly was used for an apartment dividing wall between the units. It was also used as a dividing wall between the units and the service areas.

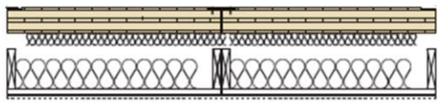
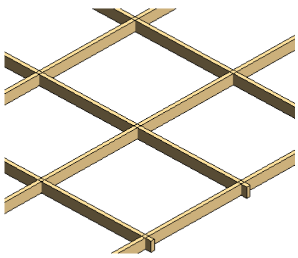
Table 8: Structural details for an internal wall

Internal Wall construction	**Wall layers from outside to inside**	**Total thickness/ mm**	**U-value/ (W/(m²K))**
	2 X 13 mm Gypsum wall board 100 mm CLT panel 30 mm Batt/noise insulation 100 CLT panels 45 Batt insulation 2 X 13 Gypsum wall board	327	0.28

Intermediate Floor Slab

The assembly of the intermediate floor slabs as seen in Table 9 was developed considering the maximum width of a CLT slab. The connections of the various CLT slabs within the entire floor slab were done with a 'T flange'.

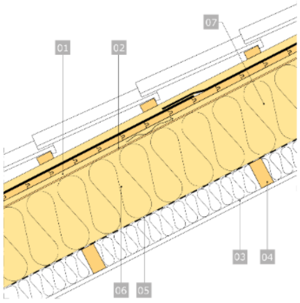
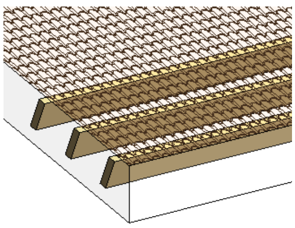
Table 9: Structural details for an intermediate floor slab

Floor construction	**Layers from top to bottom**	**Total thickness/ mm**	**U-value/ (W/(m²K))**
 **<u>Structural framing inside the floor:</u>** 	145 mm CLT Slab 70 mm batt insulation 145 mm Rockwool insulation 100 CLT panels 45 Batt insulation 2 X 13 Gypsum wall board **Timber beams within the 225 mm insulation layer** 80 X 225 mm Beam lattice of 2600 mm C/C of the beams as per the CLT dimensions.	327 80	0.28

Roof

The assembly of the roof layers was done as seen in Table 10. The roof was designed as a 'warm roof' taking into account the potential mould problems resulting from moisture accumulation in roof's wooden structure. No attic space was incorporated into the design; therefore, the habitable volume of the unit was enclosed by the roof.

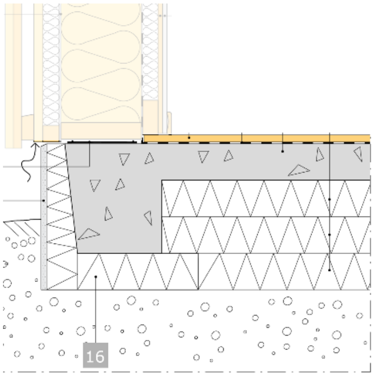
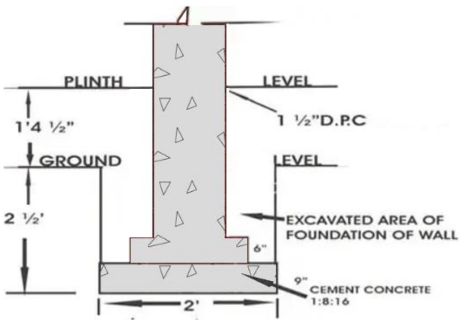
Table 10: Structural details for the roof

Roof construction	Layers from top to bottom	Total thickness/ mm	U-value/ (W/(m²K))
 **Structural framing inside the roof:**	25 mm Roofing tile 01 - 20 mm Ventilated air gap 25 mm Wood sheating chipboard for battons 02 – 15 mm Wind protection 06 - 300 mm Rockwool insulation 05 – Vapour barrier 04 – 100 mm Batt insulation 03 – 13 mm Gypsum board	506	0.10
	**Timber beams within the 300 mm insulation layer** 80 X 300 mm 500 mm C/C for the roof beams	80	

Foundation

The assembly of the foundation as seen in Table 11 was divided into two parts, namely, the raft foundation serving the single-storey buildings and the isolated pad foundation, which served the multi-storey buildings. The raft foundation consisted of a thick ground base of 500 mm. The isolated pad footing foundation was created using a concrete column for its concrete base pad. The size of the concrete column was established as 300 mm by 300 mm. A shallow isolated pad foundation was used for the multi-storey buildings with 4 floors and a deeper isolated pad footing was used for multi-storey buildings exceeding 4 floors. The depth of the column from the base floor was 800 mm into the ground for the shallow isolated pad foundation, while for the deeper, isolated pad foundation it was 1600 mm.

Table 11: Structural details for the foundation

Slab construction	Layers from top to bottom	Total thickness/ mm	U-value/ (W/(m²K))
Raft Foundation for single-storey forms: 	**Ground Slab-** 15 mm Wooden Flooring Vapour barrier 300 mm Concrete 100 mm Rockwool insulation 150 mm Gravel	565 mm	0.13
Isolated pad Foundation for multi-storey forms: 	**Ground Slab-** 15 mm Wooden Flooring Vapour barrier 300 mm Concrete 100 mm Rockwool insulation 100 mm Gravel **Column-** 300 X 300 mm Concrete column 800 mm depth – shallow foundation 1600 mm depth – deep foundation **Pad-** 1200 X 1200 mm 450 mm thickness	565 mm	0.13

2.2.3 Building archetypes and design variations

Each developed model consisted of a "package" of constant assumptions as well as changes necessary to incorporate into the design alongside the varying form.

2.2.3.1 Sub-study 1

The models, developed for the purpose of the *Sub-study 1*, were designed with the same U-values of the building components, and a constant residential area and the same window to floor ratio. Certain elements of the models where altered due to the changes in the form and are described further below.

Row-house

The "Row-house" is assembled in a shape of a row, with units sharing the walls of spaces tangent to each other. The common walls of tangent spaces are designed as described in the section 2.2.2 – Internal Load Bearing Wall. The thermal envelope is designed according to section 2.2.2. The layout with the interior walls was designed as described in section 2.2.2. The windows and doors are placed as described in section 2.2.1. The heated floor area amounts to 910.08 m^2 and is equal to the residential space floor area.

The graphical overview of the model is presented in the Figure 14.

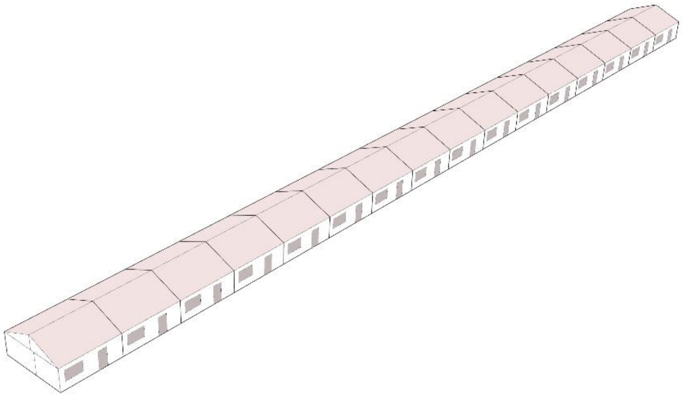


Figure 14: Illustration of the row-house form

Chain-house

The "Chain-house" consist of a "chain" of villas, separated by 3.5 m intended for parking and circulation space. Each villa is designed according to section 2.2.1. The thermal envelope is designed according to section 2.2.2. The heated floor area amounts to 910.08 m^2 and is equal to the residential space floor area. The graphical overview of the model is presented in the Figure 15.

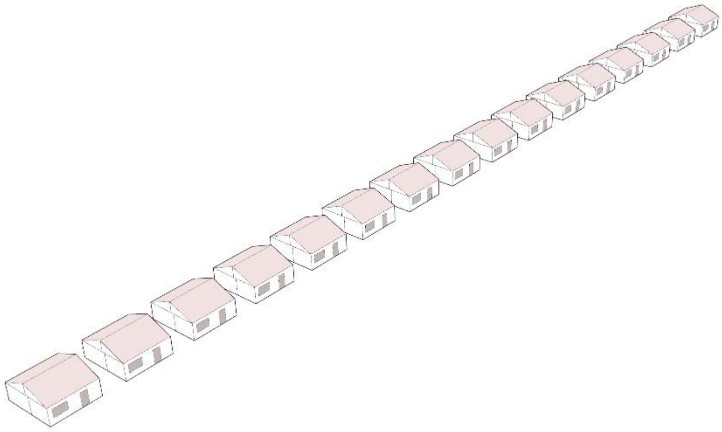


Figure 15: Illustration of the chain-house form

Staggered row-house

The "Staggered row-house" is assembled in a shape of a row with every other unit moved towards the North by 1/3 of the wall length. The area of the walls where the units are tangent to each other was designed according to section 2.2.2 – Internal Load Bearing Wall. The thermal envelope is designed according to section 2.2.2. The layout with the interior walls was designed as described in section 2.2.2. The windows and doors are placed as described in section 2.2.1. The heated floor area amounts to 910.08 m^2 and is equal to the residential space floor area. The graphical overview of the model is presented in the Figure 16.

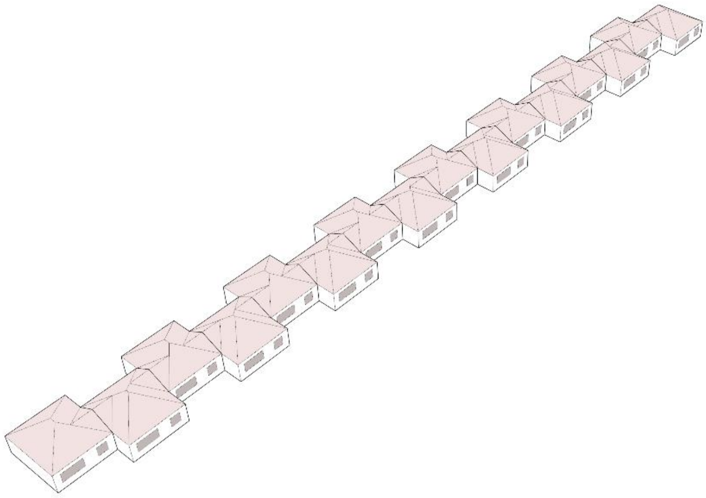


Figure 16: Illustration of the staggered-house form

Mid-rise compact

The "Mid-rise compact" model was shaped as a result of allocating four units on each floor of a 4-storey building. Additional space was created in the middle of the building and holds a corridor, a stairwell and an elevator. Windows were added on each floor next to the stairwell for fire safety reasons (Boverket, 2020), and the U-value of the glazing was adopted as 0.76 W/(m^2K). The properties for the frame of the window were kept as described in section 2.2.1. A double pitched roof spreads over the residential spaces and service areas. The shared walls of tangent spaces, including the service area, are designed according to section 2.2.2 – Internal Load Bearing Wall. The intermediate slabs are designed according to the section 2.2.2 – Intermediate Floor Slab. Layout of the apartments with the interior walls was designed and the doors placed as in subsection 2.2.1. Windows are moved from the walls tangent to the service area and placed on West and East façades, but the properties of the windows are maintained, with the same U-values of the glazing kept on the North and East façade as well as on the South and West façade. There is a common entrance to the building in the service space. The heated floor area amounts to 1094.80 m^2, whereas the residential space floor area is the same as in the single-storey models, equal to 910.08 m^2. The graphical overview of the model is presented in the Figure 17.

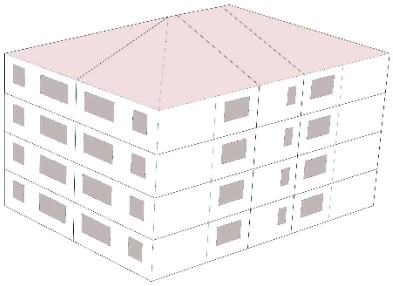


Figure 17: Illustration of the mid-rise compact form

Mid-rise staggered

The "Mid-rise staggered" model was based on the "Mid-rise compact" model, with the dimensions of the units modified, but amounting to the same floor area, and the units rotated, allowing to create balcony spaces. Doors were added to the units to connect the residential spaces with the balconies. The roof automatically generated with the Revit "roof" function was further used in the model. Additional service area, building foundation, shared walls of tangent spaces and windows in the residential space were formed in accordance with the "Midrise compact" design. Intermediate slabs were designed according to the section 2.2.2 – Intermediate Floor Slab, simultaneously serving as the balcony floor. The layout with the interior walls was adjusted, following the units' rotation. The apartment doors were kept in the same position as in the "Mid-rise compact" model. The heated floor area amounts to 1094.80 m^2, whereas the residential space floor area is equal to 910.08 m^2.
The graphical overview of the model is presented in the Figure 18.

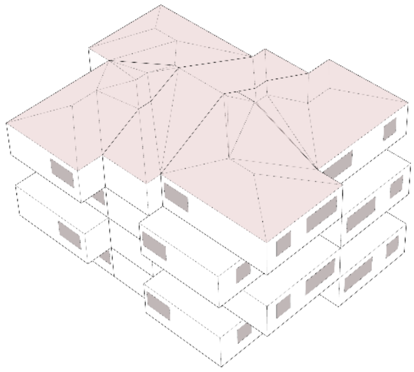
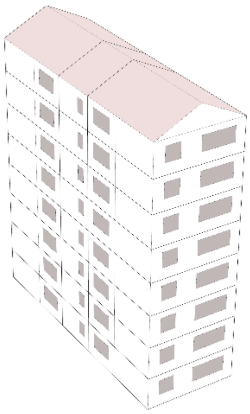


Figure 18: Illustration of the mid-rise staggered form

High-rise

The "High-rise" model was developed with two units on each of the eight floors and a service area in the middle. The service area included a corridor, an elevator and a stairwell with a window on each floor, as the service area in the "Mid-rise compact" and "Mid-rise staggered" models. A double pitched roof was incorporated in the design. The foundation, the shared walls of tangent spaces and intermediate slabs were designed as described in section 2.2.2. The windows are placed on the South, North and West façades. The East façade is left window-less. The layout with the interior walls and the door placement was established as in the "Mid-rise" compact design. The heated floor area amounts to 1132.18 m^2, whereas the residential space floor area is equal to 910.08 m^2. The slightly larger heated floor area compared to the "Mid-rise compact" and "Mid-rise staggered" models, was a result of a slightly increased width of the service space, imposed by the need to accommodate the stairwell and elevator shaft in a space twice as short. The graphical overview the model is presented in the Figure 19.



.
Figure 19: Illustration of the high-rise form

2.2.3.2 Sub-study 2

The models, developed for the purpose of the Sub-study 2, were designed with the same envelope U-value and a constant window to floor ratio. The graphical overview of the models is presented in the Figure 20.

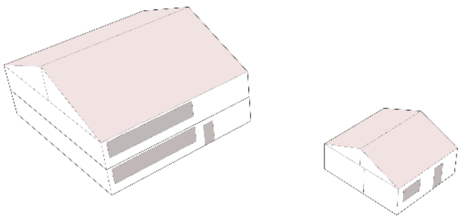


Figure 20: Illustration of the small scale and the scaled unit for

Scaled unit

The "Scaled unit" is based on a single villa, scaled by a factor of two. Additional floor is added to the building. The are no internal, room-dividing walls included in the model, as the space allocation could not be performed in the same way as it was done for the other models, described in the *Sub-study 1*. Furthermore, no staircase was incorporated into the model. The doors are placed in the same position as described in section 2.2.1. Area of the windows was increased to reach the WFR of the other models and divided between both floors. The heated floor area is equal to the residential space floor area and amounts to 455.04 m^2.

Small unit

A "Small unit" was created based on the "Chain-house" unit, without the internal walls, for the sake of the further comparison with the "Scaled unit". The heated floor area of the "Small unit" is equal to 56.88 m^2.

2.2.4 Form defining properties

Two different factors were found in literature for the purpose of the study, in order to describe the different building forms in a precise and consistent way and determine a correlation between the energy performance and environmental impact of a building and its form. The calculated values for each building form were then assembled in a table and presented in 3.1.1.

Form Factor

The form factor was calculated as the ratio of the envelope area (A_{om}) to the volume of the building, A/V, expressed in 1/m, and has been used in the analysis to describe the general shape of the building. The lower the value of the form factor the lower is the expected energy demand of the building and its environmental impact (Lylykangas, n.d.), (NHBC Foundation, 2016).

Heat-loss Form Factor

Heat-loss form factor was introduced in the analysis as an alternative to the "Form factor" described earlier, representing the relationship between the envelope area (A_{om}) and the heated floor area (A_{temp}). Similarly, as in case of the "Form factor" a lower value would indicate a better building performance in terms of energy demand (Lylykangas, n.d.).

2.2.5 Energy demand calculations

Assumptions were made and calculations performed in order to establish the energy demand of each analysed building. The space heating energy, domestic hot water energy and property electricity, accounting for the fans, pumps, property lighting and elevator energy, where considered when determining the energy demand.

2.2.5.1 General assumptions and constant values

General assumptions were made for all the buildings and are presented in the Table 12. The values retrieved from the standards and literature review were assigned to the residential spaces of a single-dwelling and a multi-dwelling house, and the service area. In this study the "Chain-house" and "Scaled unit" are treated as the single-dwelling house, whereas the "Row-house", "Staggered row-house", "Mid-rise compact", "Mid-rise staggered" and "High-rise" fall under the category of the multi-dwelling house.

Table 12: General assumptions for energy calculations

Parameter	Description	Residential spaces		Service areas	Source
		Value for a single-dwelling house*	Value for a multi-dwelling building**		
Heating source	Space heating & domestic hot water	District heating			-
Domestic hot water Energy	Annual energy	20 kWh/ ($m^2{}_{Atemp}$ · year)	25 kWh/ ($m^2{}_{Atemp}$ · year)		*Sveby*
Manual window opening	Annual additional energy losses	4.0 kWh/ (m^2A_{temp} · year)			*Sveby*
Energy savings from hot water heat recovery	Annual energy savings, 10% of domestic hot water energy	2.0 kWh/ ($m^2{}_{Atemp}$ · year)	2.5 kWh/ ($m^2{}_{Atemp}$ · year)		*Sveby*
Infiltration rate for a building with heat recovery	At 50Pa pressure difference	0.3 l/s/m²	0.5 l/s/m²		*Sveby*
SFP	Fan power with heat recovery	1.5 kW/(m³/s)		-	*BBR*
Elevator energy	Annual energy	-		950 kWh	Nipkow & Schalcher, 2018

*chain-house, scaled unit
**row-house, staggered row-house, mid-rise compact, mid-rise staggered, high-rise

The domestic hot water energy values, as well as the annual savings from the hot water heat recovery, were accounted for when calculating the energy demand of the building and the primary energy number. The Annual energy losses resulting from manually opening the windows were considered solely in the primary energy (EPpet) calculations. Infiltration rate values were used to later calculate the infiltration rate, expressed in ACH. The calculation is described further in the subsection 2.2.5.3. The SFP value was used in the calculations, described in subsection 2.2.5.3, in order to determine the fan pressure rise. The elevator energy was accounted for in the primary energy calculations and was included in the property electricity demand of the building.

2.2.5.2 Form-specific calculations

Calculations of the energy use of the pumps, included in the heating system, windows U-value and thermal bridges were performed several times to account for the impact of the changing form on the forementioned values.

Pump energy

The calculated pump energy was included in the total property electricity demand of the building and accounted for in the primary energy calculations. In order to calculate the energy needed for running the circulation pumps in the heating system, the water flow rate was established using the formula (3).

$$Q_w = 3600\pi \cdot v \left(\frac{d}{2}\right)^2 \qquad (3)$$

Where:
Q_w – water flow rate, m³/h
d – pipe inner diameter, m
v – water velocity, m/s

The water velocity and inner pipe diameter were determined using the friction chart with the assumed equal friction of 250 Pa/m. The length of the differential head was estimated at 1.5m to serve one unit. The forementioned data was used to select the pump model from the Grundfos website (GrundFos, n.d.) and obtain the pump energy for a single unit. The obtained value was multiplied by the number of units to determine the energy needed to run the pumps serving the entire building. If the total volume of the building could not be expressed in an integer of units, the additional pump energy was accounted for using a mathematical proportion based on the calculated pump energy and space heating results, retrieved from the simulations.

Windows

With the varying form of the buildings, the windows location varied in relation to the originally described in section 2.2.1. The assumption was made that the windows placed on the West façade of the building will remain of the same glazing U-value as windows placed on the South façade. The same rule was applied to the buildings placed on the East and North façades. Windows U-value was calculated for each window with the formula (4).

$$U_{win} = \frac{A_g U_{cog} + A_f U_f + L_g \Psi}{A_g + A_f} \qquad (4)$$

Where:
U_{win} – window heat transfer coefficient, W/(m^{2}K)
A_g – glazing area, m^2
U_{cog} – center of glass heat transfer coefficient, W/(m^{2}K)
A_f – frame area, m^2
U_f – frame heat transfer coefficient, W/(m^{2}K)
L_g – glazing perimeter, m
Ψ – linear heat transfer coefficient of the glazing edge, W/(mK)

Thermal bridges

As no detailed thermal bridges simulation was performed in the study, the thermal bridges were accounted for by increasing the U-value of all the envelope elements by 20%, following available literature on the subject (Berggren & Wall, 2013).

2.2.5.3 Energy simulations

Performing simulations and calculations regarding the building's performance required establishing assumptions about input values. Energy simulations were performed using the Climate Studio plugin of the Rhino software and, the program inputs, assumptions and limitations regarding the simulations are described in this section.

Thermal zones

A separate thermal zone with corresponding settings was assigned to each unit in the model. The service area consisted of multiple zones, one at each floor of the building, and appropriate settings input. Adiabatic surfaces were assigned between the tangent units, on the vertical and horizontal plane. Ground properties were set on designated surfaces. Data from Copenhagen weather file was used in the simulations, allowing to reflect the micro-climate conditions of Malmö. It was assumed in the study that the internal heat gains will have an impact on the space heating demand, therefore the internal loads were specified. The settings for the zones were calculated or assumed and are further described below and the values presented in Table 13.

People load

As one of the simulation input was the people load, the people density was calculated and metabolic rate was assumed. Two people were expected to live in one unit and the density was calculated by dividing that number by the floor area of the residential space. An average metabolic rate was determined as a value for "standing relaxed" activity specified in ASHRAE standard 55 (ASHRAE, 2010). An occupation schedule was set as Climate Studio default for residential buildings.

Equipment and lighting load

The equipment load for the household appliances was determined based on the Sveby (SVEBY, 2009), where annual values were determined for electrical energy use of a single-dwelling building and a multi-dwelling building, per household and per resident. The annual residential electricity use was calculated not to exceed the maximum value of 30 kWh/m^2 specified in Sveby. The 21% of the electricity use was allocated towards apartment lighting, as indicated in Sveby. It was stated in the document that 70% of the energy use can be utilized as emitted heat, allowing to establish the loads for equipment and lighting. Electrical power was calculated based on the emitted energy values and divided by the residential space floor area to obtain the power density. The lighting power density for the service spaces was calculated based on the number and efficiency of luminaires used in similar spaces in office buildings (Swedish Standards Institute, 2017), due to the lack of values standardized for residential buildings. Schedule for the lighting and equipment in residential spaces was set as Climate Studio default for residential buildings whereas the schedule for lighting in service areas was set manually, based on reasonable assumptions of space occupation.

