# Methodology and parameters to analyse daylighting and energy use in dense cities: A literature review

Emanuele Pepe[1,2*], Marie-Claude Dubois[1], Niko Gentile[1], Ricardo Bernardo[1]
[1] Division of Energy and Building Design, Department of Building and Environmental Technology, Lund University, Lund, Sweden
[2]Skanska Sverige AB, Stockholm, Sweden
** corresponding author: emanuele.pepe@ebd.lth.se*

## Abstract

Low energy buildings are key to reduce global energy use. However, achieving low energy use and good daylight levels simultaneously in dense cities is challenging. This article reviews relevant studies dealing with energy use and daylighting in dense residential urban blocks located in Nordic climates. The literature review combines a systematic and a 'snowball' search approach. Findings indicate that previous research relies heavily on parametric design as a tool. Few density metrics were found particularly relevant to describe the interplay between density, daylight, and energy use.

However, the limited body of research achieved so far in the Nordic climate makes it difficult to draw a clear conclusion, suggesting that additional research is required.

## Introduction

The global tendency is to build dense cities to utilise less transportation energy per capita, with evidence revealing that high-density areas are more convivial for walking and cycling (Saelens et al., 2003). However, studies claiming energy benefits with urban density typically focus solely upon few variables and neglect others (Steemers, 2003), (Sorrell, 2015). Larivière and Lafrance (1999) already remarked that there is a need for a broad multi-disciplinary basis to analyse energy use in cities. Building taller and denser cities might increase energy saving potential if performed correctly, although this turns out to be largely unclear and not yet well defined when taking into consideration multi-disciplinary parameters and metrics.

Due to the high latitudes and low solar altitudes associated with Nordic countries, urban density plays a key role, as urban geometry highly influences solar access in comparison to other urban areas globally. Within northern Europe, dense areas, or overshadowing, is a well-known issue. The limited access to daylight, especially during the winter, is also aggravated by overcast skies, which are dominant during the winter (Strømann-Andersen and Sattrup, 2013).

Based on a literature review, this article presents key existing scientific knowledge and develops a hypothesis on which further research can be developed. The novelty of this literature review is to focus on cross-disciplinary metrics, identify the most relevant metrics, and suggest a coherent methodology for assessing daylighting and energy use in dense residential urban blocks in Nordic countries.

To attain a comprehensive overview on the objectives, the following question was articulated:

Which methodology (workflow, modelling, software packages, analysis,), parameters, and metrics are the most relevant to employ when assessing energy use (heatload) and daylighting within a Nordic dense residential building block?

## Methodology

A review of the scientific literature was conducted by combining a systematic and a 'snowball' search approach within the reference list of identified articles. This systematic search was performed across the Scopus database and conducted during June 2021, using a set of keywords chained with the Boolean operator "AND" and "OR" for synonyms: daylight OR passive solar AND dens* OR urban* AND energy. All articles were subsequently scrutinized, based upon title and abstract. Inclusion criteria included: building block analysis and design, daylighting metrics, heat load metrics for Nordic and temperate climates. Exclusion criteria were district level analysis and design, skyscrapers, hot climate, cooling, solar and photovoltaics.

## Results

The search identified 582 sources, 79 were considered relevant from the inclusion criteria, of which only 15 were considered relevant for the Nordic climate. This section describes the main findings outlined in these 15 articles.

The first subsection presents an overview of the different methodologies, namely, methodology integration, performance analysis, software packages, and analytical workflows to evaluate a residential building block. The second subsection presents a detailed overview of the relevant parameters and metrics used in residential building blocks and dense city. A summary of the main findings from all relevant studies identified in this literature review is presented in Table 1.

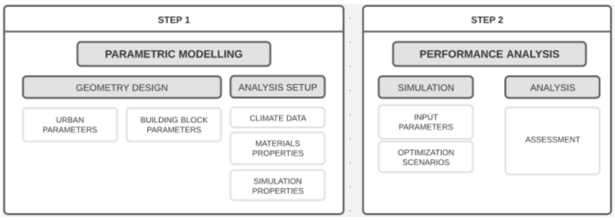
*Table 1: Illustration of key findings by previous articles*