Ventilation

The heating setpoint for residential spaces was determined according to BBR and distinguished from the hating setpoint of the service areas. The mechanical ventilation was set to a of minimum fresh air required by the BBR. A sensible heat recovery system was included in the simulations with the efficiency of the system based on the value found in literature. The fan pressure rise was calculated as one of the zone inputs, based on the assumed SFP value and the fan efficiency value found in literature (Nilsson J Lars, 1994). Formulas (5) and (6) were used for the calculations:

$$W_t = \frac{V \cdot \Delta p_{tot}}{\eta_{tot}} \qquad (5)$$

Where:
W_t – electric power to fan, kW
V – airflow rate through fan, m^3/s
Δp_{tot} – total pressure rise of the fan, kPa
η_{tot} – total efficiency of the fan, -

$$SFP = \frac{W_t}{V} \qquad (6)$$

Where:
SFP – specific fan power, kW/ (m^3/s)

From the two forementioned formulas the fan pressure rise was calculated by substitution and expressed in Pascals. No distinction was assumed between the supply and exhaust system values and the pressure rise was calculated only once.

Infiltration

In order to be considered as input to the simulations, infiltration rate had to be expressed in “air changes per hour”. It was assumed that infiltration is happening through the façade and roof and the ACH was calculated based on the predetermined values of infiltration per m^2 of the envelope for each model. Subsequently the value was adjusted based on the assumed calculation method of the simulation software which requires the value of ACH at 4Pa pressure difference. A component in Honeybee, a Rhinoceros plug-in, was used to convert the value of infiltration rate at 50Pa, specified in Sveby, to the value at 4Pa pressure difference. A number of infiltration coefficients was specified according to *Energy+* library, in order to illustrate the weather conditions varying by season.

Thermal zones inputs summary

A summary of thermal zone inputs is presented in Table 13.

Table 13: Summary of the thermal zones input specific to Climate Studio (CS) software

<table>
<tr><th rowspan="2">Parameter</th><th rowspan="2">Description</th><th colspan="4">Residential spaces</th><th rowspan="2" colspan="2">Residential spaces</th><th rowspan="2">Source</th></tr>
<tr><th colspan="2">Value for a single-dwelling house*</th><th colspan="2">Value for a multi-dwelling house*</th></tr>
<tr><td>People load</td><td>People density</td><td colspan="4">0.04 p/m^2</td><td colspan="2">-</td><td>Calculated</td></tr>
<tr><td></td><td>Metabolic rate</td><td colspan="4">1.2 met</td><td colspan="2"></td><td>ASHRAE 55</td></tr>
<tr><td>Equipment load</td><td>Equipment power density</td><td colspan="2">4.3 W/m^2</td><td colspan="2">4.0 W/m^2</td><td colspan="2">-</td><td>Sveby</td></tr>
<tr><td>Lighting load</td><td>Lighting power density</td><td colspan="2">2.1 W/m^2*</td><td colspan="2">1.5 W/m^2*</td><td colspan="2">1.6 W/m^2**</td><td>*Sveby, **calculated</td></tr>
<tr><td>Heating setpoint</td><td>Air temperature</td><td colspan="4">21°C*</td><td colspan="2">15°C**</td><td>*Sveby, **assumed</td></tr>
<tr><td>Mechanical ventilation, minimum fresh air amount</td><td>Minimum amount of fresh air</td><td colspan="6">0.35 l/s/m^2</td><td>BBR</td></tr>
<tr><td>Heat recovery system</td><td>System efficiency</td><td colspan="4">75%</td><td colspan="2">-</td><td>-</td></tr>
<tr><td></td><td>Fan pressure rise</td><td colspan="4">1760 Pa</td><td colspan="2">-</td><td>Calculated</td></tr>
<tr><td rowspan="5">Infiltration</td><td rowspan="5">ACH, at 4 Pa pressure difference</td><td rowspan="2">Chain-house</td><td rowspan="2">0.16</td><td>Row-house</td><td>0.18</td><td rowspan="2">Mid-rise compact</td><td rowspan="2">0.11</td><td rowspan="5">Calculated</td></tr>
<tr><td>Staggered row-house</td><td>0.21</td></tr>
<tr><td rowspan="3">Scaled unit</td><td rowspan="3">0.08</td><td>Mid-rise compact</td><td>0.11</td><td>Mid-rise staggered</td><td>0.15</td></tr>
<tr><td>Mid-rise staggered</td><td>0.15</td><td rowspan="2">Hig-hrise</td><td rowspan="2">0.15</td></tr>
<tr><td>Highrise</td><td>0.15</td></tr>
<tr><td></td><td>Constant coefficient</td><td colspan="6">0.606</td><td rowspan="4">Energy+ library</td></tr>
<tr><td></td><td>Temperature coefficient</td><td colspan="6">0.03636</td></tr>
<tr><td></td><td>Wind velocity coefficient</td><td colspan="6">0.1177</td></tr>
<tr><td></td><td>Wind velocity squared coefficient</td><td colspan="6">0</td></tr>
</table>

2.2.5.4 BBR verification

The U_{mean} value, followed by the primary energy number were calculated in order to establish if the buildings' design and performance comply with the BBR requirements.

U_{mean}

The U_{mean} was calculated as described in the sub-section 1.1.2.1 ,and the thermal bridges were accounted for in the U-value of the envelope elements, as described in the sub-section 2.2.5.2.

EPpet

Primary energy number, EPpet was calculated according to the sub-section 1.1.2.1, with the geographical factor, Fgeo, selected according to the location of Malmö, equal to 0.8.

2.2.5.5 Presentation of results

The results of the energy simulations and calculations were presented as displayed in the Table 14.

Table 14: Breakdown of the presentation of results for Sub-study 1 and Sub-study 2

Study	Energy demand results	BBR verification
Shoebox Study		
Sub-study 1	• Energy demand per m^2 of the heated floor area • Energy demand per m^2 of the residential space floor area	• U_{mean} values • Primary energy values
Sub-study 2	• Energy demand per m^2 of the heated floor area	• U_{mean} values • Primary energy values

Energy demand

The assessed energy demand of the buildings consisted of the space heating energy, domestic hot water heating energy with heat recovery and property electricity. In the *Sub-study 1* the results were displayed separately per m^2 of the heated floor area and per m^2 of the residential space floor area. In *Sub-study 2* the results were expressed solely per m^2 of the heated floor area as, for the considered buildings, the residential space floor area was equal to the heated floor area.

BBR verification

U_{mean} value was displayed separately for the buildings considered in the *Sub-study 1* and *Sub-study 2*.
Primary energy value was presented, along the maximum value of 75 kWh/m^2_{Atemp}, allowed for multi-dwelling buildings, specified by the BBR, for the *Sub-study 1*, and 90 kWh/m^2_{Atemp} allowed for single-dwelling buildings, exceeding the heated floor area of 130 m^2, for the *Sub-study 2*.

2.2.6 LCA calculations

The LCA calculations were carried out using the One Click LCA software. LCA for the study was conducted in various phases which are described below and was carried out in an interactive process.

2.2.6.1 Goal and scope

The goal of LCA was to assess the global warming potential of different buildings, located in Malmö, Sweden, complying with the BBR requirements regarding the energy performance. The GWP was expressed as the carbon footprint of the building, measured in kg of CO_2 eq per m^2 of the heated floor area and per m^2 of the residential space floor area, separately.

Functional unit

Two different functional units were adopted in the study and incorporated into the analysis, accounting for the heated floor area and the residential space floor area of the building. Total GWP of the building complying with the BBR, expressed per m^2 of the heated floor area was evaluated. Separately the total GWP of the building complying with the BBR, expressed per m^2 of the residential space floor area, was assessed.

Analysis period

The analysis period considered in the study was established for a span of 50 years and the lifespan of the materials adopted for the study was according to the EPD's selected for every material.

2.2.6.2 Inventory analysis

The EPD's chosen for the purpose of the study were selected from the database of Nordic manufacturers of building elements, with production sites located in Sweden. Considered EPD's include detailed technical descriptions of the building products and comply with EN15804 and/or ISO 14025 standards. All EU databases comply with the EN 15804 standard and North American databases comply with the ISO 14040/44 standard.
The environmental impact of electricity and district heating use was calculated using the One Click LCA database, which accounts for energy production fuel mixes provided for each country by International Energy Agency (IEA) (International Energy Agency, 2017). The impact of the fuels (both production and exhaust) has been calculated based on the Ecoinvent 3.3 -database.

Boundary conditions and inputs

The LCA was considered from cradle to grave (A1 to C) for all the analysed building forms. Life Cycle Stages according to EN 15804:2012 were included in the study as presented in the Table 15. Stages marked in grey were not considered as part of the study.

The buildings modelled in the Revit software were exported to One Click LCA software to obtain a quantity list. Each layer of the building's structure was categorized according to the elements of the considered building. A material was selected for each layer from the EPD database. The quantities of materials were illustrated either by volume or area and thickness. When choosing the EPD for a material, the material thickness, density and thermal conductivity were considered.

The selected EPD's were then used by One Click LCA software to calculate the emissions in stages A1-A3 and C for the materials in the building elements.

Table 15: Lifecycle stages according to EN 15804:2012

Raw material supply	**Transport**	**Manufacturing**	**Transport to building site**	**Installation into building**	Use/application	Maintenance	Repair	Replacement	Refurbishment	**Operational energy use**	Operational water use	**Deconstruction/demolition**	**Transport**	**Waste processing**	**Disposal**	Reuse	Recovery	Recycling
A1	**A2**	**A3**	**A4**	**A5**	B1	B2	B3	B4	B5	**B6**	B7	**C1**	**C2**	**C3**	**C4**	D	D	D
x			**x**	**x**	x					**x**	x	**x**				x		

Since the buildings considered in the study were assembled on a hypothetical construction site, the location in Malmö was not specified and the transport distances for stage A4 have been assumed as default values in One Click LCA for all the analysed buildings.

The calculation of the emissions for stage A5 was conducted using the gross floor area (GFA) as an input to determine the emissions during the construction scenario. Since the construction and installation phase is dependent on multiple factors that occur on the site, the 'rough construction scenario' was selected in One Click LCA to be used for the study. The A5 stage was considered in the study, as it is a part of the mandatory regulations of Boverket for a climate declaration.

The stage B6, i.e., the operational energy, consisted of two parts. The first part accounted for the electricity consumption (kWh). The electricity was delivered to the building by the electricity grid in Sweden. Facility electricity, referred to as property electricity in the energy analysis, was considered in the study. The input for facility electricity, was obtained from the energy calculations carried out for each building as described in the section 2.2.5. The source for the electricity grid was selected in One Click LCA as 'Electricity, Sweden(kWh) – One Click LCA/ several profiles'. The global warming potential (GWP) considered for the source by One Click LCA was equal to 2.59 kg $_{CO_2\,eq}$ /kWh. The second part of the operational energy accounted for heat consumption (kWh) by space heating and domestic hot water. The heat was delivered to the building by the

district heating network of Malmö. The inputs for the space heating and domestic hot water were obtained from the energy calculations described in 2.2.5.1 for each of the buildings. The source for the district heating network in Malmö was selected in One Click LCA as 'District heat, Malmö Sweden (kWh) – One Click LCA/Several profiles'. The GWP considered for the source by One Click LCA was equal to 1.03 kg $_{CO_2\,eq}$/kWh. Stage C was calculated by One Click LCA based on the inputs made in stages A1 – A3.
The calculation period considered for the analysis in One Click LCA was 50 years.

2.2.6.3 Impact assessment

The emissions of the analysed buildings were converted to a relatable impact with potential to affect humans and the eco system. The total calculated impact was based on the inputs form the forementioned stages within the system boundary of the inventory analysis. The impact assessment category chosen for the purpose of the study was the global warming potential.

2.2.6.4 One Click LCA software

The One Click LCA plug-in used for the Revit integration was 'One Click LCA Setup Revit 4.0.2'. One Click LCA software is used to collect data regarding the materials accounted for in the structure of the assessed design, from the materials' EPD's. Based on the amounts of materials retrieved from the Revit model, or specified manually, and the corresponding EPD's, the environmental impact of an analysed building is calculated. Different impact assessment categories are available in One Click LCA, however only the global warming potential, expressed in kg of CO_2 was considered in the study.

One Click LCA allows to calculate the emissions in Life Cycle Stages, comprised of the A1-A3, A4, A5, B1-B6, C1-C4 and D stage, however not all stages were considered in the study, as illustrated in the Table 15.
The emissions in most of the Life Cycle Categories depend on the user specified input, however when assessing the A4 stage, default values can be used. For the A5 stage, a rough scenario is suggested by the software. The software accounts for various energy consumption types: the electricity use, including the facility electricity and household electricity, energy for space heating and domestic hot water and cooling energy, however only the facility electricity, the space heating energy and domestic hot water energy were taken into account in the study. The obtained results are presented for the chosen analysis period and expressed per m^2 of the specified floor area.

2.2.6.5 Presentation of results

The results of the LCA calculations were presented as displayed in the Table 16.

Table 16: Breakdown of the presentation of results for Sub-study 1 and Sub-study 2

Study	LCA results
Shoebox Study	
Sub-study 1	• GWP in life cycle stages per m^2 of the heated floor area • GWP in life cycle stages per m^2 of the residential space floor area • GWP per category per m^2 of the heated floor area • GWP of the volume of materials per building category per m^2 of the heated floor area
Sub-study 2	• GWP in life cycle stages per m^2 of the heated floor area • GWP per category per m^2 of the heated floor area • GWP of the volume of materials per building category per m^2 of the heated floor area

The LCA analysis of the buildings was divided into three parts; the carbon emissions produced in life cycle stages, the carbon emissions produced in the different categories and the emissions of volume of materials allocated in the building components of the different categories. The results were shown individually for *Sub-study 1* and *Sub-study 2*.

The GWP associated with life cycle stages was presented separately for the A1-A3, A4, A5, B6 and C1-C4 stage. The environmental impact of the buildings expressed through the carbon footprint of different categories, included accounting for the emissions of foundation, floors slabs, ceilings and roofs, walls, windows and doors, columns, other structural materials, district heating use, electricity use and construction site scenarios.
The volume of materials used by each of the analysed buildings was calculated for four major building components categories, including the 'foundation and substructure', 'intermediate floor slabs, roof, horizontal structural beams, roofing deck', 'external and internal walls' and the 'columns' and presented together with the corresponding emissions, allowing to form a link between the GWP to the volume of materials used in each building.

The environmental impact allocated in life cycle stages was presented in kilograms of CO_2 eq per m^2 of the heated floor area as well as per m^2 of the residential space floor area for the *Sub-study 1*. The heated floor area was equal to residential space floor area of the buildings analysed in *Sub-study 2*, therefore only the emissions per m^2 of the heated floor area were presented. The results of carbon emissions produced in the different categories were expressed in kilograms of CO_2 eq per m^2 of the heated floor area. The results obtained in the volumetric analysis were expressed in m^3 of materials per m^2 of the heated floor area on one axis and in kilograms of CO_2 eq per m^2 of the heated floor area on the other axis.

Grouping of building elements in the categories considered in One Click LCA

Due to differences in nomenclature of the building elements in the categories accounted for by One Click LCA and the elements considered in the assessed buildings, a Table 17 was created, explaining how different elements included in the structure of the buildings is accounted for by different categories specified in One Click LCA.

Table 17: Grouping of building components in One Click LCA

Category in One Click LCA	Structure component in the building
Foundation and substructure	Foundation and ground floor slab
	Basement including internal walls, ground retaining walls, intermediate floor slabs
Intermediate floor slabs, roof, horizontal structural beams, roofing deck	Intermediate slabs
	Roof
	Horizontal structural beams in the intermediate floor slab
	Roofing beams and truss
External and internal walls	External load bearing walls
	Internal load bearing walls
	Internal partition walls
Columns	Columns
Windows and doors	Windows and doors
Other structural elements	Other structural elements

2.3 The case study of Rogaland/ project by Arkitema

The real-life project "Rogaland", set in Malmö, developed by the company ARKITEMA was included in the study and its energy demand as well as environmental impact were analysed as it was done for the buildings considered in the *Shoebox Study*. The *Rogaland* building consisted of three apartment blocks situated on top of a basement which top served as a circulation space between the buildings and was partially sunk in the ground, as illustrated in the Figure 21.

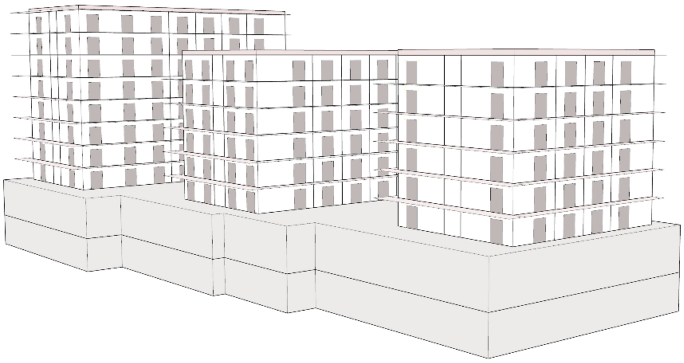
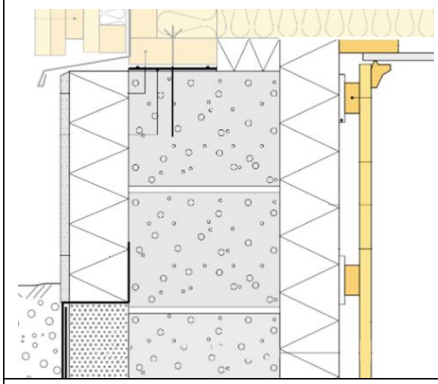
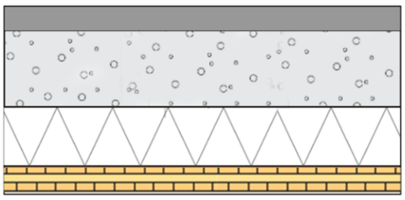
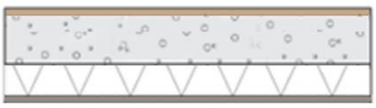


Figure 21: Illustration of the Rogaland building

The same glazing and frame U-value were selected for the South/West and North/East windows, as described in the 2.2.1.

The building structure consisted of the elements described in 2.2.2, as for most elements the same structural assembly as in the building forms of the *Shoebox Study*, was used. In addition, a ground retaining wall and a floor slab positioned on top of the basement were introduced to the design with the layers assembly illustrated in the Table 18 (*TräGuiden - En Digital Handbok För Trä Och Träbyggande*, n.d.), (Postma Mark et al., 2016).

Table 18: Structural assembly introduced into the design of the Rogaland building

Element Construction	**Layers from outside to inside**	**Total thickness (mm)**	**U-value (W/m²K)**
Retaining Wall 	15 mm Cladding Vapour retarder 100 mm Rockwool insulation 250 mm Concrete 90 mm Batt insulation 20 mm Gypsum wall board	475	0.12
Podium Floor 	200 mm Concrete walkway Vapour retarder 600 mm Concrete 475 mm Rigid insulation 200 mm CLT 25 mm Interior tiles	1500	0.06
Intermediate Floor 	15 mm flooring Vapour retarder 150 mm Concrete slab 100 mm Rockwool insulation 20 mm Gypsum ceiling board	300	0.15

2.3.1 Performance prediction based on the Shoebox Sub-study 1 findings

The performance of the building was predicted based on the correlation between the form-defining properties, described in the section 2.2.4, and the results of energy demand and environmental impact of the buildings developed in the *Sub-study 1*.

Prediction of the energy demand of the Rogaland building

Prediction of the energy demand was carried out, considering the performance of the "Mid-rise compact", "Mid-rise staggered" and "High-rise" building, which, due to the multi-storey character of said buildings, allowed for a more accurate estimation. Mathematical proportion of the energy demand of the considered buildings and the corresponding form factor values was established, and the predicted numerical value of the energy demand was determined for the *Rogaland* building.

Prediction of the GWP of the Rogaland building

Similarly to the prediction of the energy demand, calculations were carried out to establish a numerical value of the GWP for the *Rogaland* building. Similarly as in the energy demand prediction, only the "Mid-rise compact", "Mid-rise staggered" and "High-rise" building were used as the base for calculation.

Two methods of calculating the predicated value were introduced.

In the first method, the mathematical proportion was established based on the GWP associated with three chosen categories in the considered buildings and their impact on the total emissions, together with corresponding form-defining properties. The GWP of 'foundation and substructure', 'intermediate floor slabs, roof, horizontal structural beams, roofing deck' and 'external and internal walls' categories were considered for each building, as part of the calculation. Following the process, described more extensively in the APPENDIX II, the predicted numerical value of the GWP for the *Rogaland* building was established.

In the second method, mathematical proportion of the total GWP, calculated for the considered buildings, and the form factor values was used, allowing to obtain the total GWP of the *Rogaland* building by cross-multiplication.

2.3.2 Performance analysis

The building's performance was assessed through the simulations of energy demand and LCA calculations, carried out as described in section 2.2.5 and section 2.2.6. The analysis was conducted separately for the apartment blocks and the basement.

Energy demand calculations

The assumptions and simulation inputs were established according to the section 2.2.5. The values input in the project were selected based on the standard values for a multi-dwelling building, according to the Table 12. The basement was defined as a *service area* with the same ventilation requirement and lighting load as specified in Table 13.

The heating setpoint for the basement was set to 12°C. The infiltration rate at 4Pa, expressed in ACH, was calculated, based on the value for multi-dwelling buildings, specified in the Table 12, separately for each of the building blocks and for the basement and is presented below, in the Table 19. The values were obtained based on the exposed surface of the façade and roof of each element.

Table 19: Calculated values of ACH for apartments of the different blocks

	Apartment block - south	Apartment block - middle	Apartment block - north	Basement
Infiltration rate, ACH, at 4Pa	0.10	0.11	0.09	0.04

The pump energy was assumed for each apartment based on the proportion between the average apartment area, the "unit" area and the pump energy value established for each "unit" as described in sub-section 2.2.5.2. The additional pump energy required to serve the service spaces was considered and calculated as described in sub-section 2.2.5.2. Outdoor lighting was introduced in the outdoor circulation space and the electrical energy use was calculated with an average illuminance value of 35 lux, specified for outdoor lamps (Wigan Council Street Lighting, n.d.). The lighting power density, used in the calculation, was based on the value calculated for service areas, the assumed schedule and the floor area of the circulation space. Three elevators with the energy demand specified in the Table 12, were considered in the project. Thermal bridges and other energy losses were accounted for as described in the sub-section 2.2.5.2 and section 2.4.

BBR verification

The U_{mean} and EPpet were calculated in the same way as it was done in the *Shoebox Study*.

Presentation of results

The results of the energy simulations and calculations were presented as displayed in the Table 20 below.

Table 20: Breakdown of the presentation of results for the Case-study

Energy demand results	**BBR verification**
Case Study	
• Energy demand per m² of the heated floor area • Energy demand per m² of the residential space floor area	• U_{mean} values • Primary energy values

The energy demand was presented separately for the apartment blocks and the basement and expressed per m² of the total building heated floor area, followed by the results expressed per m² of the residential space floor area.

LCA calculations

The LCA calculations were conducted according to section 2.2.6. The goal and scope was the same as mentioned previously in section 2.2.6.1 and the inventory analysis followed the same methodology as described in section 2.2.6.2. Similarly, as described in the section 2.2.6.3, global warming potential was chosen as the impact assessment category. The interpretation of results was done as described in the section 2.2.6.5.

Presentation of results

The results of the LCA calculations were presented as displayed in the Table 21 below.

Table 21: Breakdown of the presentation of results for the Case-study

LCA results
Case Study
• GWP in life cycle stages per m² of the heated floor area • GWP in life cycle stages per m² of the residential space floor area • GWP per category per m² of the heated floor area • GWP of the volume of materials per building category per m² of the heated floor area

The GWP was presented separately for the apartment blocks and the basement. The total heated floor area of the building was considered when the results were expressed per m² of the heated floor area for the basement or the apartment blocks. The GWP in life cycle stages was presented additionally per m^2 of the residential space floor area.

2.3.3 Verification of the prediction

The results of energy demand and global warming potential obtained in the energy simulations and LCA calculations were compared against the predicted values in order to verify the prediction.

2.4 Study simplifications

In this section the limitations regarding the simulations and calculations performed in the paper are described.

2.4.1 Energy simulations

Limitations regarding the energy simulations were recognized and addressed in the development of energy models.

Thermal bridges

The thermal bridges were accounted for in the study by increasing the U-value of the envelope as described in the sub-section 2.2.5.2. It is, however, worth mentioning that when assessing the design of the "Staggered row-house" and "Mid-rise staggered" it could be noted that the complicated shape and large number of edges, would most likely result in increased heat losses due to thermal bridges, compared to the more compact building forms. Lacking a clear assumption about the value that could allocate higher heat losses associated with thermal bridges in the buildings with staggered forms, the impact of thermal bridges was assumed to be constant for all the analysed buildings. Moreover, the thermal bridges occurring due to balconies in the Rogaland building, were perceived to influence the heat losses, however, were not accounted for in the calculations.

Additional thermal losses

As there was no available doors input in the simulation tool, the impact of doors on the building envelope was accounted for by adjusting the U-value of the external walls. With the service area in the building and entrances to apartments located on the internal wall, the U-value of that wall was also adjusted. The impact was established by calculating the area ratio of the doors to the walls with doors. Subsequently the ratio was multiplied by the U-value of the doors and the U-value of the walls was increased by the obtained value. Additionally, when defining the U-values of the glazing and frame of the windows, the frame U-value was increased in order to account for the thermal losses through glazing edges which are not considered in the simulation tool.

Shading

No urban context was developed for the energy model, therefore no shading from the surrounding was taken into account. Shading devices or external shading for windows were not considered with the exception of the *Rogaland* building, where the balconies were modelled as shading surfaces due to their large size and impact on the solar gains.

Modelling

The models were created according to the internal measurements and no internal walls or intermediate slabs thickness was accounted for in the building volume.

2.4.2 LCA calculations

Limitations regarding the LCA calculations are considered in the study and are described below.

1) In the stage A4, the default distance was considered.
2) For the A5 stage the generalized construction site scenario was included.
3) Stages B1-B5 were not included in the results from the analysis.
4) Stage D and the biogenic carbon impact were not accounted for in the study.
5) "T-flange" connections, included in the structure of the slabs, as mentioned in section 2.2.2, were not considered in the LCA analysis.

6) The environmental impact of the buildings considered in the *Sub-study 1* was not clearly comparable with the *Case Study* building, when analysing the emissions in the foundation category, due to an additional substructure (basement) added to the foundation in the *Rogaland* building.

3 Results

The study results are presented and described in subsections 3.1 - 3.2.
In order to allow for an easy reference, a Table 22, including the values of the heated floor area of the buildings considered in the *Sub-study 1* and *Sub-study 2 and Case Study* was introduced in this section. Residential space floor area is additionally displayed for the buildings of the *Sub-study 1 and Case Study*, as it was considered a part of the analysis.

Table 22: Values of the heated floor areas and the residential space floor areas for all the buildings considered in the study

	Sub-study 1						Case Study
Form	Row-house	Chain-house	Staggered row-house	Mid-rise compact	Mid-rise staggered	High-rise	Rogaland
Heated floor area/ m^2	910.08	910.08	910.08	1094.80	1094.80	1132.18	12169.20
Residential space floor area/ m^2	910.08	910.08	910.08	910.08	910.08	910.08	6210.62
	Sub-study 2						
Form	Scaled unit			Small unit			
Heated floor area/ m^2	56.88			455.04			

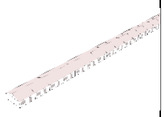
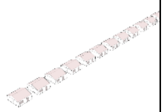
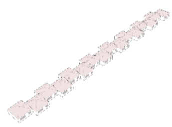
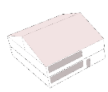
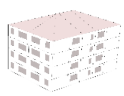
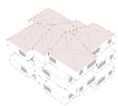
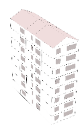
3.1 Shoebox study

The results of energy simulations and calculations and LCA calculations done for the *Shoebox Study* are presented in subsections 3.1.1 - 3.1.3.

3.1.1 Form defining properties

The calculated values of form defining properties were combined for the building archetypes analysed in *Sub-study 1* and *Sub-study 2* and presented in Table 23.

Table 23: Form-defining properties of the buildings assessed in the Shoebox Study

Form	Single-storey building forms				Multi-storey building forms		
	Sub-study 1			*Sub-study 2*	*Sub-study 1*		
	Row-house	Chain-house	Staggered row-house	Scaled unit	Mid-rise Compact	Mid-rise staggered	High-rise
Image							
FF A/V /(1/m)	0.8	1.1	0.9	0.5	0.4	0.5	0.5
HLFF	2.8	3.7	3.1	1.8	1.2	1.4	1.3

The lowest value of the form factor as well as the lowest value of the heat-loss form factor was achieved by the "Mid-rise compact" building, whereas the highest values for those were established by the "Chain-house".

3.1.2 Energy Demand Calculations

The energy demand simulation results are presented separately for the *Sub-study 1* and *Sub-study 2*. The verification of results according to the BBR was performed subsequently for the *Sub-study 1* and *Sub-study 2*, and the U_{mean} and EPpet values are displayed.

Sub-study 1

The values of energy demand for the “Row-house”, “Chain-house”, “Staggered row-house”, “Mid-rise compact”, “Mid-rise staggered” and “High-rise” building are presented below, followed by the values of U_{mean} and EPpet calculated for each building considered in the *Sub-study 1*.

Energy demand

The energy demand results are presented separately per m^2 of the heated floor area, in the Figure 22, and per m^2 of the residential space floor area, in the Figure 23.

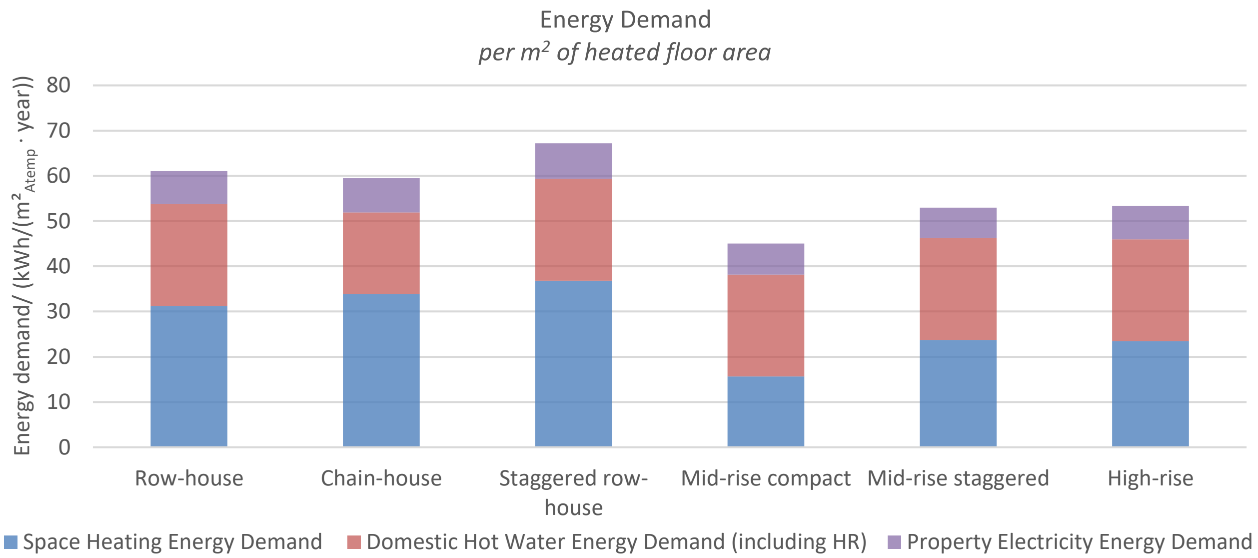


Figure 22: Energy demand of the buildings analysed in Sub-study 1

As seen in Figure 22, the space heating energy had substantial influence on the total energy demand of the building and was observed to be the highest for the “Staggered row-house”. The lowest value was established by the “Mid-rise compact” building. Similar performance was observed when looking at the results of “Mid-rise staggered” and “High-rise” building, with the value for the “High-rise” exceeding the “Mid-rise staggered” value by 0.31 kWh/(m^2_{Atemp}·year). The “Chain-house” space heating energy demand value settled between the “Row-house” and the “Staggered Row-house” values. The energy demand for domestic hot water was constant for all the building archetypes except the “Chain-house”, according to Sveby. The property electricity use was similar for all the buildings with notably lower values for the “Mid-rise compact” and “Mid-rise staggered” building.

When analysing Figure 23 it was observed that with the results expressed per m^2 of the residential space floor area, the “Staggered row-house” had the highest total energy demand whereas the lowest value was achieved by the “Mid-rise compact” building. The “Mid-rise staggered” and “Chain-house” performed similarly. The same observation could be made for the “Row-house” and the “High-rise”. The space heating energy demand was seen to be higher for the single-storey buildings compared to the multi-storey buildings. The trend was reversed in the case of domestic hot water energy demand. Similarly, the property electricity demand was higher for the multi-storey buildings than for the single-storey buildings.

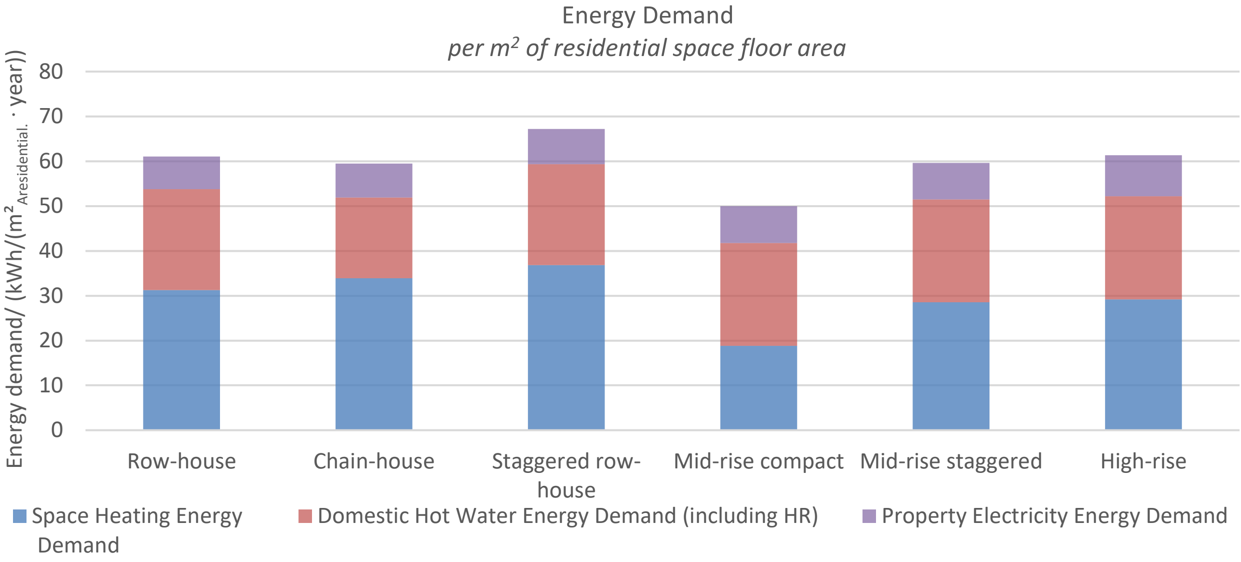


Figure 23: Energy demand of the buildings analysed in Sub-study 1

BBR verification

The U_{mean} values calculated for the buildings analysed in the *Sub-study 1* are presented in the Table 24. As seen in the , none of the values exceeds the maximum of 0.4 W/(m²K), established by the BBR.

Table 24: Calculated values of the U_{mean}

Building archetype	Row-house	Chain-house	Staggered row-house	Mid-rise compact	Mid-rise staggered	High-rise
Umean/ (W/(m²K))	0.19	0.18	0.19	0.23	0.24	0.22

The EPpet values calculated for all the buildings considered in the *Sub-study 1* are presented in the Figure 24. A dotted line was created in order to illustrate the value required by the BBR for multi-dwelling buildings

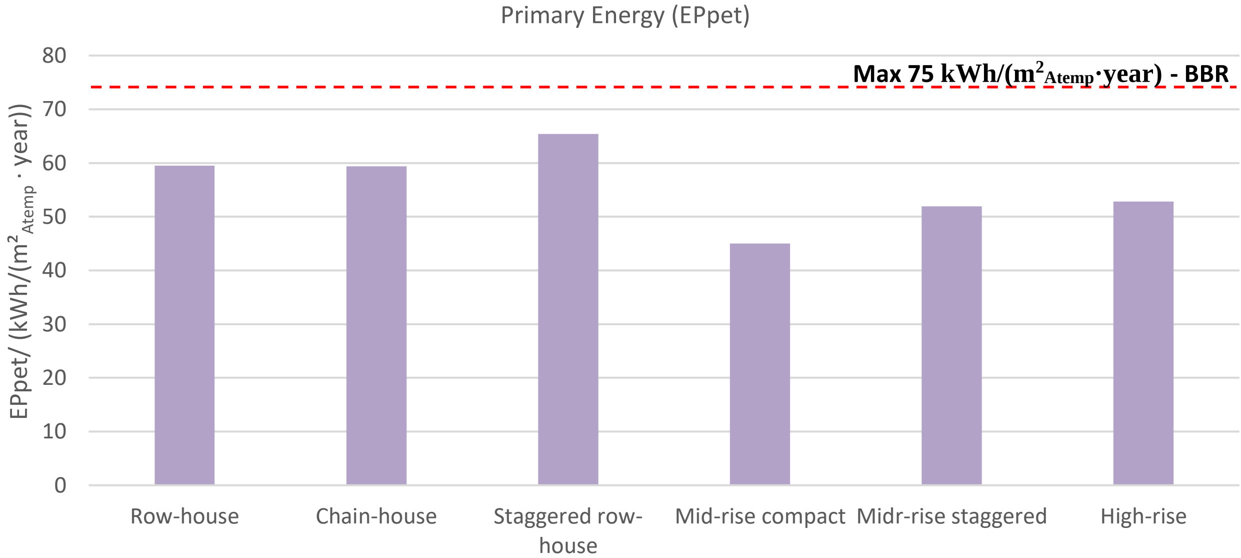


Figure 24: Verification of the primary energy results for the buildings analysed in Sub-study 1

When analysing the Figure 24 an observation could be made that the primary energy demand calculated for all the analysed buildings falls below the value of 75 kWh/(m^2_{Atemp}·year), required by the BBR. As seen in the Figure 24 the highest value of EPpet is represented by the “Staggered row-house”. The EPpet values of the “Row-house” and “Chain-house” are positioned similarly with the “Row-house” ranking slightly higher at 59.5 kWh/(m^2_{Atemp}·year) and the “Chain-house” at 59.4 kWh/(m^2_{Aemp}·year). The “Mid-rise compact” building achieved the lowest EPpet amongst the other buildings. The “Mid-rise staggered” and “High-rise” building were seen to perform similarly, with the EPpet value at 52.8 kWh/(m^2_{Atemp}·year) for the “High-rise” and 51.9 kWh/(m^2_{Atemp}·year) for the “Mid-rise staggered”.

Sub-study 2

The results of the energy demand for the “Scaled unit” and “Small unit” are presented in Figure 25. followed by the values of U_{mean} and EPpet calculated for each building considered in the *Sub-study 2.*

Energy demand

The energy demand results are considered only per m^2 of the heated floor area, as the residential space floor area is equal to the heated floor area for both analysed buildings.

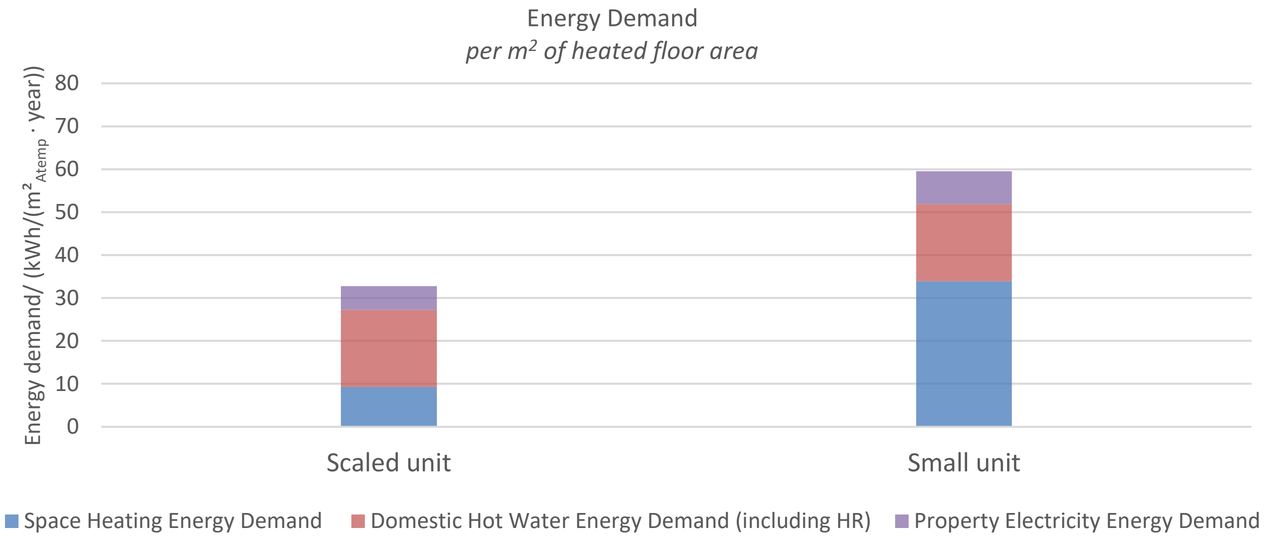


Figure 25: Energy demand of the buildings analysed in Sub-study 2

The space heating energy use displayed in the Figure 25 was observed to be significantly lower for the “Scaled unit” than for the “Small unit”. The domestic hot water energy demand amounted to the same value for both buildings, according to Sveby. The property electricity demand was seen to be lower for the “Scaled unit” with the difference of 2.16 kWh/(m^2_{Atemp}·year) between the two buildings.

BBR verification

The U_{mean} values calculated for the buildings analysed in the *Sub-study 2* are presented in the Table 25.
As seen in the Table 25, none of the values exceeds the maximum of 0.4 W/(m^{2}K), established by the BBR.

Table 25: Calculated values of the U_{mean}

Building archetype	Small unit	Scaled unit
Umean/ (W/(m^{2}K))	0.18	0.19

The EPpet values calculated for all the buildings considered in the *Sub-study 2* are presented in the Figure 26. A dotted line was created in order to illustrate the value required by the BBR for single-dwelling buildings with the heated floor area exceeding 130 m^2.

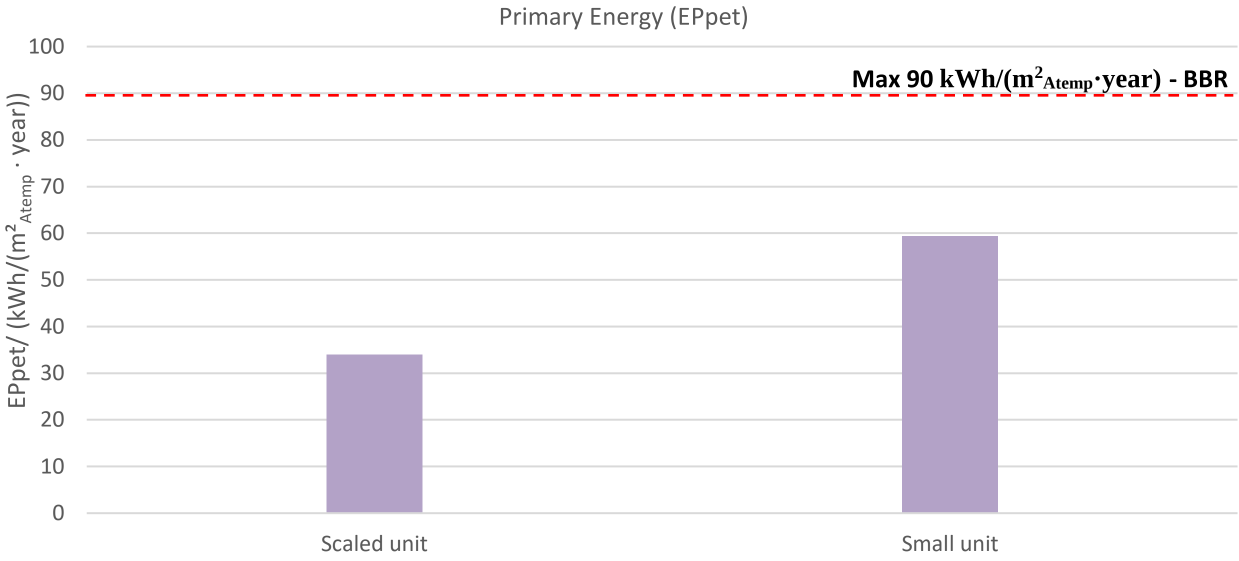


Figure 26: Verification of the primary energy results for the buildings analysed in Sub-Study 2

When assessing the Figure 26, it was observed that the primary energy demand calculated for both analysed buildings drop below the value of 90 kWh/(m^2_{Atemp}·year), required by the BBR. The value obtained for the "Scaled unit" was significantly lower than for the "Small unit", ranking at about 34 kWh/(m^2_{Atemp}·year). The value for the "Small unit" was equal to 59.4 kWh/(m^2_{Atemp}·year).

3.1.3 LCA Calculations

The values of GWP obtained from the calculations for the analysed buildings are presented below. Performance of the buildings is displayed separately for the *Sub-study 1* and *Sub-study 2.*

Sub-study 1

The carbon footprint of the "Row-house", "Chain-house", "Staggered row-house", "Mid-rise compact", "Mid-rise staggered" and "High-rise" building is shown separately in selected life cycle stages and per category. The analysis of volume of materials and associated emissions is presented as rearmost.

GWP in the life-cycle stages

The environmental impact of the buildings, calculated in life cycle stages is presented in the Figure 27 and Figure 28, with the results expressed per m^2 of the heated floor area and per m^2 of the residential space floor area respectively.