| Reference | Objective | Finding/s |
|---|---|---|
| Aksamija (2012) | Parameters / Metrics | Level of Development (LOD) and implementation |
| Sacks et al. (2018) | Parameters / Metrics | Level of Development (LOD) stratifications BIM |
| Aksamija (2018) | Methodology | Prevailing software solutions: building information modelling (BIM) software, and non-BIM software |
| Ayoub (2019) | Methodology | Software package comparison; Grasshopper and daylight prediction methods |
| Natanian and Auer (2020) | Methodology | Grasshopper software package; use of parametric and performance-based designs |
| Littlefair (2001), Strømann-Andersen and Sattrup (2013) | Parameters / Metrics | Basic geometry constraints influence the final building energy and daylight provision |
| Strømann-Andersen and Sattrup (2011) | Parameters / Metrics<br>Urban Design | Geometry of urban canyons (H/W ratio) had a relative impact on total energy use and solar distribution |
| Ko (2013) | Parameters / Metrics<br>Urban Design | Urban canyon height/width ratio (H/W) and envelope "surface-to-volume' ratio (S/V)<br>used for analysing urban density and its influence on energy use and solar potential |
| Vartholomaios (2017) | Parameters / Metrics<br>Urban Design | S/V ratio most connection to the heatload<br>H/W ratio most connection to solar provision |
| Bournas and Dubois (2019) | Parameters / Metrics<br>Urban Design | Urban density [$m^3/m^2$] correlates to room daylight factor criterion |
| Li et al. (2009) | Parameters / Metrics<br>Building Block<br>Concept Design | Vertical Daylight Factor (VDF) - daylight is significantly reduced in a heavily obstructed dense building block |
| Mardaljevic and Roy (2016) | Parameters / Metrics<br>Building Block<br>Concept Design | Sunlight Beam Index (SBI) - daylight is significantly reduced in a heavily obstructed dense building block |
| Sattrup and Strømann-Andersen (2013),<br>ŠPrah & Košir (2019) | Parameters / Metrics<br>Building Block<br>Concept Design | Floor Area Ratio (FAR), and overall plot ratio density, are used as control variables to regulate maximum density |
| Chatzipoulka et al. (2018),<br>Bournas (2020) | Parameters / Metrics<br>Building Block<br>Concept Design | Vertical Sky Component (VSC) can be a powerful predictor of daylight performance |
| Bournas (2021) | Parameters / Metrics<br>Building Block<br>Concept Design | Combining building typologies within same block can be a solution to balance daylighting and density |
| Sattrup and Strømann-Andersen (2013) | Parameters / Metrics<br>Detailed building block design | -Nordic countries are heating energy use dominated<br>-Density above 250%, there is a reduction in daylighting, without any major energy benefit<br>-Daylight Autonomy (DA) highly correlates passive solar gain levels<br>-Specific building typology with same density effect up to 48% DA , and up to 16% of the total energy performance |
| Bournas (2020) | Parameters / Metrics<br>Detailed building block design | Useful Daylight Illuminance (UDI) displayed the strongest association with urban density / associated significantly with mean building height of surroundings and heatload |

### Articles focusing on methodology

The reviewed articles revealed that the most common and effective workflow for analysing cross-disciplinary metrics was by implementing a 3D simulation tool. Prevailing software solutions, include both building information modelling (BIM) software, and non-BIM software system (Aksamija, 2018),such as Revit with Insight360 and Sefaira, for BIM system, and Grasshopper with plugins, such as Ladybug, Dragonfly, Honeybee, and Colibri, as non-BIM system (Aksamija, 2018; Ayoub, 2019;Natanian and Auer, 2020). The first stage of this workflow included parametric modelling, followed by performance analysis. Parametric modelling entails geometric design with urban parameters, building block design and parameters, and analysis setup with the use of software packages, materials and simulation properties, and climate data. Performance analysis include simulations and analyses. Performance analysis metrics involve simulation input parameters reflecting the building regulation requirements and optimization scenarios, which also includes benchmarks to assess performance (Fig.1).

*Fig. 1: Workflow implementation – from author*




Natanian and Auer (2020) presented a clear workflow with the help of recent parametric modelling tools to integrate energy and environmental quality from early design phases (EDP), using urban performance simulation engines. Their simulation was implemented in the hot and dry Mediterranean climate, although it could be reproduced and expanded to different climatic and urban scenarios. The authors analysed various scenarios with a set of predefined design parameters for urban scale (e.g., typology and street width) and building scale parameters (e.g., glass-to-floor ratio, GFR or window to wall ratio, WWR), in Grasshopper with Ladybug plugin tools (Dragonfly, Honeybee, and Ladybug). Other parameters, such as simulation inputs and climatic data, were set as fixed, according to the Israeli building regulation standards. Performance metrics, energy demand, spatial daylight autonomy, and universal thermal climate index were calculated for different building block forms through multiple environmental simulation programs (EnergyPlus, Radiance, Envi-met, and Urban Weather Generator). The results from each simulation were streamed back to Grasshopper to calculate energy balance, daylighting, and outdoor comfort.

### Articles focusing on relevant parameters and metrics

To identify the level of detail required at each stage, the level of development (LOD) was taken into consideration, which allows the architecture, engineering, and construction (AEC) industry to specify the BIM level of detail at different stages (Sacks et al., 2018). Aksamija (2012) estimated that a minimum LOD of 300 – 400 was required when considering detailed analysis, such as energy use and daylighting within a building block. At the EDP level analysis, requires instead a minimum LOD of 200 (Aksamija, 2012).

### Urban design parameters and metrics

Recent research concluded that urban density has a great impact on building block performance in terms of daylighting and energy use and can be improved by securing a distance between buildings in relation to building heights (Berge, 2009; Strømann-Andersen and Sattrup, 2013; Bournas, 2021). EDP (LOD 200) will have a great impact on the building energy use and daylighting, according to Strømann-Andersen and Sattrup (2013). The authors measured energy use with primary energy needs: domestic hot water, mechanical ventilation, cooling load, and heating load). At EDP, it is possible to analyse urban canyons' height-to-width (H/W) ratio and the building's 'surface-to-volume' ratio (S/V) when analysing the effect of urban density on energy use and solar potential (Ko, 2013). These ratios indicate the density of buildings and their relationship to their environment, where a low S/V ratio results in a reduction of heat losses, and lower H/W ratios lead to the admission of more solar radiation (Vartholomaios, 2017). At the beginning of this century, Littlefair (2001) reviewed previous studies and discussed the link between urban geometry and building´s energy performance. Littlefair (2001) research based on European cities, highlight especially site layout obscuration as the link to individual building's energy performance by solar radiations. Later, Ratti et al. (2005), tested three case study cities of London, Toulouse and Berlin with the integrated energy model LT model (lighting and thermal) coupled with DEMs energy simulations. The authors found an effect of urban morphology on the annual energy use of non-domestic buildings of almost 10%. Thereafter, the concept of utilising urban canyon H/W ratios became a key concept to use in urban planning. More recently, Strømann-Andersen and Sattrup (2011) defined six different canyons ranging from 3.0 to 0.5 H/W ratio. With a fixed WWR of 30% and a density plot ratio perimeter block pattern ranging from 200 to 400% (compactness of the surface-to-floor-area ratio) of a five-storey building with a height of 15 m in Copenhagen. In this study, the RADIANCE-based simulation environment DAYSIM was used for all dynamic simulations of outdoor and indoor illuminance by daylight. Energy calculations were performed with primary energy needs: domestic hot water, mechanical ventilation, cooling load, and heating load), using the simulation tool IES-Virtual Environment 6.0.2, ApacheSim/RADIANCE. Sattrup and Strømann-Andersen (2011) found that the geometry of urban canyons had a relative impact, compared to free horizon sites, increasing the energy use by up to 19% in residential buildings . The authors further highlighted that if the context around the building intensified in density with high H/W ratios, the energy use would increase proportionally by up to 30%, depending on building orientation. In a later study, Bournas and Dubois (2019) found that urban density [m³/m²] correlated with room daylight factor (DF) criterion using Grasshopper with Honeybee plugin. They found that density above 2 m³/m² negatively affected daylight compliance of the analysed building block in Sweden.

## Building block design parameters and metrics

Metrics such as vertical sky component (VSC), sky view factor (SVF), or vertical daylight factor (VDF) are related to the portion of visible sky from a specific point of the building façade (and windows). These metrics can thus contribute to reflections at EDP, regarding spatial relation between the building facade and the sky dome. Li et al. (2009), using VDF, claimed that daylight is significantly reduced in a heavily obstructed dense building block and outlined that rooms on lower floors facing high-rise buildings have a decreased view of the sky dome and consequently, a reduction of internal DF. The study conducted by Bournas (2020) highlighted that the VSC and GFR, strongly affects the DF compliance rate. Moreover, previous investigations have shown that the VSC can be a powerful predictor of daylight performance for buildings at EDP (Chatzipoulka et al., 2018). Another recent predictor, which includes surrounding obstructions and window relation to sun position, is the Sunlight Beam Index (SBI) developed by Mardaljevic and Roy (2016).

Regarding key simulation parameters and metrics, the floor area ratio (FAR) metric alone is not a good performance indicator for daylighting and energy according to ŠPrah & Košir (2019). However, FAR, and overall plot ratio density percentage, are used as a control variable to regulate maximum density and contribute to design the right building type and form (Sattrup and Strømann-Andersen, 2013; Bournas, 2020). Sattrup and Strømann-Andersen (2013) concluded that there is an optimal range for urban density, where daylight availability and energy efficiency are ensured between 150% and 275%, when considering a specific FAR ratio with a specific building form. Recently, findings from Bournas (2020) showed that building types with severely shaded apertures (‘large courtyard blocks’, ‘post-modern reforms’ and ‘exterior circulation’ typologies) typically have a low DF compliance rate. High-rise towers were typically ranked first or second, and post-modern reforms, large courtyards, and exterior circulation types consistently underperformed. Furthermore, Bournas (2021) suggested that a combination of high- and low-rise buildings could contribute to balance daylighting, density, and the number of apartments desired by developers, and confirmed that combining typologies can even be a solution within the same block.