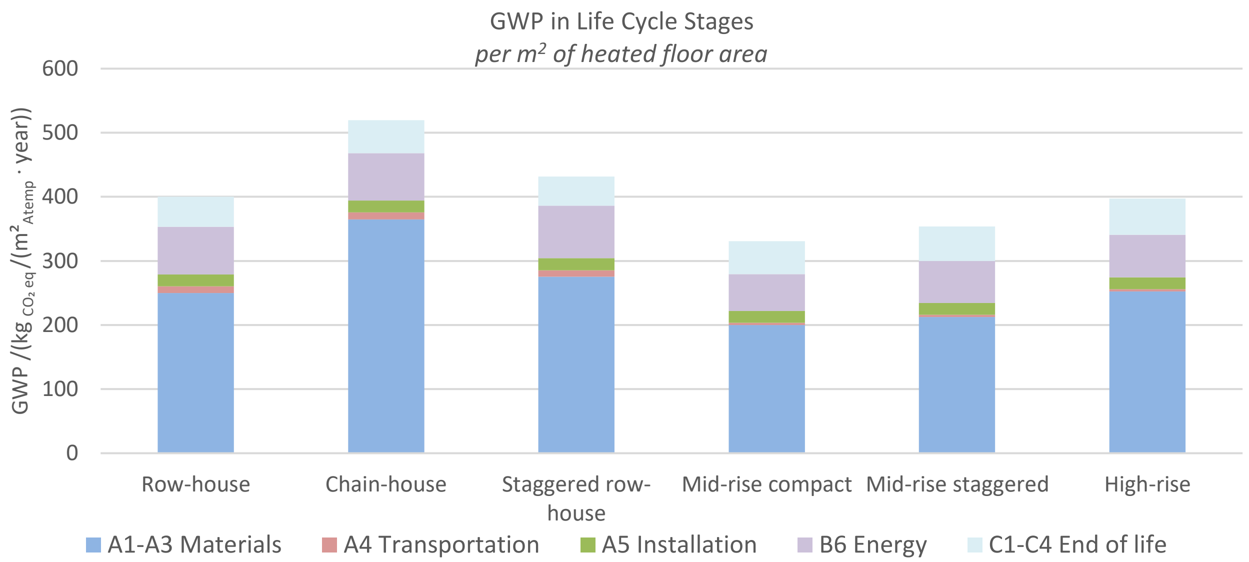


Figure 27: Total GWP assessed through life-cycle stages for the buildings analysed in Sub-study 1

When evaluating the Figure 27 it was observed that the impact from the A1-A3 stages amounts to about 80% of the total carbon emissions and ranks the highest for the “Chain-house”. The lowest value was established by the “Mid-rise staggered” building. The emissions in the B6 stage were seen to be lower for the multi-storey buildings than for the single-storey buildings, with the lowest amount yielded by the “Mid-rise compact” building. Impact in the end of life, i.e., C1-C4, stages, was observed to slightly vary between different buildings, with the lowest value for the “Staggered row-house” and the highest for the “High-rise” building. Emissions from transportation stage were seen to be the highest for the “Chain-house” and the lowest for the “High-rise” building. The “Row-house” and “Staggered row-house” emissions for that stage amounted to fairly similar values. Emissions from installation stage remained constant for all analysed buildings. When comparing the total emissions, it was noted that the value obtained for the “Row-house” was slightly higher than the one obtained for the “High-rise” building with a difference of 3.2 kg $_{CO_2\,eq}$ /m$^2_{Atemp}$.

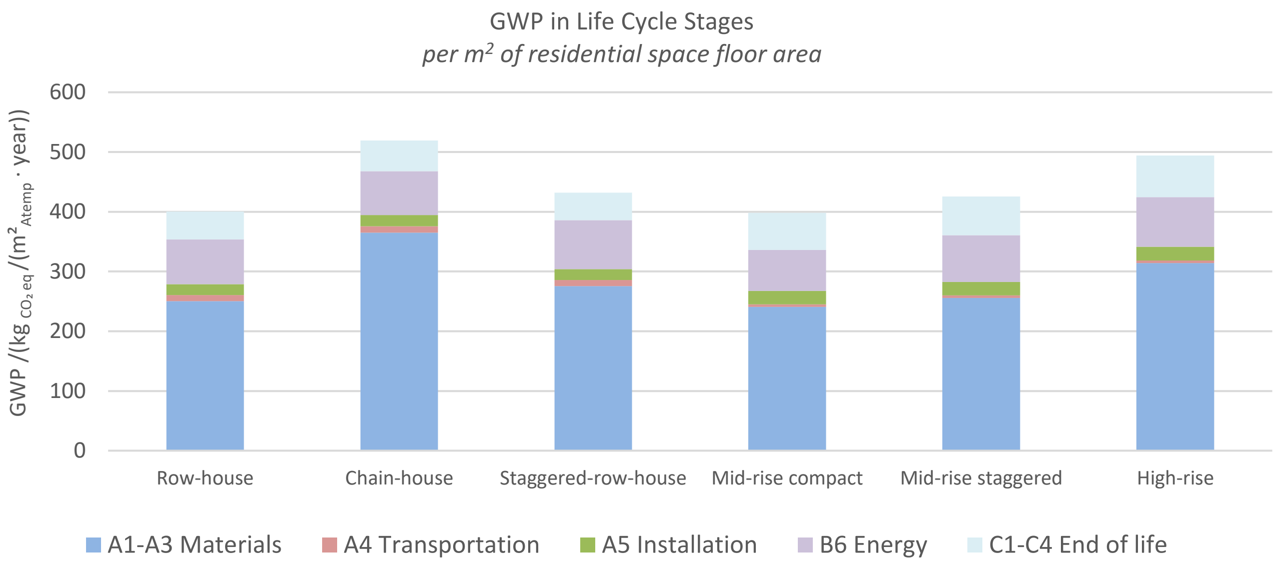


Figure 28: Total GWP assessed through life-cycle stages for the buildings analysed in Sub-study 1

When assessing the Figure 28 it was observed that the highest total emissions were produced for the “Chain-house”. On the other hand, the lowest carbon footprint was observed for the “Mid-rise compact” building, outperforming the “Row-house” by a relatively low value of 2.5 kg $_{CO_2\,eq}$ /m$^2_{Aresidential}$. The “Mid-rise staggered” building was seen to perform similarly to the “Staggered row-house”, with a difference of 1.2 kg $_{CO_2\,eq}$ /m$^2_{Aresidential}$, and the higher value assigned to the “Staggered row-house”. It was observed that the second highest footprint was attributed to the “High-rise” building. When analysing the results, it could be noted that the biggest impact on the overall emissions was allocated in the stages A1-A3, followed by B6 stage and lastly stages C1-C4. The A4 and A5 stages accounted for the lowest carbon footprint amongst the considered stages.

GWP per category

The carbon footprint associated with different categories is presented in the Figure 29, with the results expressed per m^2 of the heated floor area.

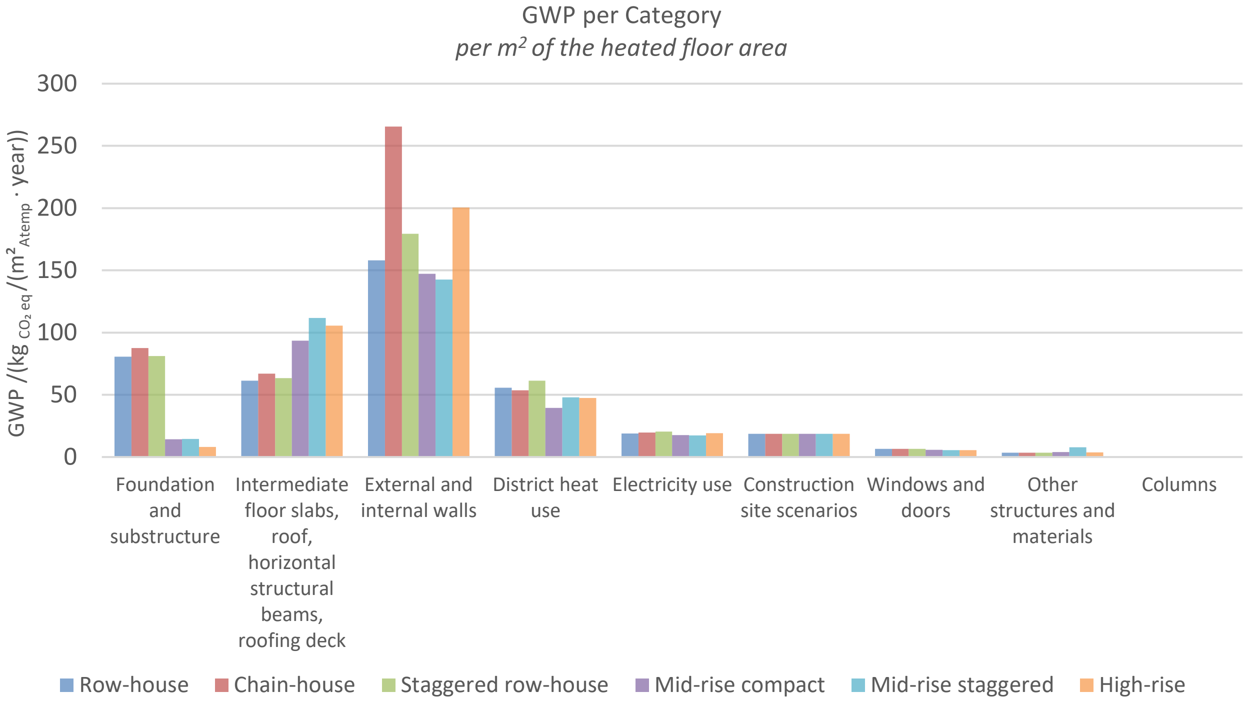


Figure 29: The GWP calculated per category for the buildings analysed in Sub-study 1

As seen in the Figure 29, the overall carbon footprint of the 'external and the internal' walls category was the highest compared to the other categories, with the highest value for the "Chain-house", and the lowest for the "Mid-rise staggered" building, with only slightly higher value for the "Mid-rise compact".

On the other hand, the environmental impact of the 'intermediate floor slabs, roof, horizontal structural beams, roofing deck' category was the highest for the "Mid-rise staggered" building and the "Row-house" was seen to perform the best in that category, with similar results to the "Staggered row-house". The impact of 'foundation and substructure' category was notably higher for the single-storey buildings than for the multi-storey buildings with the "Chain-house" emissions highest amongst the single-storey buildings. The "Mid-rise staggered" building was seen to perform the worst in this category amongst the multi-storey buildings, with the results relatively similar to the "Mid-rise compact".

The district heating use category was seen to have the highest environmental impact in case of the "Staggered row-house" and the lowest value was established by the "Mid-rise compact" building. The environmental impact associated with the remaining categories was similar for all analysed buildings.

The carbon footprint of the 'columns' category was the lowest compared to the impact of other categories. Said category was invisible in the figure Figure 29 due to the scale of the graph, amounting to 0.15 kg $_{CO_2\,eq}$ /m$^2_{Atemp}$, for the "Chain-house", 0.06 kg $_{CO_2\,eq}$ /m$^2_{Atemp}$ for the "Row-house", 0.08 kg $_{CO_2\,eq}$ /m$^2_{Atemp}$ for the "Staggered row-house", 0.53 kg $_{CO_2\,eq}$ /m$^2_{Atemp}$ for the "High-rise", 0.31 kg $_{CO_2\,eq}$ /m$^2_{Atemp}$ for the "Mid-rise compact", 0.36 kg $_{CO_2\,eq}$ /m$^2_{Atemp}$ for the "Mid-rise staggered" building.

Volume of materials and GWP

The analysis joining the volumes of materials used in the building elements with their carbon emissions is displayed in Figure 30.The results are expressed per m^2 of the heated floor area.

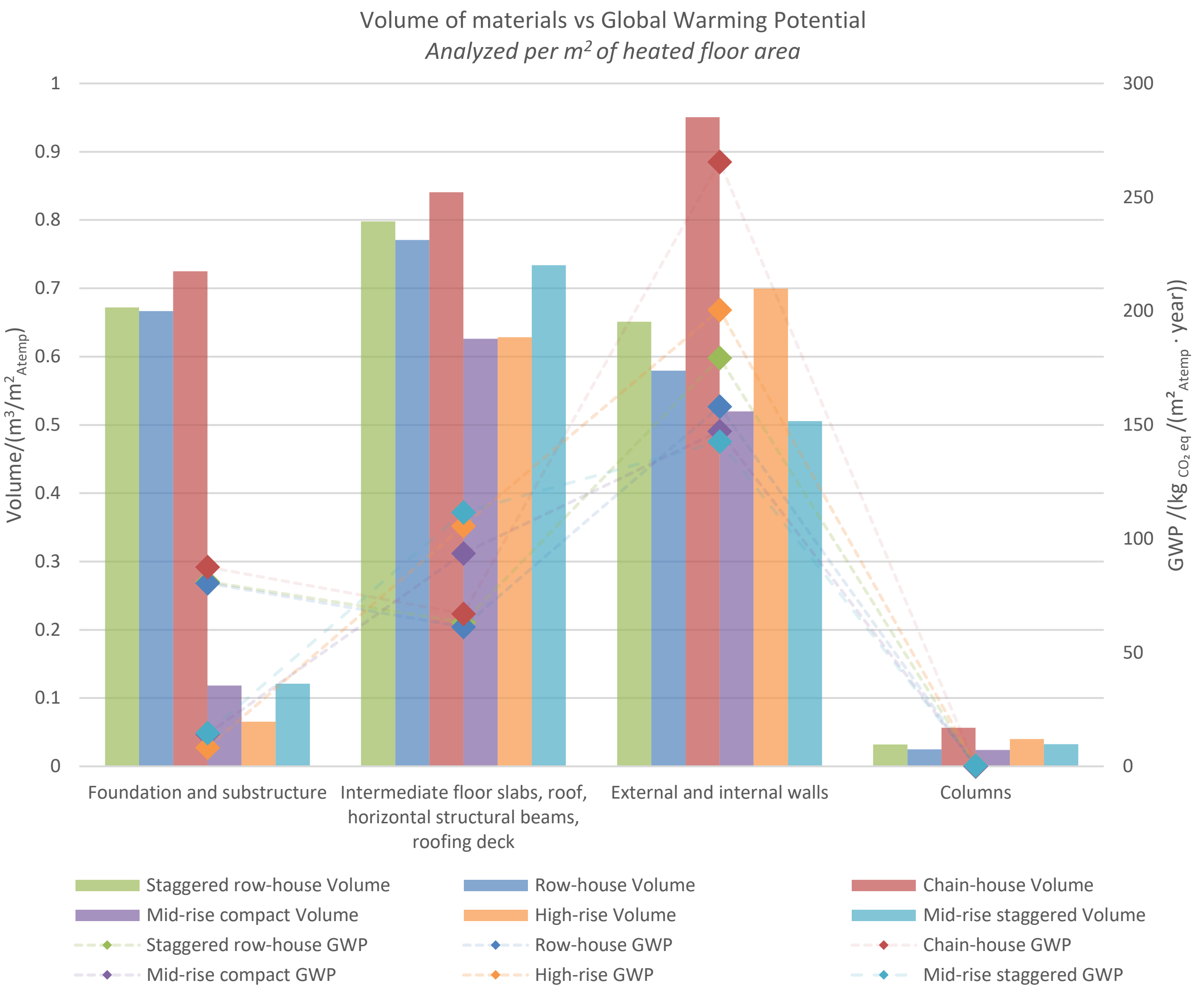


Figure 30: Volumes of materials in chosen categories in respect to the GWP, for the buildings analysed in Sub-study 1

When analysing the Figure 30, it was observed that the "Chain-house" accounted for the highest volumes of materials in all examined categories. However, the emissions associated with the "Chain-house" were observed to be the highest only in case of the 'foundation and substructure' and 'external and internal walls' categories.

It was noted that the volumes of materials accumulated for the single-storey buildings much exceeded the amount needed for the multi-storey buildings, in the category of 'foundation and substructure', with the lowest value established for the "High-rise" building. The same trend was observed for the GWP.

When assessing the results in the 'intermediate floor slabs, roof, horizontal structural beams, roofing deck' category, it could be noted that the "Mid-rise compact" and "High-rise" building accumulated nearly the same amount of materials, however the GWP was higher for the "High-rise" building. The highest GWP in that category was assigned to the "Mid-rise staggered" building, followed by the "High-rise" and "Mid-rise compact" building. The GWP of single-storey buildings was observed to be significantly lower than of the multi-storey buildings in said category.

When analysing the volume of 'external and the internal walls' category, the "Mid-rise staggered" building ranked the lowest amongst all compared buildings with a slightly higher value obtained for the "Mid-rise compact". The "High-rise" building was observed to yield the second highest value, following the "Chain-house". The same order was established when assessing the values of GWP.

As the volume and GWP of the 'columns' category was difficult to analyse for different buildings, when looking at the Figure 30 due to the scale of the graph, a separate assessment was done and presented in the Figure 31.

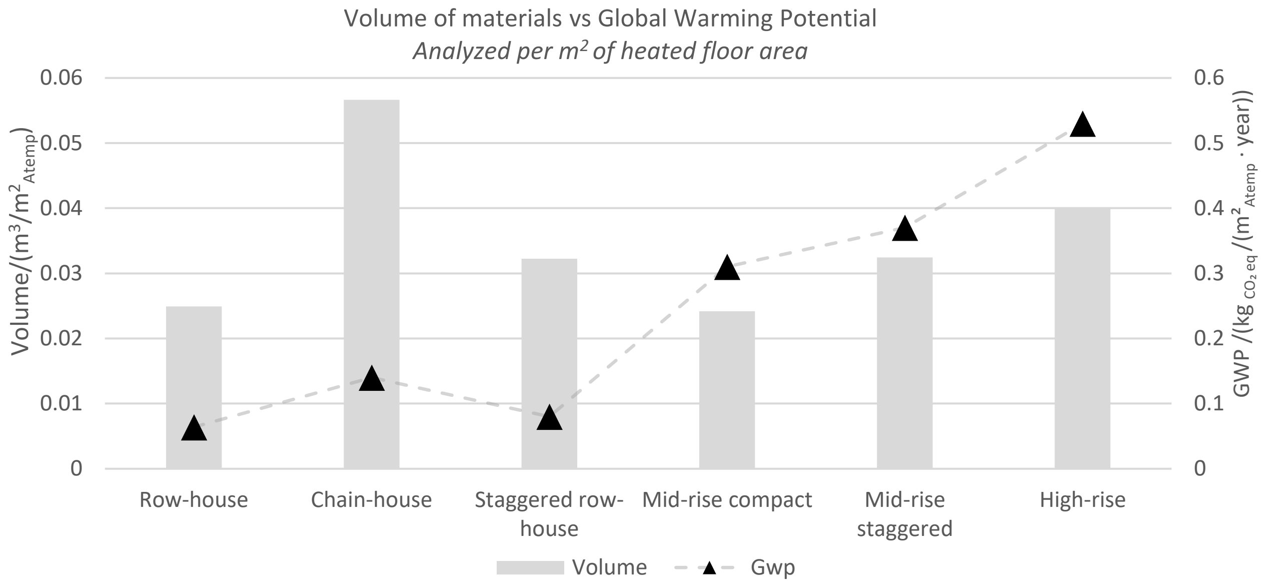


Figure 31: Volumes of materials in columns in respect to the GWP, for the buildings analysed in Sub-study 1

When analysing the Figure 31, it could be observed that the "Chain-house" building accumulated the highest volume of materials, whereas the lowest value was established by the "Mid-rise compact" building. When assessing the emissions, the highest value was noted for the "High-rise" and the lowest - for the "Row-house" building. The GWP was observed to be significantly higher for the multi-storey buildings than for the single-storey buildings.

Sub-study 2

The carbon footprint of the "Scaled unit" and "Small unit" is presented separately in selected life cycle stages, displayed in Figure 32, and per category, shown in Figure 33.

Environmental impact in the life-cycle stages

The environmental impact calculated in life cycle stages is presented in the Figure 32, with the results expressed per m^2 of the heated floor area.

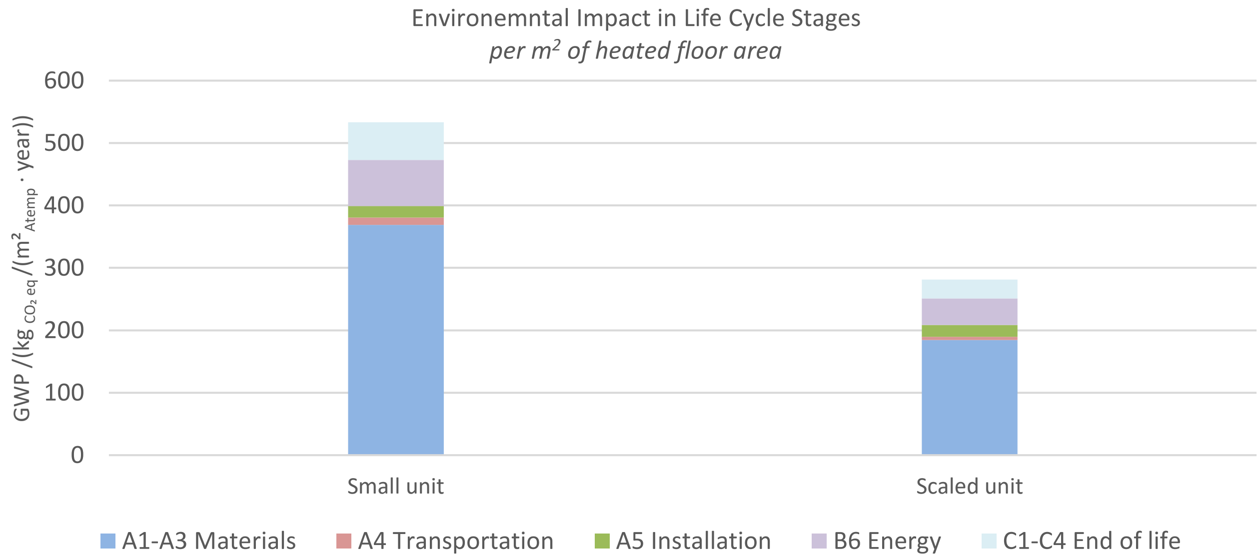


Figure 32: Total GWP assessed through life-cycle stages for the buildings analysed in Sub-study 2

While examining the Figure 32, it was noted that the highest emissions occur in the A1-A3 stages. The environmental impact per m^2 of the heated floor area of the "Small unit" was seen to exceed the impact of the

"Scaled unit" almost twice in the A1-A3, A4, B6 and C1-C4 stages. The emissions occurring in the installation stage were constant for both buildings.

GWP per category

The carbon footprint associated with different categories is presented in the Figure 33, with the results expressed per m^2 of the heated floor area.

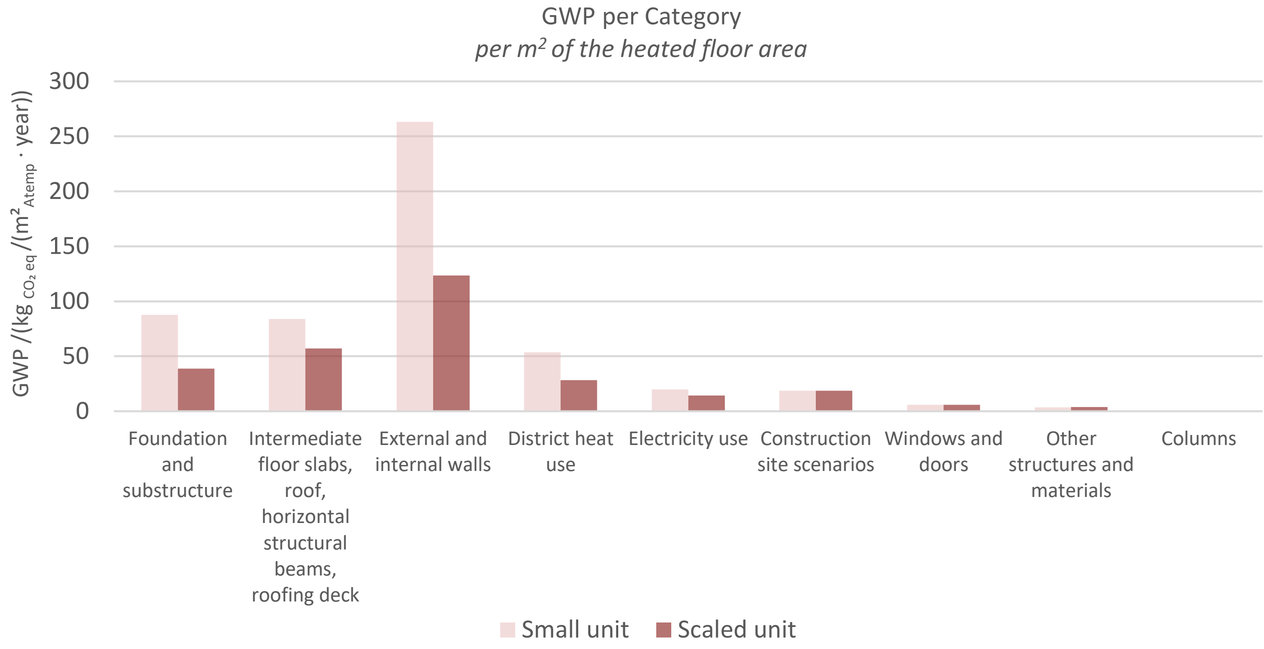


Figure 33: The GWP calculated per category for the buildings analysed in Sub-study 2

When analysing the Figure 33, it could be noted that the carbon footprint of all examined elements per m^2 of the building's heated floor area was lower for the "Scaled unit" building than for the "Small unit" building. The biggest difference between the buildings' performance was observed in the environmental impact of the 'external and internal walls' category. Emissions related to the 'foundation and substructure' category were also significantly higher for the "Small unit".

The impact of the district heating use for the "Small unit" was observed to be almost twice as high as for the "Scale unit". The carbon footprint of the 'intermediate floor slabs, roof, horizontal structural beams, roofing deck' category for the "Scaled unit" yielded about 70% of the "Scaled unit" value. The same trend was observed for the electricity use. The impact of the remaining elements was observed to be nearly the same for the "Small unit" as for the "Scaled unit" building.

The carbon footprint of 'columns' category was the lowest amongst all categories and amounted to 0.14 kg $_{CO_2\,eq}$ /m^2_{Atemp}, for the "Small unit" and 0.6 kg $_{CO_2\,eq}$ /m^2_{Atemp} for the "Scaled unit".

Volume of materials and GWP

The analysis joining the volumes of materials used in the building elements with their carbon emissions is displayed in Figure 34. The results are expressed per m^2 of the heated floor area.

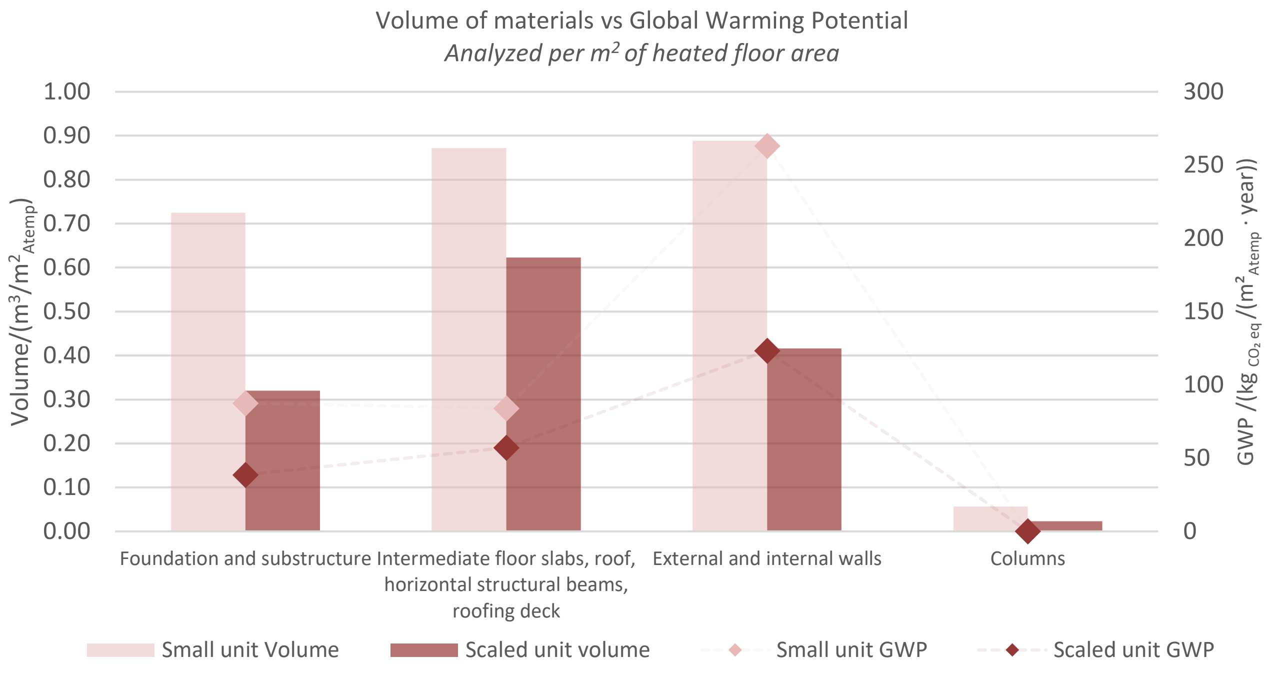


Figure 34: Volumes of materials in chosen categories in respect to the GWP, for the buildings analysed in Sub-study 2

As seen in the Figure 34, the volume of materials used for the "Scaled unit" was almost half of the amount used for the "Small unit" in the categories 'foundation and sub-structure' and 'external and internal walls', when analysing the results per m^2 of heated floor area. The same relationship was observed in the 'columns' category. The difference between the buildings was smaller in the 'intermediate floor slabs, roof, horizontal structural beams, roofing deck' category, however the trend remained the same for all categories. A similar tendency was observed when assessing the GWP in all the categories. The highest GWP, and the biggest difference in the values for the two analysed buildings was seen in the 'external and internal walls' category.

3.2 Case Study – Rogaland building by Arkitema

The results of energy simulations and LCA calculations from the *Case Study* of a building developed by Arkitema company, are presented in sub-sections 3.2.1 - 3.2.2.

3.2.1 Energy demand calculations

The values of energy demand obtained from the simulations for the analysed building are presented below. Performance of the building was assessed separately for the apartment blocks and the basement, with the values expressed per m^2 of the total building heated floor area in the Figure 35 and per m^2 of residential space floor area in the Figure 36. The performance of the apartment blocks and the basement was distinguished as the design and assumptions regarding both varied significantly.

Energy Demand

As seen in the Figure 35, the energy demand for space heating of the basement was almost twice as high as the space heating demand of the apartment blocks. However, when comparing the domestic hot water energy demand, it was noted that the value obtained for the apartment blocks was much higher, elevating the total value of the energy demand above the value established for the basement. The values of property electricity demand were relatively similar amounting to 0.94 and 1.12 kWh/(m^2_{Atemp}·year) for the apartment blocks and the basement respectively.

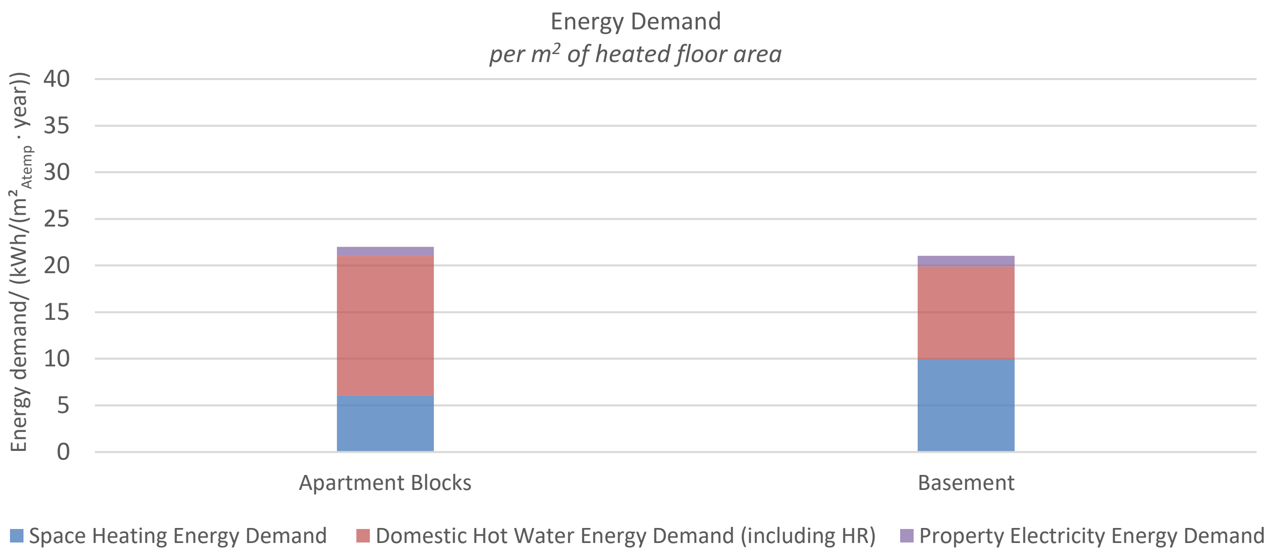


Figure 35: Energy demand for the apartment blocks and the basement in the Rogaland building

When analysing the Figure 36, it could be observed that the total energy demand of the apartment blocks is higher than of the basement however the space heating demand remains lower for the apartment blocks. The value of the domestic hot water was seen to be significantly higher for the apartment blocks however the value of the property electricity demand of the basement exceeds the value obtained for the apartment blocks by 0.3 $kWh/(m^2_{Atemp}\cdot year)$.

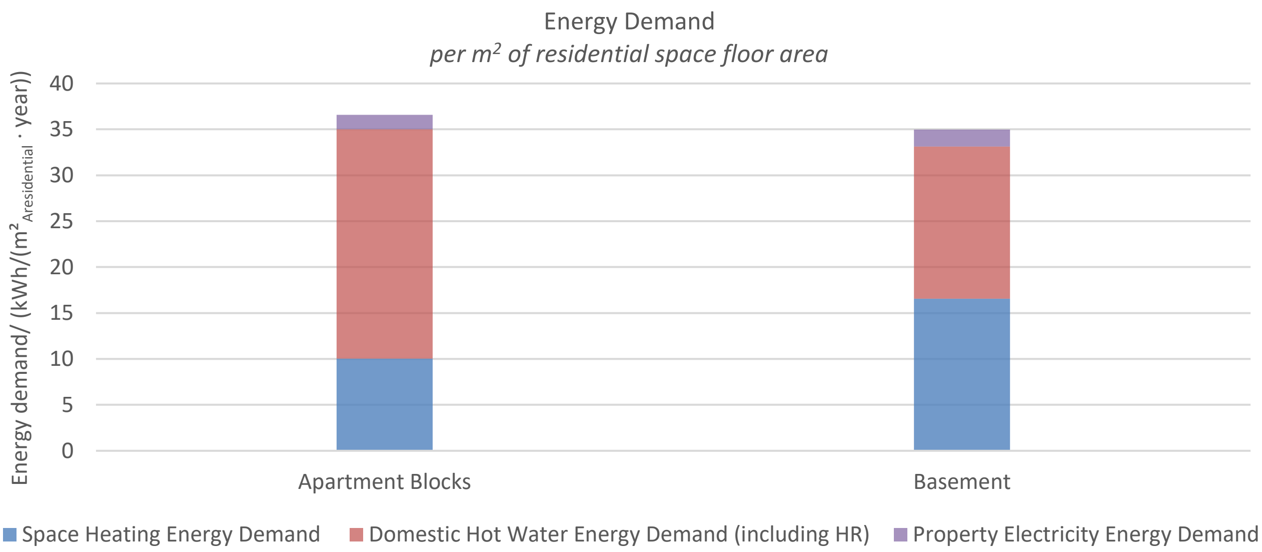


Figure 36: Energy demand for the apartment blocks and the basement in the Rogaland building

BBR verification

The primary energy value calculated for the evaluated building is presented in Table 26Table 26 along with the U_{mean} value of the building envelope. As seen in the Table 26, the calculated values are below the BBR's requirement of the EPpet = 75 $kWh/(m^2_{Atemp}\cdot year)$ and the U_{mean} = 0.4 $W/(m^2K)$.

Table 26: Primary energy result and U_{mean} value calculated for the Rogaland building

EP pet/ ($kWh/(m^2_{Atemp}\cdot year)$)	Umean/ ($W/(m^2K)$)
41.46	0.31

3.2.2 LCA calculations

The environmental impact of the building analysed in the *Case Study* is presented separately according to the life cycle stages and per category. The volumes of materials used and their GWP are displayed at the end. The values are presented separately for the apartment blocks and the basement in relation to the total building heated floor area.

Environmental impact in the life-cycle stages

The environmental impact calculated in life cycle stages is presented in the Figure 37 and Figure 38, with the results expressed per m^2 of the heated floor area and per m^2 of the residential space floor area respectively.

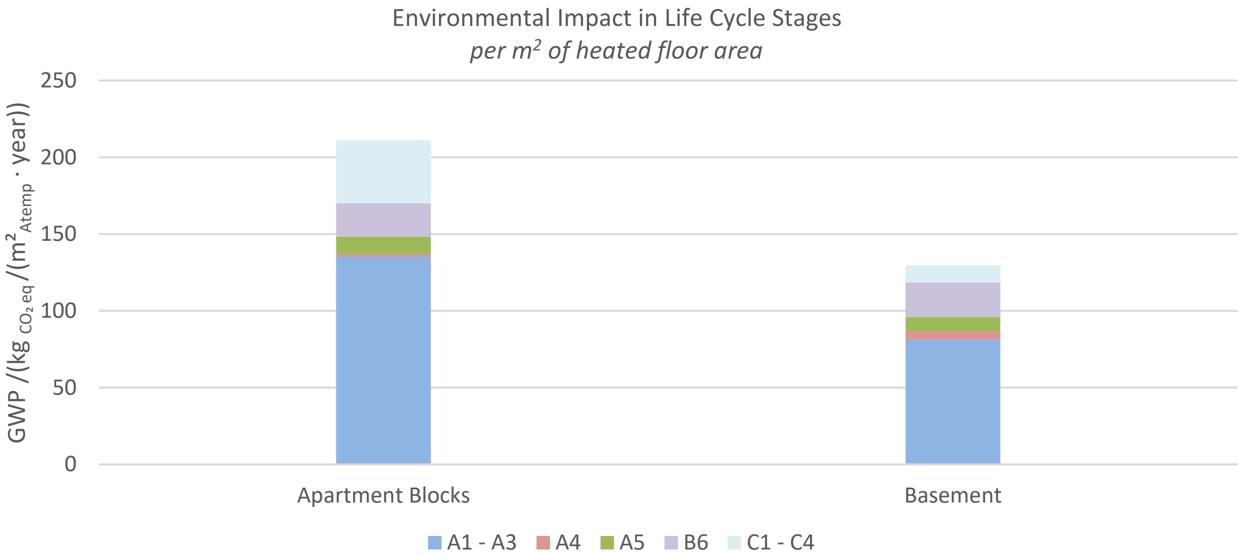


Figure 37: Total GWP assessed through the life-cycle stages for the Rogaland building

When analysing Figure 37, the highest environmental impact was allocated to the A1-A3 stages for both the apartment blocks and the basement. The emissions in the A4 stage were the lowest for the apartment blocks as well as the basement and amounted to 1.8 kg $_{CO_2\ eq}$ /m$^2_{Atemp}$ and 5.38 kg $_{CO_2\ eq}$ /m$^2_{Atemp}$ respectively. The impact allocated to the stage A5 was relatively similar for both analysed spaces. A corresponding relationship was observed when looking at the B6 stage, whereas in the stages C1-C4 the carbon footprint of the apartment blocks was nearly four times as high as the carbon footprint of the basement

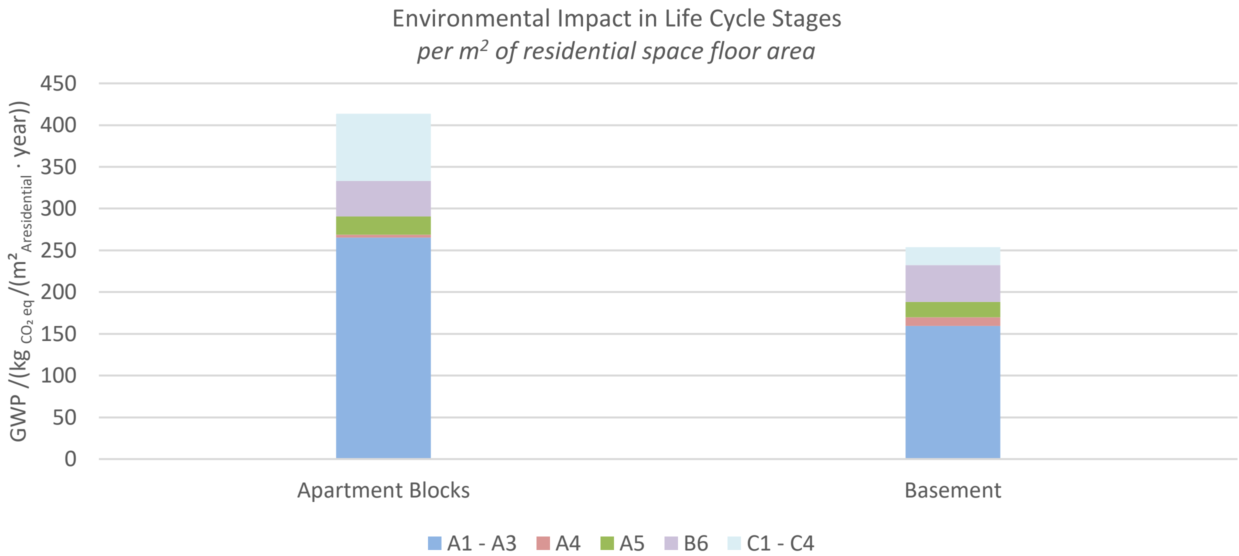


Figure 38: Total GWP assessed through the life-cycle stages for the Rogaland building

When analysing the Figure 38, the highest impact of the A1-A3 stages was observed for both analysed spaces, followed by the C1-C4, B6 and A5 stage. The carbon footprint of the apartment blocks was exceeding the impact of the basement in most of the considered life cycle stages, except for the B6 and A4 stage where the basement accounted for the higher GWP amongst the two spaces.

GWP per category

The carbon footprint associated with different categories is presented in the Figure 39, with the results expressed per m^2 of the heated floor area.

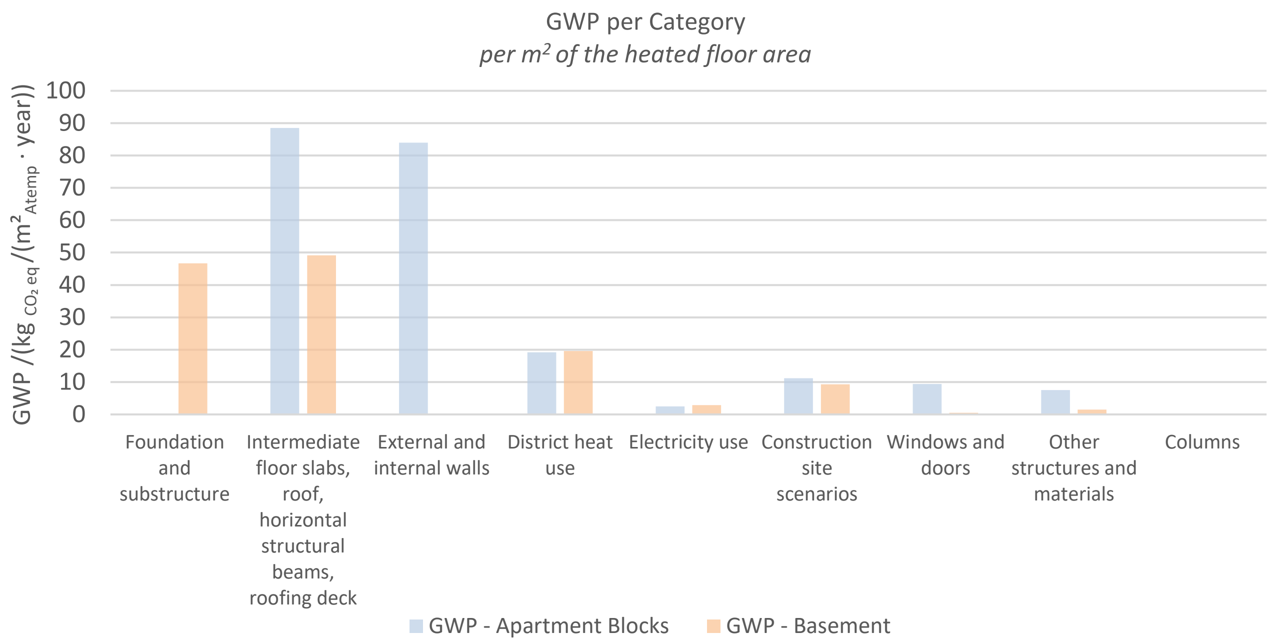


Figure 39: The GWP calculated per category for the Rogaland building

When analysing the Figure 39, it could be observed that the highest environmental impact, in case of the both analysed spaces, is assigned to the 'intermediate floor slabs, roof, horizontal structural beams, roofing deck' category, where the GWP of the basement amounted to more than a half of the GWP value obtained for the apartments.

Impact of the 'foundation and sub-structure' category was considered only for the basement and was seen to be slightly lower than the impact of the 'intermediate floor slabs, roof, horizontal structural beams, roofing deck' category for the same space.

The 'external and internal walls' category impact was considered only for the apartments and the value ranked the second highest amongst the carbon footprint of all the categories analysed for that space. The impact of the district heat use and electricity use yielded similar values of GWP for both of the spaces. Windows and doors as well as other structures were observed to have significantly lower environmental impact for the basement than for the apartments, whereas for the construction site scenarios, the GWP of the basement was considered slightly lower.

The GWP of the 'columns' category, not visible in the Figure 39 due to the scale of the graph, amounted to 0.03 kg $_{CO_2\,eq}$ /m^2_{Atemp} and 0.16 kg $_{CO_2\,eq}$ /m^2_{Atemp} for the apartment blocks and the basement respectively.

Volume of materials and GWP

The analysis joining the volumes of materials used in the building elements with their carbon emissions is displayed in Figure 40. The results are expressed per m² of the heated floor area.

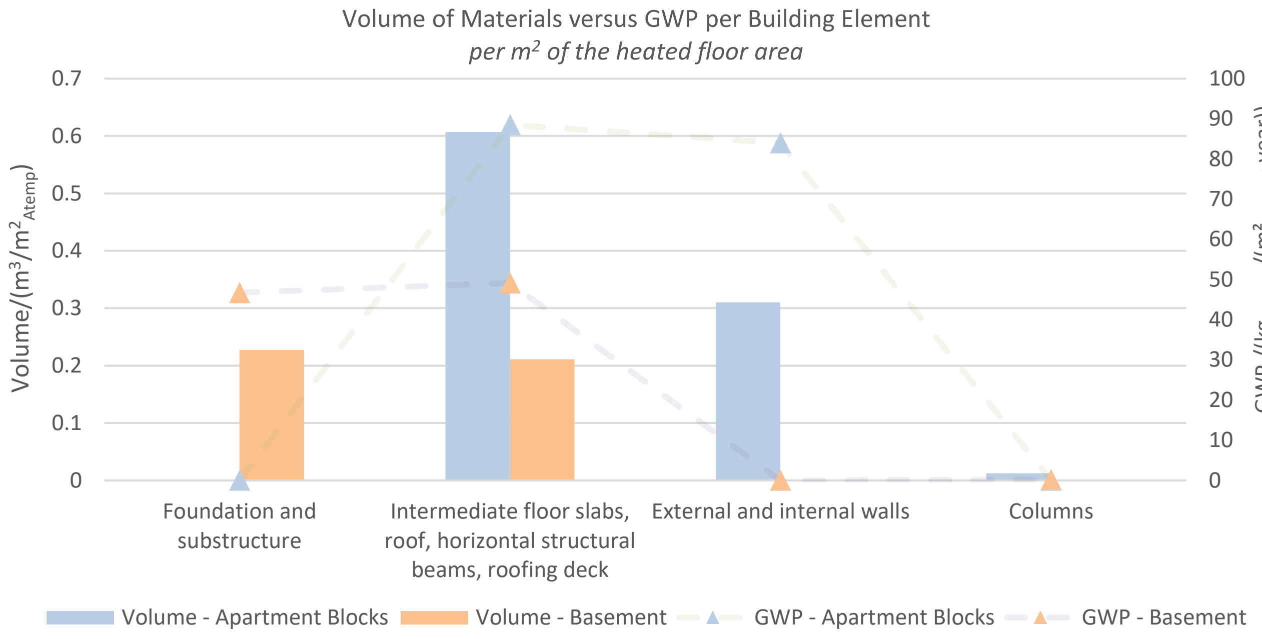


Figure 40: Volumes of materials in chosen categories in respect to the GWP, for the Rogaland building

As seen in the Figure 40, the volume of materials allocated in the ‘intermediate floor slabs, roof, horizontal structural beams, roofing deck’ category was notably lower for the basement than for the apartments. The volume of materials accounted for in the ‘foundation and sub-structure’ category of the basement was seen to slightly exceed the value obtained for the ‘intermediate floor slabs, roof, horizontal structural beams, roofing deck’ category in the same space. The columns considered in the apartment blocks had a significantly lower volume compared to the other building elements, included in the analysis. The columns were accounted for in the foundation included in the basement, however their volume was negligible, amounting to 0.00075 m^3/m^2_{Atemp}.

When analysing the GWP it could be observed that the emissions associated with the ‘intermediate floor slabs, roof, horizontal structural beams, roofing deck’ category are significantly higher for the apartment blocks than for the basement. The trend was observed to remain the same as for the materials volume, however the values of GWP are not proportional to the volume values. The GWP calculated for the apartment blocks was seen to be similar in the category accounting for the intermediate slabs and roof as in the ‘external and internal walls’ category, however the volume of materials differed significantly between categories.

4 Analysis

The analysis of the results was first carried out for the *Shoebox Study* where the results of energy demand and environmental impact of the considered buildings was compared in relation to the form defining properties. The results were assessed per m^2 of the heated floor area. Additionally, the relationship between the volume of materials used and their GWP per m^2 of the heated floor area was examined for each building. The analysis was performed sequentially for the *Sub-study 1* and *Sub-study 2.*

Based on the results obtained from the *Sub-study 1* and the corresponding form-defining properties, an attempt was made to predict the performance of the *Case Study* - Rogaland building. Subsequently the actual energy demand and GWP of the Rogaland building was simulated and the results compared against the prediction in order to verify the accuracy of the predicted values. Moreover, the relationship between the volume of materials and their GWP per m^2 of the heated floor area was analysed.

Ultimately the simulated performance of the Rogaland building was compared to the performance of the other buildings considered in the *Sub-study 1,* accounting for the correlation between the building's energy demand, the GWP, and the form-defining properties. The results were assessed separately per m^2 of the heated floor area and per m2 of the residential space floor area

4.1 Shoebox Study

The analysis of the results obtained in the *Shoebox Study was* carried out by first assessing the relationship of the building form, energy demand and GWP, presented in the subsection 4.1.1. Subsequently an analysis of materials volume in building elements with their GWP was performed and described in subsection 4.1.2.

4.1.1 Assessment of the relationship of the building form, energy demand and GWP

The assessment of the relationship between the building form, the energy demand and GWP was performed separately based on the results obtained in the *Sub-study 1*and *Sub-study 2.*

Sub-study 1

In the Figure 41 the energy demand and environmental performance of the "Row-house", "Chain-house", "Staggered row-house", "Mid-rise compact", "Mid-rise staggered" and "High-rise" building were compared. The results are expressed per m^2 of the heated floor area.

A Table 27 with the form defining properties of each building form analysed in the *Sub-study 1* was shown in this section in order to allow forming a direct link between the results described in the graphs and factors displayed in the table.

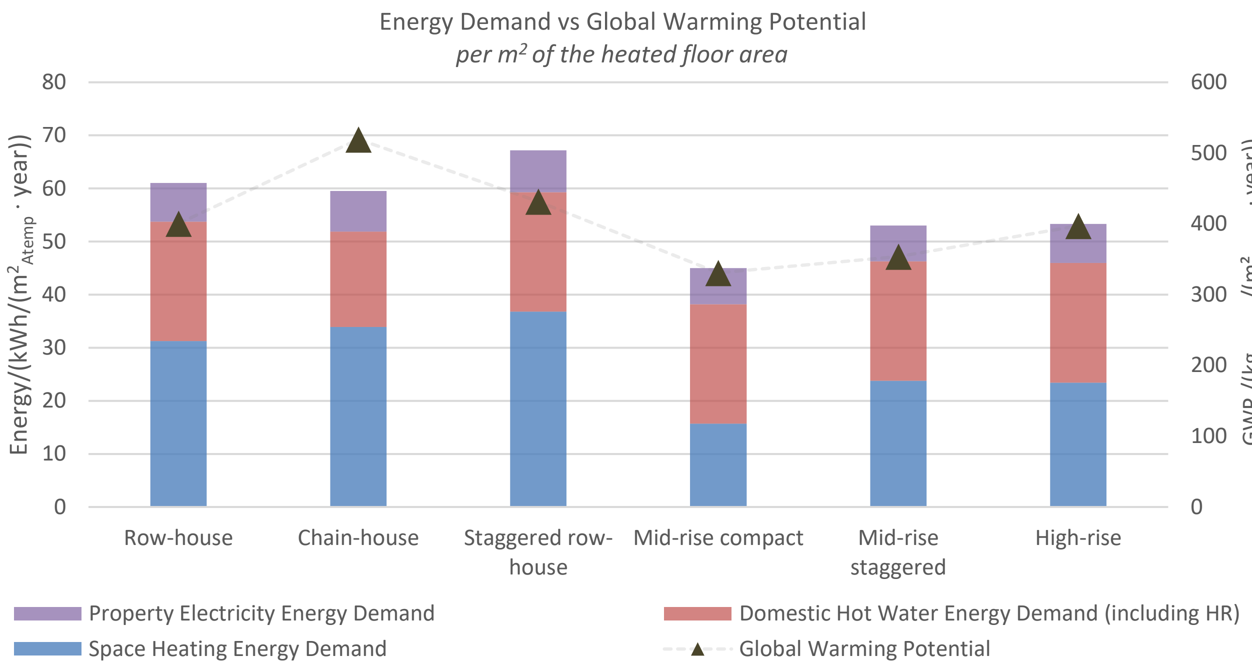


Figure 41: Comparison of the energy demand in respect to the total GWP for the buildings analysed in Sub-study 1

Table 27: Form-defining properties for the building analysed in Sub-study 1

Building form	Single-storey forms			Multi-storey forms		
	Row-house	Chain-house	Staggered row-house	Mid-rise Compact	Mid-rise staggered	High-rise
Form Factor A/V/ (1/m)	0.8	1.1	0.9	0.4	0.5	0.5
Heat-loss Form Factor	2.8	3.7	3.1	1.2	1.4	1.3

It can be seen on the Figure 41, that the “Mid-rise compact” building, with the lowest value of the form factor and heat-loss form factor, performed the best in terms of both, energy demand as well as environmental impact. The “Chain-house” building, with the highest form factor and heat-loss form factor, was observed to surpass the performance of the other single-storey buildings in terms of total energy demand however it deemed the worst when analysing the environmental impact. The lowest total energy demand of the “Chain-house” building occurred due to the significantly lower domestic hot water energy demand value for the single-dwelling houses, however the energy demand for space heating and property electricity exceeded the values obtained for the “Row-house”. The space heating energy demand and property electricity demand of the “Chain-house” was observed to be lower than of the “Staggered row-house”, which could be caused by the higher infiltration rate of the “Staggered row-house”. The significantly higher GWP of the “Chain-house”, compared to other buildings, can be explained by the highest area of external walls, which, as presented in the Figure 29, contribute to the highest carbon footprint amongst the other categories.

When comparing the “Row-house” with the “Staggered row-house” it could be noted that the higher energy demand was caused by the higher area of exposed envelope, leading to more heat losses. Accordingly, the values of form factor and heat-loss form factor for the “Staggered row-house” were higher than for the “Row-house”. The higher exposed envelope area with more insulation than in the internal walls contributed also to the higher GWP of the “Staggered row-house”. Another remark concerning the area of the exposed envelope could be made when comparing the “Mid-rise compact” and “Mid-rise staggered” buildings, where the exposed floor slabs in the “Mid-rise staggered form” consist of higher volume of structural elements, leading to higher GWP. Additional contributing factor in the higher environmental impact of the “Mid-rise staggered” building is a more complicated roof geometry, with a higher volume of materials as seen in Figure 30.

The “Mid-rise staggered” and “High-rise” buildings performed similarly in terms of the energy demand, however the environmental impact was notably higher for the “High-rise” building, attributed to the high impact of the external walls as seen in Figure 29, outweighing the building’s performance in other categories. It is worth mentioning here however, that the “High-rise” building had a slightly higher heated floor area than the “Mid-rise staggered” building, allowing to present more favourable results for the “High-rise” building, than if the total values were analysed. The trend observed for the results with generally lower energy demand and GWP for the multi-storey buildings is similarly associated with the higher heated floor area, accounted for in mid-rise and high-rise buildings, than in single-storey buildings. A general remark could be made the GWP is proportional to the form factor and heat-loss form factor values.

Sub-study 2

The comparison of the energy demand and environmental impact of the “Scaled unit” and “Small unit” buildings was presented in the Figure 42.

A Table 28 with the form defining properties of each building form analysed in the *Sub-study 2* was shown in this section in order to allow forming a direct link between the results described in the graphs and ratios displayed in the table.

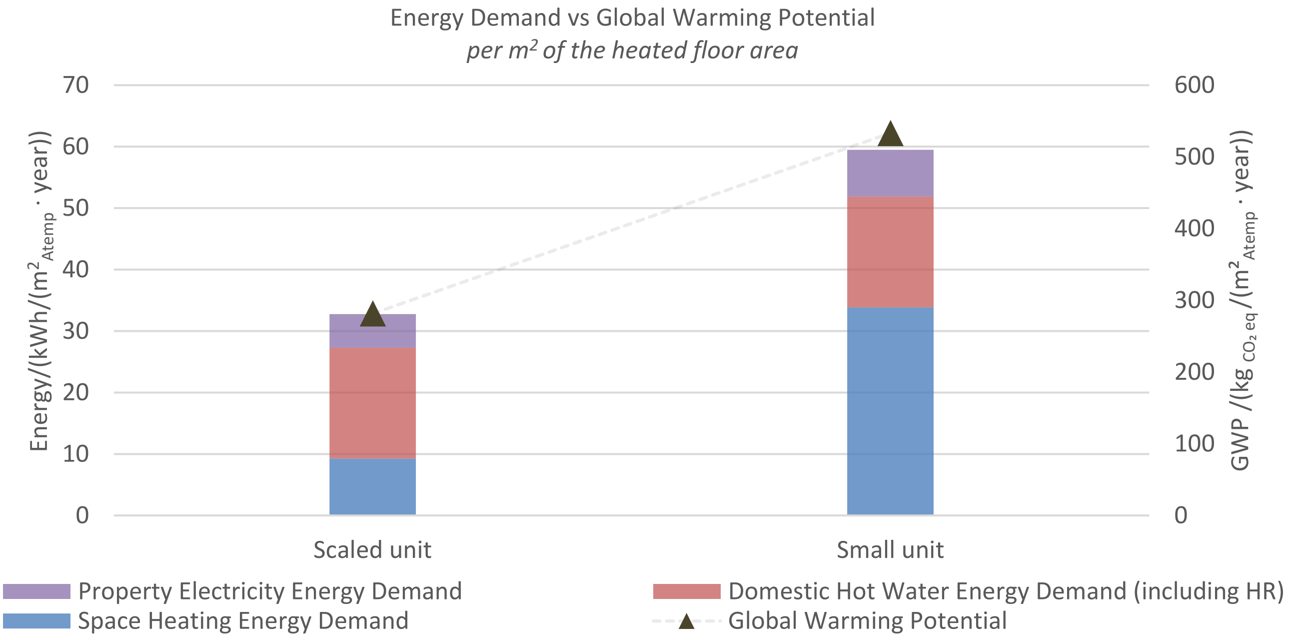


Figure 42: Comparison of the energy demand in respect to the total GWP for the buildings analysed in Sub-study 2

Table 28: Form-defining properties for the building analysed in Sub-study 2

Building form	Scaled unit	Small unit
Form Factor A/V /(1/m)	0.5	1.1
Heat-loss Form Factor	1.8	3.7

When analysing the results presented in the Figure 42, it could be noted that by increasing the scale of the model by a factor of 2, the energy demand as well as the environmental impact were halved. Such phenomenon could be explained by the fact that the heated floor area was significantly increased with the additional floor added to the “Scaled unit” building, allowing to distribute the total energy demand and carbon footprint over a larger area. Additionally, with the much lower value of the form factor and heat-loss form factor for the “Scaled unit”, a better performance of the building compared to the “Small unit” was expected

4.1.2 Volume of materials vs GWP

The relationship between the volume of materials used in the building elements was assessed together with the associated GWP, based on the results obtained in the *Sub-study 1*and *Sub-study 2,* and described further in this sub-section.

Sub-study 1

When analysing the Figure 30, presented in the sub-section 3.1.3 it could be observed that “Chain-house” consisted of the highest volume of materials in all examined categories, however there was no clear conclusion when analysing the lowest volumes of materials in each category. Similarly, a transparent trend for the GWP results could not be established, however it has been noted that the carbon footprint of the “Chain-house” in all categories deemed the highest amongst the single-storey buildings. The “Chain-house’s” peaking results were caused by the highest exposed envelope area contributing to the largest emissions due to the thick insulation layer.

When analysing the first category of building elements displayed in the Figure 30, i.e., the ‘foundation and sub-structure’ category, it could be noted that the volume of materials as well as their environmental impact deemed significantly higher for the multi-storey buildings compared to the single-storey buildings. The “Chain-house” ranked the highest in said category in both, material volume and GWP, due to its highest gross floor area, impacted by the thickness of the external walls. The lowest GWP as well as material volume of the ‘foundation and sub-structure’ category were established by the “High-rise” building due to the lowest footprint compared to other analysed buildings.

Looking at the second category displayed in the Figure 30, i.e. the ‘intermediate floor slabs, roof, horizontal structural beams, roofing deck’ category, it could be observed that the volume of materials per m^2 of heated floor area for the “Mid-rise compact” and “Highrise” building are relatively similar and amount to 0.626 and 0.628 m^3/m^2 respectively. However, when analysing the total volume it could be seen that the difference between the two buildings amounts to 25.5 m^3. An observation was made that such a contrast between the total results and the volume expressed per m^2 of the heated floor area was caused by a slightly larger service space and therefore greater ‘Atemp’ of the “High-rise” building. Due to the difference in the size of the service space, the GWP expressed per m^2 of the heated floor area too deemed higher for the “High-rise” building, caused by a larger amount of materials attributed to the intermediate floor slab.

It was observed that the lower impact of the insulation in the roof for the “High-rise” building (equal to 4.98 kg $_{CO_2\ eq}$ / (m^2_{Atemp}·year)) than for the “Mid-rise compact” building (equal to 9.50 kg $_{CO_2\ eq}$ / (m^2_{Atemp}·year)) did not make up for the high GWP value of the CLT structure present in the floor slabs, leaving the total carbon footprint of the “High-rise” building higher than the “Mid-rise compact” , equal to 30.56 kg $_{CO_2\ eq}$ / (m^2_{Atemp}·year) and 25.58 kg $_{CO_2\ eq}$ / (m^2_{Atemp}·year) respectively in the forementioned category. Additionally, it could be noted that in said category, the “Mid-rise staggered” building accounted for the highest volume of materials as well as the highest carbon emissions.

When comparing the results obtained for the single-storey buildings against the results of multi-storey buildings for the ‘intermediate floor slabs, roof, horizontal structural beams, roofing deck’ category, it was observed that the single-storey buildings generally consist of higher volumes of materials per m^2 of the heated floor area than the multi-storey buildings. The structural framing, i.e. the roof beams and trusses play a significant role in the total material volume, notably increasing the results. Inversely, the emissions of the multi-storey buildings were observed to be higher in said category due to the presence of intermediate floor slabs consisting of the CLT structure. For example, it was noted that the volume of the “Row-house” amounted to higher values than of the “Mid-rise staggered” building, when expressed per m^2 of heated floor area, however the emissions of the “Mid-rise staggered” building were significantly higher than of the “Row-house” due to the impact of the CLT structure in the floor slabs.

When analysing the results obtained for the third category displayed in the graph, i.e., ‘external and internal walls’ category, the volume of materials as well as the highest GWP was assigned to the “High-rise” building. The GWP exceeding the values of the “Mid-rise compact” and “Mid-rise staggered” building, were attributed to the higher amount of insulation found in the external walls. The walls of the “Mid-rise compact” building appeared to consist of slightly higher material volume than the “Mid-rise staggered” building, due to the higher volume of the internal walls of the “Mid-rise compact” building, equal to to 0.16 m^3/m^2_{Atemp} and 0.14 m^3/m^2_{Atemp} respectively ,with practically the same volume of the external walls. Moreover, it was noticed that the higher GWP of the “Mid-rise compact”, compared to the “Mid-rise staggered” building, in the forementioned category, was caused by the CLT structure found in the internal walls, and equal to 29.94 kg $_{CO_2\ eq}$ / (m^2_{Atemp}·year) for the “Mid-rise compact” and 26.99 kg $_{CO_2\ eq}$ / (m^2_{Atemp}·year) for the “Mid-rise staggered” building. Analysing the results obtained for the single-storey buildings allowed to form an observation that the "Row-house" building accounted for the lowest volume of materials as well as the lowest GWP, due to its lowest area of external walls compared to the "Chain-house" and "Staggered row-house".

A separate analysis was conducted, focusing on the volume and GWP of the columns in considered buildings. The results of the analysis are presented in the Figure 31 in the sub-section 3.2.2.

When analysing the volume and GWP for the single-storey and multi-storey buildings separately, a proportional relationship of the materials' volume and GWP of the columns in different buildings could be observed. However, while assessing all the buildings together, it could be noted that the GWP calculated for the multi-storey buildings much exceeds the values obtained for the single-storey buildings, with relatively similar volumes of materials. The higher impact observed for the multi-storey buildings was caused by the concrete columns, present in the foundation of the multi-storey buildings. The impact of the columns in the "High-rise" building was seen to be the highest amongst all the analysed buildings, due to the largest concrete columns included in the foundation of the 'High-rise" building.

Sub-study 2

When analysing the results presented in the Figure 34 it can be noted that the volumes of materials per m^2 of heated floor area is significantly higher for the "Small unit" building in all considered categories. Such outcome of the study is attributed to the large heated floor area of the "Scaled unit" compared to the "Small unit". For the same reason the GWP is higher for the "Small unit" in all instances. It is, however, worth considering that the relationship between the two compared buildings is not the same in all categories, with relatively similar values of GWP accounted for by the 'intermediate floor slabs, roof, horizontal structural beams, roofing deck' category, and almost twice as different value obtained in the 'external and internal walls' category. An observation could be made that the difference in the materials volume used by the two buildings is proportional to the difference in the carbon emissions.

4.2 Case study

The *Case Study* analysis comprised of a prediction of performance of the *Rogaland* building that entailed estimating the results of energy demand and GWP per m^2 of the heated floor area of the building. Energy simulations and LCA calculations were later performed and the results compared against the predicted values.

Initially an analysis of the relationship between the form factor of the *Rogaland* building and the form factor of the other buildings was performed. Examining said relationship and the results of the energy demand and GWP obtained in *Sub-study 1* allowed to estimate the performance of *Rogaland* building. Only the values obtained for the Mid-rise and High-rise buildings were used in the process, due to the multi-storey character of said buildings and higher relatability to the *Rogaland* building, allowing for a more precise prediction of the results.

The form factor was chosen the determining characteristic, as it allows to formulate a clear relationship between the shape of the building, its energy demand and the environmental impact (The Challenge of Shape and Form, n.d.).

A Table 29 with the calculated values of the form factor was used for prediction of energy demand was showed in this section in order to allow for an easy reference when estimating the performance of *Rogaland* building.

Table 29: Form-defining properties of the multi-storey buildings of Sub-study 1 along with the Rogaland building

	Mid-rise Compact	Mid-rise staggered	High-rise	Rogaland
Form Factor A/V/ (1/m)	0.4	0.5	0.5	0.3

4.2.1 Prediction of the energy demand of the Rogaland building

The estimation of the energy demand for the *Rogaland* building was carried out based on the form factor established for the analysed building archetypes. When analysing the results of the *Shoebox Study* it could be seen that generally the buildings with lower form factor were seen to have a lower space heating energy demand and overall better energy performance.

The results of energy demand of the best- and worst-performing buildings along with their form factors were used to estimate the value of energy demand for the *Rogaland* building.

As seen in the Table 30 the form factor as well as the value of the space heating energy demand per m^2 of the heated floor area were the lowest for the "Mid-rise compact" building, with the form factor equal to 0.4 1/m and the space heating energy demand of 15.68 kWh/(m$^2_{Atemp}$·year). The values were used in a cross-multiplication with the form factor of the *Rogaland* building, equal to 0.3 1/m, allowing to establish the space heating energy demand for the *Rogaland* building. The same technique was used to obtain the value of the property electricity demand.

Subsequently, the forementioned process was introduced to calculate the energy demand of the *Rogaland* building in relation to the worst-performing building, the "High-rise", and the values were obtained for the space heating energy demand as well as property electricity demand.

An average was calculated from the values established for the *Rogaland* building in relation to the "Mid-rise compact" and "High-rise" building. The average was then perceived as the estimated result of space heating energy and property electricity demand for the *Rogaland* building.

The value of energy demand for domestic hot water could be calculated as a constant value per m^2 of the heated floor area that was assumed for multi-dwelling buildings, according to Sveby, hence its value was not used in the estimation and was added separately to the final result. The predicted values for the space heating energy demand and property electricity demand were presented in the Table 30 along with the total result accounting for the domestic hot water energy demand.

Table 30: Form factor values of the multi-storey buildings of Sub-study 1 along with Rogaland building in respect to the energy demand

Proportional method of results prediction						
	Space Heating Energy Demand / (kWh/ (m$^2_{Atemp}$ · year))	Property Electricity Energy demand / (kWh/ (m$^2_{Atemp}$ · year))	Domestic Hot Water Energy Demand including HR / (kWh/ (m$^2_{Atemp}$ · year))	Form Factor A/V	Total	Total with Domestic Hot Water
Best Case - Midrise Compact	15.68	6.83	22.50	0.4	22.51	45.01
Worst Case- High Rise	23.44	7.38	22.50	0.5	30.82	53.32
Arkitema vs Midrise estimated	10.91	4.75	22.50	0.3	15.67	38.17
Arkitema vs Highrise estimated	14.11	4.43	22.50	0.3	18.55	41.05
Akitema Mean Estimated	12.51	4.59	22.50		**17.11**	**39.61**

4.2.2 Prediction of the GWP of the Rogaland building

Two methods, described below, were used in order to estimate the GWP of the Rogaland building.

Method 1

In order to obtain the predicted GWP value for the *Rogaland* building, calculations were performed based on the relationship between the values of ratios presented in the Table 34, in APPENDIX II, and the emissions determined for the 'foundation and substructure' category, the 'intermediate slab & roof category' and the 'exterior and interior walls' category, in the "Mid-rise compact", "Mid-rise staggered" and "High-rise" buildings. The three forementioned categories were considered in the calculations due to their highest impact on the total GWP o each building, among the other building elements.

New ratios describing the building form, were introduced in the analysis, corresponding to the building components with the highest emissions. The newly introduced ratios and complete calculation are described in the APPENDIX II.

Method 2

The second method of calculating the predicted value of GWP for the *Rogaland* building entailed a simple proportion of the total emissions values for the "Mid-rise compact" – best performing, and "High-rise" – worst performing amongst the considered buildings and the corresponding form factor values along with the form factor of the *Rogaland* building. Said relationship allowed to determine a numerical value of environmental impact of the *Rogaland* building by cross-multiplication, and the result is displayed in the Table 31.

Table 31: Values used for interpolation along with the calculated results for the Rogaland building

Form	Form factor	Total GWP/ (kg $_{CO_2\ eq}$ /($m^2{}_{Atemp}$·year))
Mid-rise compact (Best Case)	0.4	330.81
High-rise (Worst Case)	0.5	397.21
Proportion of Arkitema with Midrise compact (Best Case)	0.3	248.10
Proportion of Arkitema with High-rise (Worst Case)	0.3	238.36
Average value for Arkitema with best and worst case	0.3	243.28

4.2.3 Verification of the predicted values by comparison of the predicted and simulated energy demand and GWP of the Rogaland building

A comparison of the predicted and simulated performance of the *Rogaland* building was carried out, to assess the accuracy of the energy demand and GWP prediction.

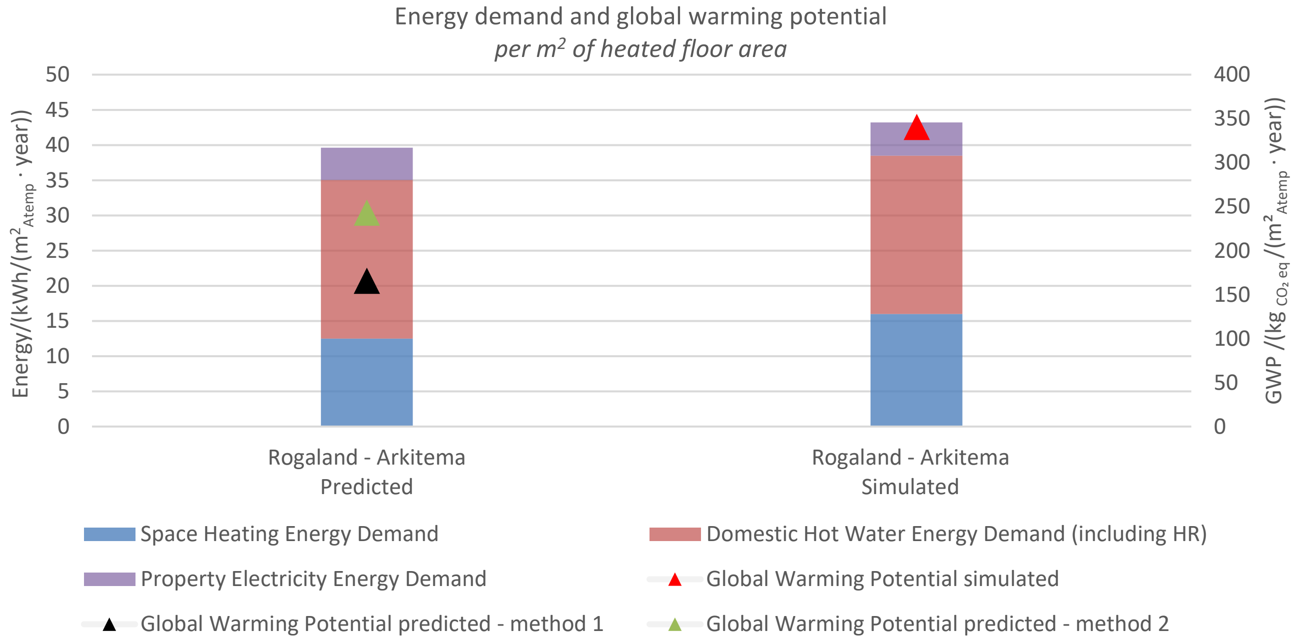


Figure 43: Comparison of the simulated results and predicted results of energy demand and GWP for the Rogaland building

As seen in the Figure 43, the predicted result of the energy demand per m^2 of the heated floor area was relatively similar to the simulated value, with the total result amounting to 39.61 kWh/ (m^2_{Atemp}·year) and 43.19 kWh/ (m^2_{Atemp}·year) respectively. The difference in the results was mostly attributed to the space heating energy demand, with the simulated value exceeding the predicted value by 3.47 kWh/ (m^2_{Atemp}·year). The results of property electricity demand varied slightly, with the simulated and predicted value equal to 4.71 kWh/ (m^2_{Atemp}·year) and 4.59 kWh/ (m^2_{Atemp}·year) respectively.

A more notable difference between the two cases was observed when analysing the GWP results. The predicted value of total emissions was equal to 165.60 kg $_{CO_2\,eq}$ / (m^2_{Atemp}·year), when the calculations were performed by the means of the first method, and 243.28 kg $_{CO_2\,eq}$ / (m^2_{Atemp}·year) when the second method was applied, whereas the simulated result amounted to 340.5 kg $_{CO_2\,eq}$ / (m^2_{Atemp}·year). It could be noted that the prediction done with a simpler method, yielded values closer to the simulated result.

4.2.4 Volume of materials vs GWP

When analysing the Figure 40 it could be observed that the volume of materials used in the apartment blocks and in the basement is not evenly distributed, nor are the emissions associated with the materials. The building elements are allocated in the spaces with only the 'intermediate floor slabs, roof, horizontal structural beams, roofing deck' category occurring in both, the apartment blocks and the basement. The volume of materials used in the basement accounts for about one third of the materials used in the apartment blocks, however the emissions associated with basement materials exceeds half of the emissions attributed to the materials in the apartment blocks. The inconsistency can be explained by the impact of the concrete layer in the intermediate slab of the basement, contributing to a higher GWP. The GWP associated with 'intermediate floor slabs, roof, horizontal structural beams, roofing deck' category was observed to be similar to the 'external and internal walls' GWP for the apartment blocks, with the volume of materials nearly twice as small in the latter category. The forementioned relation could be explained by the high impact of thermal insulation in the external walls, contributing highly to the total GWP value, without reflection in the volume of materials.

4.3 Assessment of the building performance in relation to the form, in the context of Sub-study 1 and Case Study, with respect to Atemp and Aresidential

The energy demand and GWP of the buildings analysed in the *Sub-study 1* was compared with the simulated performance of the *Rogaland* building in relation to the form-defining properties. The results were assessed separately per m^2 of the heated floor area, see Figure 44 and per m^2 of the residential space floor area, see Figure 45 and compared against each-other.

A Table 32 with the form-defining properties of each building analysed in the *Sub-study 1* and *Case Study* was shown in this section in order to allow forming a direct link between the results described in the graphs and factors displayed in the table.

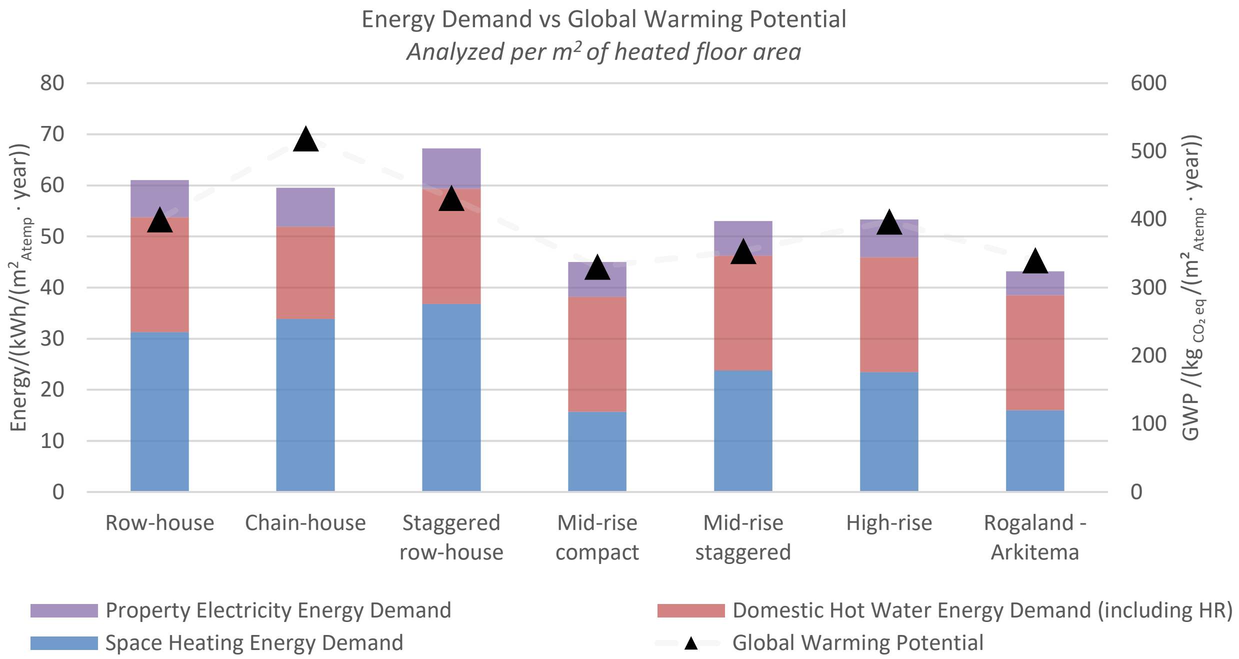


Figure 44: Energy demand and GWP for the buildings analysed in the Sub-study 1 along with the Rogaland building

Table 32: Summary table of the form defining-properties for single-storey and multi-storey buildings along with the Rogaland building

Building form	Single-storey forms			Multi-storey forms			
	Row-house	Chain-house	Staggered row-house	Mid-rise Compact	Mid-rise staggered	High-rise	Rogaland
Form Factor A/V / (1/m)	0.8	1.1	0.9	0.4	0.5	0.5	0.3
Heat-loss Form Factor	2.8	3.7	3.1	1.2	1.4	1.3	0.9

As seen in the Figure 44, the *Rogaland* building performs the best compared to the other buildings when the energy demand per m^2 of the heated floor area is considered. A correlation of the lowest energy demand with the lowest values of the form factor and heat-loss for factor was observed here.

The most similar performance to the *Rogaland* buildings, amongst all the considered buildings, was observed for the "Mid-rise compact", however it was noted that the *Rogaland* building form yielded a higher value of the total GWP than the "Mid-rise compact" building, which could be attributed to the high impact of the large basement in the *Rogaland* building, accounted for in the 'foundation and substructure category', composed out of concrete elements. The energy demand result for the *Rogaland* building form was observed to be lower than for the "Mid-rise compact" building.

A presumption could be made here that the form factor could not allow for an accurate determination of the trend of the environmental impact, as concrete elements in the basement of the *Rogaland* building, not included in the other buildings, had a big impact on the total emissions.

When analysing Figure 45 it was observed that with the results expressed per m^2 of residential space floor area, the energy demand as well as environmental impact have increased for the "Mid-rise compact", "Mid-rise staggered", "High-rise" and the Rogaland buildings compared to the results presented in Figure 44. The results obtained for the single-storey buildings remained unchanged in both analyses, as the heated floor area in those forms was equal to the residential space floor area.

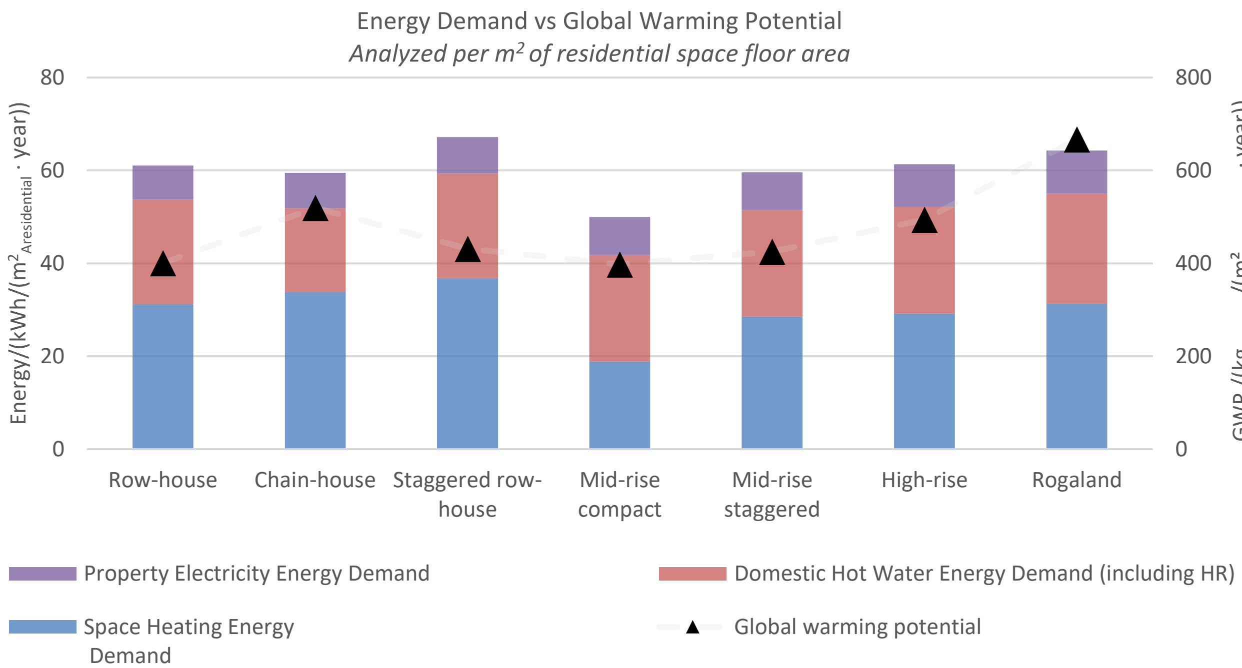


Figure 45: Energy demand and GWP for the buildings analysed in the Sub-study 1 along with the Rogaland building

The values of total energy demand for multi-storey buildings have increased in the Figure 44 compared to Figure 45 leading to very similar results obtained per m^2 of residential space floor area for the “Row-house” and “High-rise” form as well as for the “Chain-house” and “Mid-staggered” buildings. Moreover, the Rogaland building was seen to perform the worst amongst the multi-storey buildings and second worst overall.

The value of the GWP attributed to the “Mid-rise compact” building, remained the lowest compared to the other buildings in both analyses. In the second analyses the highest value of the GWP was represented by the Rogaland building, significantly exceeding the results obtained for the other buildings. When assessing the performance of the remaining multi-storey buildings, it could be observed that the GWP presented in the Figure 44 is much more nearing the GWP of the single-storey buildings, compared to the results presented in the Figure 45 The GWP of the “Mid-rise staggered” building was seen to exceed the value of the “Chain-house” and the “High-rise” building was observed to perform worse than the “Row-house”.

It was noted that the higher heated floor area of the building compared to the residential space floor area, had a big impact on the results expressed per m^2 of the residential space floor area, changing the trend observed in the initially analysed results, expressed per m^2 of the heated floor area. It could be concluded that the extreme difference in the performance of the Rogaland building, when the two different units were considered, was associated with the large basement, included in the heated floor area but excluded from the residential space floor area.

When assessing the results along with the form-defining properties, it could be noted that the form factor and heat-loss form factor can no longer indicate the building’s performance when the results are expressed per m^2 of the residential space floor area.

5 Discussion and conclusions

Based on the study findings it can be concluded that when analysing the form-defining properties of different building archetypes, relative performance of the buildings in terms of energy demand and environmental impact can be determined. The form factor, followed by the correspondent heat-loss form factor, was seen to be the most relatable when assessing the energy demand and carbon emissions of different buildings. Generally, the lower form factor and heat-loss form factor allowed to expect a lower energy demand and global warming potential.

It is, however, crucial to consider the building-specific inputs, based on the standards and building codes depending on the single-dwelling or multi-dwelling character of the building. When analysing the performance of different buildings in relation to the form-defining properties, it was observed that, with the higher form factor, the "Chain-house" was performing better than the "Row-house" in terms of the total energy demand, due to a different assumption regarding the domestic hot water energy demand, specified in Sveby. Therefore, a conclusion has been made that the form factor cannot always be an indicator of the building's performance regarding the total energy demand. Additionally, the relative performance of the analysed buildings might be different if building standards of another country were considered.

Moreover, when analysing the values indicated by the Swedish standards of infiltration rate and household electricity, it was noticed that the values for single-dwelling and multi-dwelling buildings vary in a way that might not illustrate the real-life conditions, as the infiltration depends largely on craftsmanship, whereas the electricity use is influenced by the user. Therefore, theoretically, said values could remain constant regardless of the building character. As the infiltration rate, as well as electrical energy use, accounting for internal loads, impact the space heating demand, less differentiation between the energy demand of different buildings would be observed if the values were kept constant for different forementioned building types.

When analysing the embodied impact of a building, it is necessary to consider a varying structure of the building components, determined by the building geometry. The changes regarding the building's structural design impact the carbon emissions associated with the materials used in the building.

When establishing the form-defining properties for the purpose of the GWP prediction with the first method, the area of the roof and the intermediate slabs area were compiled and considered jointly in relation to the heated floor area. Said measure could be applied as the same structural materials were used in both components and the combined result of carbon emissions was presented when analysing the impact of different building elements in the LCA. However, if the structure of the components would differ significantly and a more detailed analysis was required, it would be recommended that the roof area/A_{temp} and intermediate slab area/ A_{temp} were presented separately and the global warming potential analysed individually.

Based on the study of the building scale, assessed in the *Sub-study 2,* an observation could be made that the performance of a building, in terms of energy demand and carbon emissions, could be largely improved when an additional storey is added to a larger building, compared to a smaller scale building, when assessing the results per m^2 of the heated floor area. It could be concluded that even with the increased building size and volume, leading to higher energy demand and amount of materials used, the final performance can be more advantageous for a large building than a small building. A much-increased heated floor area of the larger building, allows to allocate the total energy demand and carbon emissions, leading to lower values obtained in the end.

When analysing the performance of buildings with large heated floor area compared to the residential space area, a correlation could be observed in the results. As the heated floor area is considered for spaces with temperature above 10°C (Boverket, 2020) the service and circulation areas are often taken into account. With typically lower heating demand in such spaces, it becomes an advantage to express the total building energy demand per m^2 of the heated floor area. More realistic, however less advantageous, way of expressing the results, was established, with the energy demand and carbon emissions calculated per m^2 of the residential space floor area, believed to allow for a more relatable comparison of the performance of buildings with different forms. Calculating the ratio of residential space (liveable) floor area to the heated floor area could allow to draw conclusions about the 'realistic' performance of the building in the early design stage.

When estimating a potential impact of other building characteristics, not considered in the study, on the building performance, a remark about the window to floor ratio was made. The WFR remained constant for all the building models developed in the study, however, was slightly higher for the *Case Study* building. A higher WFR can either lead to an increase of the heating energy demand, due to higher thermal losses through the building envelope, or to higher solar gains, leading to reduction of heating energy demand. Therefore, no clear conclusion regarding the WFR's impact on energy demand can be made when comparing two designs with a different WFR value. However, if a contrasting approach was taken, accounting for the fact that in most residential buildings in Sweden the solar gains are not utilised to decrease the heating energy demand, it could be assumed that higher WFR would be perceived only as a cause of increased thermal losses and possible overheating during the summer months.

The form factor was found to have a large impact on the energy demand when building's performance was analysed in cold climates, however, according to literature, the influence of the form factor on the energy demand was significantly lower, when the assessment took place in warmer climates (Depecker et al., 2001). It could be concluded that the study would benefit from an additional analysis, where a warmer climate would be considered, however, the study inputs and assumptions would have to be adjusted accordingly, following the building regulations applicable in the selected country.

In addition, a further assessment, exploring application of a different structural material and/or different U-value of the building envelope in the considered building forms, as described by Danielski, Fröling and Joelsson (Danielski et al., n.d.), could expand the study findings and improve the analysis. Performing a parametric study would be recommended.

When relating to the future work, it could be concluded that, with Sweden's goal to become climate neutral by 2045, which entails transitioning to renewable energy sources, more focus in the LCA should be put on the embodied carbon of buildings (Swedish Ministry of Infrastructure, n.d.), (Zetterberg et al., 2021).

It would be viable to include a cost analysis in the future work, due to its importance in the decision-making process.

6 References

Adalberth, K. (2000). *Energy use and environmental impact of new residential buildings*.

Amiri, A., Ottelin, J., Sorvari, J., & Junnila, S. (2020). Cities as carbon sinks - Classification of wooden buildings. *Environmental Research Letters*, *15*(9). https://doi.org/10.1088/1748-9326/aba134

Andersen, J. H., Rasmussen, N. L., & Ryberg, M. W. (2022). Comparative life cycle assessment of cross laminated timber building and concrete building with special focus on biogenic carbon. *Energy and Buildings*, *254*. https://doi.org/10.1016/j.enbuild.2021.111604

ASHRAE. (2010). *Thermal Environmental Conditions for Human Occupancy - ASHRAE STANDARD 55*. www.ashrae.org

Astrup, A., Nipsect, J., Christiansen, K., & Schmidt, A. (n.d.). *Life cycle assessment (LCA)-a guide to approaches, experiences and information sources Environmental Assessment of PVC and Selected Alternative Materials View project UNEP project View project*. https://www.researchgate.net/publication/299446257

B. John Garrick. (2008). *Quantifying and Controlling Catastrophic Risks*.

Beemsterboer, S. (2019). *THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING Simplifying LCA use in the life cycle of residential buildings in Sweden*.

Berggren, B., & Wall, M. (2013). Calculation of thermal bridges in (Nordic) building envelopes - Risk of performance failure due to inconsistent use of methodology. *Energy and Buildings*, *65*, 331–339. https://doi.org/10.1016/j.enbuild.2013.06.021

Boverket. (2020). *Konsoliderad version av Boverkets byggregler (2011:6) – föreskrifter och allmänna råd*.

Brismark, J., Malmqvist, T., & Borgström, S. (2022). Climate Mitigation in the Swedish Single-Family Homes Industry and Potentials for LCA as Decision Support. *Buildings*, *12*(5), 588. https://doi.org/10.3390/buildings12050588

Budig, M., Heckmann, O., Ng Qi Boon, A., Hudert, M., Lork, C., & Cheah, L. (2020). *DATA-DRIVEN EMBODIED CARBON EVALUATION OF EARLY BUILDING DESIGN ITERATIONS*.

Bülow-Hübe, H. (n.d.). *Energy-Efficient Window Systems Effects on Energy Use and Daylight in Buildings*. www.byggark.lth.se

Catalina, T., Virgone, J., Bernard, C., Lyon, U., & Iordache, V. (n.d.). *Study on the impact of the building form on the energy consumption ANR SUPERBAT View project Radon measurements in Romanian dwellings View project STUDY ON THE IMPACT OF THE BUILDING FORM ON THE ENERGY CONSUMPTION*. https://www.researchgate.net/publication/267858062

ching-architecture_form_space_order. (n.d.).

Cuéllar-Franca, R. M., & Azapagic, A. (2012). Environmental impacts of the UK residential sector: Life cycle assessment of houses. *Building and Environment*, *54*, 86–99. https://doi.org/10.1016/j.buildenv.2012.02.005

D'Amico, B., & Pomponi, F. (2019). A compactness measure of sustainable building forms. *Royal Society Open Science*, *6*(6). https://doi.org/10.1098/rsos.181265

Danielski, I., Fröling, M., & Joelsson, A. (n.d.). *THE IMPACT OF THE SHAPE FACTOR ON FINAL ENERGY DEMAND IN RESIDENTIAL BUILDINGS IN NORDIC CLIMATES*.

Depecker, P., Menezo, C., Virgone, J., & Lepers, S. (2001). Design of buildings shape and energetic consumption. In *Building and Environment* (Vol. 36). www.elsevier.com/locate/buildenv

European Comission. (n.d.). *Energy efficiency targets*. Retrieved May 14, 2022, from https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficiency-targets-directive-and-rules/energy-efficiency-targets_en

Famuyibo, A. A., Duffy, A., & Strachan, P. (2013). Achieving a holistic view of the life cycle performance of existing dwellings. *Building and Environment*, *70*, 90–101. https://doi.org/10.1016/j.buildenv.2013.08.016

Ferdous, T., & Gorgolewski, M. (n.d.). DETERMINING THE EFFECT OF BUILDING GEOMETRY ON ENERGY USE PATTERNS OF OFFICE BUILDINGS IN TORONTO. In *Journal of Green Building*. http://meridian.allenpress.com/jgb/article-pdf/9/2/124/1766416/1943-4618-9_2_124.pdf

Foraboschi, P., Mercanzin, M., & Trabucco, D. (2014). Sustainable structural design of tall buildings based on embodied energy. *Energy and Buildings*, *68*(PARTA), 254–269. https://doi.org/10.1016/j.enbuild.2013.09.003

Government of France. (2020). *RÉNOVER MIEUX : LEÇONS D'EUROPE*.

Gratia, E., & de Herde, A. (2003). Design of low energy office buildings. *Energy and Buildings*, *35*(5), 473–491. https://doi.org/10.1016/S0378-7788(02)00160-3
GrundFos. (n.d.). *ALPHA2 L - Circulator pump*. Retrieved May 15, 2022, from https://product-selection.grundfos.com/products/alpha/alpha2-l?tab=documentation
Gustavsson, L., & Joelsson, A. (2010). Life cycle primary energy analysis of residential buildings. *Energy and Buildings*, *42*(2), 210–220. https://doi.org/10.1016/j.enbuild.2009.08.017
Hemsath, T. L., & Alagheband Bandhosseini, K. (2015). Sensitivity analysis evaluating basic building geometry's effect on energy use. *Renewable Energy*, *76*, 526–538. https://doi.org/10.1016/j.renene.2014.11.044
Ibrahim Dincer, & Azzam Abu-Rayash. (2020). *Energy Sustainability*. https://reader.elsevier.com/reader/sd/pii/B9780128195567000012?token=CEB9C18C72010422476024D1D0C37D79F3B81D4D60AB607818AD1C446B561F1C96E3BF6C80DB208900C41C3BBF16BDCC&originRegion=eu-west-1&originCreation=20220514133352
International Energy Agency. (2017). *Energy production fuel mixes*.
Ivanova, S. M., & Ivanova Chief-Asst Arch, S. (2016). *Generalized criteria of energy performance evaluation in early design stages of nearly zero-energy buildings Application of Renewable Energy in modern Infrastructure View project Solar architecture View project GENERALIZED CRITERIA OF ENERGY PERFORMANCE EVALUATION IN EARLY DESIGN STAGES OF NEARLY ZERO-ENERGY BUILDINGS*. *2*(6). https://www.researchgate.net/publication/294085648
John Durkee. (2006). *Management of Industrial Cleaning Technology and Processes*. https://reader.elsevier.com/reader/sd/pii/B9780080448886500168?token=8B71C2D0FF94F80180CBB9C85C7500FE378D36467158975018D8963EFAB8C997DAEB4F7D05FBA25C7DD6F12F0A9E5224&originRegion=eu-west-1&originCreation=20220514131610
Konstantinou, T., & Prieto, A. (2018). *Environmental Design Principles for the Building Envelope and More _: Passive and Active Measures IEA EBC Annex 75-Cost-effective Building Renovation at District Level Combining Energy Efficiency & Renewables View project Beyond the Current: user preference tested design solutions for energy efficient housing renovation View project*. https://www.researchgate.net/publication/326626129
Koźniewski, E., Sadowska, B., & Banaszak, K. (2022). Geometric Aspects of Assessing the Anticipated Energy Demand of a Designed Single-Family House. *Energies*, *15*(9), 3308. https://doi.org/10.3390/en15093308
Lechner Norbert. (1991). *Heating, Cooling, Lighting - Sustainable design methods for architects* (4th Edition).
Leskovar, V. Ž., Žigart, M., Premrov, M., & Lukman, R. K. (2019). Comparative assessment of shape related cross-laminated timber building typologies focusing on environmental performance. *Journal of Cleaner Production*, *216*, 482–494. https://doi.org/10.1016/j.jclepro.2018.12.140
Lim, H. S., & Kim, G. (2018). Analysis of Energy Performance on Envelope Ratio Exposed to the Outdoor. *Advances in Civil Engineering*, *2018*. https://doi.org/10.1155/2018/7483619
Lotteau, M., Loubet, P., & Sonnemann, G. (2017). An analysis to understand how the shape of a concrete residential building influences its embodied energy and embodied carbon. *Energy and Buildings*, *154*, 1–11. https://doi.org/10.1016/j.enbuild.2017.08.048
Lylykangas, K. (n.d.). *Shape Factor as an Indicator of Heating Energy Demand Gebäudeformbeiwert als Indikator für den Heizenergie-bedarf La forme du bâtiment: un indicateur du besoin de chauffage Fattore di forma dell'edifico quale indicatore per il con-sumo dell'energia di riscaldamento Shape Factor as an Indicator of Heating Energy Demand*.
Martinsons handbok i KL-trä. (n.d.).
McKeen, P., & Fung, A. S. (2014). The effect of building aspect ratio on energy efficiency: A case study for multi-unit residential buildings in Canada. *Buildings*, *4*(3), 336–354. https://doi.org/10.3390/buildings4030336
Ministry of the Environment and Energy. (2018). *Sweden's draft integrated national energy and climate plan*.
NHBC Foundation. (2016). *The challenge of shape and form*. www.nhbcfoundation.org
Nilsson J Lars. (1994). Air-handling energy efficiency and design practices. *Energy and Buildings*.
Nipkow, J., & Schalcher, M. (2018). *Energy consumption and efficiency potentials of lifts*.
Pacheco R, Ordóñez J, & Martínez G. (2012). Energy efficient design of building - A review. *Renewable and Sustainable Energy Reviews*.
Parasonis, J. (2010). *Possibilities to Reduce the Energy Demand for Multistory Residential Buildings*. https://www.researchgate.net/publication/229040169

Parasonis Josifas, Kezikas Andrius, & Kalibatiene Diana. (2012). The relationship between the shape of a building and its energy performance. *Architectural Engineering and Design Management*. https://doi.org/10.1080/17452007.2012.675139

Pomponi, F., & Moncaster, A. (2018). Scrutinising embodied carbon in buildings: The next performance gap made manifest. In *Renewable and Sustainable Energy Reviews* (Vol. 81, pp. 2431–2442). Elsevier Ltd. https://doi.org/10.1016/j.rser.2017.06.049

Postma Mark, PE, & Walker Carl. (2016). *Whole Building Design Guide - Floor Slabs*. https://www.wbdg.org/guides-specifications/building-envelope-design-guide/below-grade-systems/floor-slabs

Rolltech Windows. (n.d.). Retrieved May 15, 2022, from https://www.winuw.de/rolltech/

Sathre, R. (2007). *Thesis for the degree of Doctor of Philosophy Life-Cycle Energy and Carbon Implications of Wood-Based Products and Construction*.

Schlanbusch, R. D., Fufa, S. M., Häkkinen, T., Vares, S., Birgisdottir, H., & Ylmén, P. (2016). Experiences with LCA in the Nordic Building Industry - Challenges, Needs and Solutions. *Energy Procedia*, *96*, 82–93. https://doi.org/10.1016/j.egypro.2016.09.106

Serrano, A. Á. R., & Álvarez, S. P. (2016). Life cycle assessment in building: A case study on the energy and emissions impact related to the choice of housing typologies and construction process in Spain. *Sustainability (Switzerland)*, *8*(3). https://doi.org/10.3390/su8030287

Smith, M. E. (2014). HOUSING IN PREMODERN CITIES: Patterns of Social and Spatial Variation. In *International Journal of Architectural Research Michael E. Smith Archnet-IJAR* (Vol. 8).

STANKOVIC, D., KOSTIC, A., NIKOLIC, V., & CVETANOVIC, A. (2018). Form in architecture and principles of design. *Architecture. Construction. Education*, *1(11)*, 57–63. https://doi.org/10.18503/2309-7434-2018-1(11)-57-63

SVEBY. (2009). *Brukarindata för energiberäkningar i bostäder*.

Swedish Energy Agency. (2015). *Windows and doors*. https://www.energimyndigheten.se/En/Sustainability/Households/Other-Energy-Consumption-in-Your-Home/Windows-and-Doors

Swedish Energy Agency. (2021). *Energy in Sweden – An overview*.

Swedish Ministry of Infrastructure. (n.d.). *Sweden's Integrated National Energy and Climate Plan*.

Swedish Ministry of the Environment. (2020). *Sweden's long-term strategy for reducing greenhouse gas emissions*.

Swedish Standards Institute. (2017). *Byggnaders energiprestanda-Energikrav för belysning-Del 1: Specifikationer, Modul M9 Energy performance of buildings-Energy requirements for lighting-Part 1: Specifications, Module M9*. www.sis.se

Takano, A., Pal, S. K., Kuittinen, M., & Alanne, K. (2015). Life cycle energy balance of residential buildings: A case study on hypothetical building models in Finland. *Energy and Buildings*, *105*, 154–164. https://doi.org/10.1016/j.enbuild.2015.07.060

The CLT Handbook CLT structures-facts and planning. (n.d.). www.traguiden.se,

TräGuiden - En digital handbok för trä och träbyggande. (n.d.). Retrieved May 14, 2022, from https://www.traguiden.se/

Trigaux, D., Allacker, K., & de Troyer, F. (2014). Model for the environmental impact assessment of neighbourhoods. *WIT Transactions on Ecology and the Environment*, *181*, 103–114. https://doi.org/10.2495/EID140091

United Nations Framework Convention on Climate Change. (n.d.). Retrieved May 11, 2022, from https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

Uzan Sacha. (2019). *Design of a low carbon building Case study of an architectural competition project SACHA UZAN KTH ROYAL INSTITUTE OF TECHNOLOGY SCHOOL OF ARCHITECTURE AND THE BUILT ENVIRONMENT*.

Wei, L., Tian, W., Zuo, J., Yang, Z. Y., Liu, Y., & Yang, S. (2016). Effects of Building Form on Energy Use for Buildings in Cold Climate Regions. *Procedia Engineering*, *146*, 182–189. https://doi.org/10.1016/j.proeng.2016.06.370

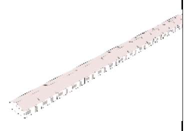
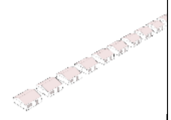
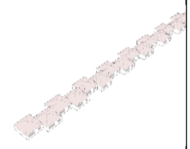
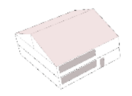
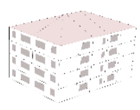
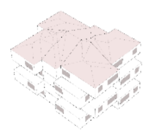
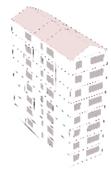
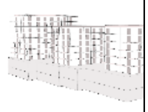
Wigan Council Street Lighting. (n.d.). *LED Street Lights-Frequently Asked Questions*.

Zetterberg, L., Larsson, H., Philipson, C., Tobin, J., Edlund, A., Buko, A., Brohede, D., Kjelbye, O., Wallnér, E., Löwhagen, C., Bodell, J., Cruseman, M., Ohlson, E., & Stock, A. (2021). *Accelerating the Climate Transition: Key Messages from Mistra Carbon Exit*.

APPENDIX I

A complete summary of the results from the study is presented in the Table 33 below.

Table 33: Results summary table

Form	Single-storey building forms				Multi-storey building forms			
	Sub-study 1			*Sub-study 2*	*Sub-study 1*			*Case Study*
	Row-house	Chain-house	Staggered row-house	Scaled unit	Mid-rise Compact	Mid-rise staggered	High-rise	Rogaland
Image								
Form-defining properties								
Form Factor A/V /(1/m)	0.8	1.1	0.9	0.5	0.4	0.5	0.5	0.3
Heat-loss Form Factor	2.8	3.7	3.1	1.8	1.2	1.4	1.3	0.9
Residential space floor area/ A_{temp}	1.0	1.0	1.0	1.0	0.8	0.8	0.8	0.5
Load bearing walls area/ A_{temp}	0.8	1.2	1.0	0.5	0.9	0.9	1.1	0.7
Roof & intermediate slab area/ A_{temp}	1.1	1.3	1.1	0.7	0.3	0.4	0.2	0.7
Foundation & basement slabs and wall area/ A_{temp}	1.0	1.0	1.0	0.5	0.3	0.3	0.1	0.4
Energy demand								
Space heating/ (kWh/ m^2_{Atemp})	31.26	33.88	36.82	9.28	15.68	23.76	23.44	15.98
Space heating/ (kWh/ $m^2_{Aliving}$)	31.26	33.87	36.81	9.28	18.85	28.57	29.16	31.31
Domestic Hot Water incl. HR/ (kWh/ m^2_{Atemp})	22.50	18.00	22.50	18.00	22.50	22.50	22.50	22.50
Domestic Hot Water incl. HR/ (kWh/ $m^2_{Aliving}$)	22.50	18.00	22.50	18.00	22.92	22.93	22.99	23.72

Property electricity/ (kWh/ m^2_{Atemp})	7.30	7.63	7.89	5.46	6.83	6.75	7.38	4.71
Property electricity/ (kWh/ $m^2_{Aliving}$)	7.30	7.63	7.89	5.46	8.22	8.11	9.18	9.23
LCA								
GWP in Life Cycle Stages/ ($kgCO_2/m^2$ m^2_{Atemp})	400.47	519.45	431.73	281.49	330.81	353.92	397.27	340.50
GWP in Life Cycle Stages/ ($kgCO_2/m^2$ $m^2_{Aliving}$)	400.47	519.45	431.73	281.49	397.95	425.69	494.23	667.18

APPENDIX II

New form-defining properties were introduced in the study, in order to account for the impact of the building components contributing highly to the total emissions, and attempt predicting the performance of the *Rogaland* building based on calculated areas of those components. The calculated ratios are presented in the Table 34.

Load bearing walls area to A_{temp} ratio

The area of load bearing walls, excluding ground retaining walls or basement walls, expressed per m^2 of the heated floor area was expected to allow to estimate a contribution of the load bearing structure in the walls to environmental impact of the building when comparing designs with the same assembly of layers in the walls and equal thicknesses. The calculated vale is seen in Table 34.

Roof & intermediate slab to A_{temp} ratio

Establishing an area of the roof and intermediate slabs expressed per m^2 of the heated floor area was anticipated to allow to make an assumption on the contribution of the roof and intermediate slab structure to environmental impact of the building when comparing designs with the same assembly of layers in the roof and intermediate slab and equal thicknesses respectively. The calculated vale is seen in Table 34.

Foundation & basement slabs and walls area to A_{temp} ratio

The ratio of the foundation slab area combined with the area of the ground retaining walls, slabs and internal structural walls, included in the basement, to the heated floor area, was expected to allow for assumptions regarding the contribution of the foundation and basement to the environmental impact of the building when comparing designs with the same assembly of layers and equal thicknesses in the foundation slab and basement structural components respectively. The calculated vale is seen in Table 34.

Table 34: Additional established form-defining properties

Building form	Single-storey forms			Multi-storey forms		
	Row-house	Chain-house	Staggered row-house	Mid-rise Compact	Mid-rise staggered	High-rise
Load bearing walls area/ A_{temp}	0.8	1.2	1.0	0.9	0.9	1.1
Roof & intermediate slab area/ A_{temp}	1.1	1.3	1.1	1.0	1.2	1.0
Foundation & basement slabs and walls area/ A_{temp}	1.0	1.0	1.0	0.3	0.3	0.1

Prediction of numerical performance of the Rogaland building – Method 1

In order to obtain the predicted GWP value for the *Rogaland* building, calculations were performed based on the relationship between the values of form-defining properties presented in the Table 34 and the emissions determined for the 'foundation and substructure' category, the 'intermediate slab & roof category' and the 'exterior and interior walls' category, in the "Mid-rise compact", "Mid-rise staggered" and "High-rise" buildings.

The share of the emissions accounted for in the considered categories, in the total emissions was calculated per each analysed building, as seen in Table 35.

Table 35: Calculated share of GWP in respect to the total GWP

Calculated share in total emissions						
	Mid-rise Compact		Mid-rise staggered		High-rise	
	GWP/ ((kg $_{CO_2\ eq}$ / (m^2_{Atemp}·year))	% of the total emissions	GWP / ((kg $_{CO_2\ eq}$ /(m^2 m^2_{Atemp}·year))	% of the total emissions	GWP / ((kg $_{CO_2\ eq}$ /(m^2 m^2_{Atemp}·year))	% of the total emissions
Foundation category emissions	14.2	4	14.63	4	8.25	02
Intermediate floor slab and roof category emissions	93.6	28	111.63	32	105.62	27
Load bearing walls category emisions	147.3	45	142.69	40	200.47	50
Total emissions of the building form	330.81		353.92		397.27	

In order to equalize the ratios, the values were normalized using a minimum value out of the four analysed buildings and three forementioned categories, equal to 0,1. The normalized values are presented in Table 36.

Table 36: Normalization of the ratios

Ratios Normalization				
	Mid-rise Compact	Mid-rise staggered	High-rise	Rogaland
External and internal load bearing walls category	9	9	11	7
Intermediate floor slab and roof category	10	12	10	7
Foundation category	3	3	1	2

Subsequently, the aim was set to find the share in total emissions of the three considered categories for the *Rogaland* building, as it was done for the other buildings and presented in the Table 35. In order to achieve that, a proportion was made with the normalized ratios and the percentage values, presented in Table 37, obtained for the "Mid-rise compact", "Mid-rise staggered" and "High-rise" building, along with the normalized ratios calculated for the *Rogaland* building. A cross-multiplication was done for each building category and each analysed building in relation to the *Rogaland* building. Subsequently an average of the obtained results was calculated for each category and presented in the Table 37, as a share of emissions of each considered element in the total emissions of the *Rogaland* building.

Table 37: Proportion method for calculating the average percentage for each category for the Rogaland building in respect to the other multi-storey buildings

Proportions for External and internal load bearing walls category	%	Proportions for Intermediate floor slab and roof category	%	Proportions for Foundation category	%
M.C vs. Arkitema	34	M.C vs. Arkitema	19	M.C vs. Arkitema	5
M.S vs. Arkitema	31	M.S vs. Arkitema	18	M.S vs. Arkitema	5
H vs. Arkitema	32	H vs. Arkitema	2	H vs. Arkitema	8
Average for Arkitema	**32**	**Average for Arkitema**	**13**	**Average for Arkitema**	**6**

**M.C – Midrise compact, M.S – Midrise Staggered, H - Highrise*

Next, the normalized ratios, presented in Table 36 were weighted with the average percentages of the impact of each category on total emissions, presented in Table 37 for the *Rogaland* building. The same procedure was done for the "Mid-rise compact", "Mid-rise staggered" and "High-rise" building, using the percentages displayed in the Table 35. The weighted ratios for all the analysed buildings were compiled in the Table 38 and summed, allowing to determine a total value comparable between the analysed buildings

Table 38: Summary of the weighted and normalised results for the multi-storey buildings along with the Rogaland building

Percent and weighting for approximation				
	Mid-rise Compact	Mid-rise staggered	High-rise	Arkitema
External and internal load bearing walls category	4.00	3.62	5.55	2.28
Intermediate floor slab and roof category	2.90	3.72	2.74	0.94
Foundation category	0.12	0.12	0.02	0.26
TOTAL	7.04	7.47	8.31	3.49

Three proportions of the total values presented in the Table 38, to the total carbon emissions known for the "Mid-rise compact", "Mid-rise staggered" and "High-rise" building were established and by cross-multiplication, the value of GWP for the *Rogaland* building was determined in relation to the three forementioned buildings. The average value, representing the total GWP predicted for the *Rogaland* building, was calculated and presented in the Table 39.

Table 39: Summary of values used for interpolation

Proportion for approximation	
Proportion of Arkitema with Midrise compact (Best Case)	164.25
Proportion of Arkitema with Highrise (Worst Case)	167.08
Proportion of Arkitema with Midrise Staggered (Intermediate Case)	165.46
AVERAGE	**165.60**

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