## Detailed building block design parameters and metrics

At detailed building block design (LOD 350 to 400), the most appropriate metrics are daylight autonomy (DA), useful daylight illuminance (UDI) and heat load density (kWh/m², year) when optimising energy and daylighting performance . Parameters which are relevant to use are: WWR, GFR, material properties (e.g. reflectance), building operation, internal heat loads (W/m²), and climatic input.

In Nordic countries, Sattrup and Strømann-Andersen (2013) demonstrated that the dominant energy end-use is heating, partly due to the low average exterior temperature of Copenhagen (8.2°C). The authors wrote that, generally, energy use increases with detached building types, and a major improvement in energy performance is achieved through additive urban forms. However when designing a building block with plot ratio density above 250%, there is a reduction in daylighting, without any major energy benefit in terms of heat load reduction (Sattrup and Strømann-Andersen, 2013). In other words, it is favourable to increase density up to a certain point, beyond which there is no energy benefit but a drawback on daylighting. The authors highlighted that there is a correlation between urban density and passive solar heat gains, although solar gains do not change proportionally with the density (plot ratio). According to this study, DA strongly correlates with passive solar heat gains. Sattrup and Strømann-Andersen (2013) results showed that a specific building typology (and building block design) may affect up to 48% of the DA in buildings with similar urban density and up to 16% of the total energy use. This correlates with the compactness of the surface-to-floor area ratios of the different typologies, together with density and compactness of the individual building.

More recently, Bournas (2020), identified the climate-based daylight metric (CBDM) useful daylight illuminance (UDI) as the one correlating best with the current Swedish criterion “static” point daylight factor (DFp) and even a higher compliance on daylight requirement of the Swedish building regulation requirements Boverkets byggregler (BBR). UDI criterion displayed the strongest association with urban density ($r_S = -0.820$, $p < 0.01$), and also is was significantly associated with the mean building height of surroundings ($p = 0.02$). Bournas concluded that daylight availability and daylight compliance are highly affected by the urban density, and that for this reason, it is imperative to formulate an evaluation criterion at EDP, perhaps at the urban scale.

Bournas (2021) showed that the prevailing method for increased accuracy in assessments is through a CBDM, which has a higher compliance rate for daylight requirements in BBR, and whereby well-planned building orientation was shown to have a positive effect on the electrical lighting use within dwellings. Bournas (2021) suggested that the UDI criterion (which can be implemented concomitantly with thermal comfort evaluations) could be further investigated and analysed for compliance assessments. The author highlighted that with the current increased trend in remote working, electrical light use could increase if a room is not adequately daylit, thereby a climate-based criterion that considers building orientation can assist in decreasing electric lighting within residential dwellings.

## Discussion

Parametric modelling presents several advantages, including the opportunity to develop innovative design forms and climate-conscious variations while still comply to local urban building regulation requirements. The prime reward from such a design strategy is the considerable reduction in time for running and programming the studies, when compared to non-parametric design strategies. Consequently, this provides additional time to evaluate additional design parameters and metrics. However, the development of multiple design possibilities must meet the industry regulation requirements and benchmarks, which will force professionals to sort and identify optimal parameter settings for future sustainable urban development.

Although the workflow presented in this article review does not offer the convenience of total design through a 'one-click' action, the association and immediate and concomitant visualisations of several design evaluations could remarkably assist design decisions. This integrative urban planning workflow still currently depends mostly on the complex Grasshopper platform. Future development of less complex software tool and possibly the implementation of an artificial intelligence (AI) software can rapidly increase the number of professionals willing to engage in such multidisciplinary mission.

Within northern Europe, regarding the concept of urban parameters and metrics, it is paramount to realise that we cannot exclude any parameter (urban canyon, building typology, orientation, building form, and façade reflectivity) because they intrinsically influence both daylighting and heating at different levels and have a long-lasting impact. For this reason, it is imperative to implement a sustainable urban building block design strategy at EDP level. In essence, the construction of dense cities could ensure adequate daylight access and energy balance if is well planned from EDP. However, this might come at the expense of neighbouring buildings that are literally overshadowed by such high-rise residential structures if the urban design parameters and metrics are not taken into consideration at a master planning level.

## Conclusions

This literature review served to shed light on key methodology, metrics and parameters that are currently established in urban planning focusing on daylighting and energy metrics and parameters.

Overall, energy use is primarily affected by density and compactness of the buildings. For residential buildings in Nordic countries, heatload is the main energy use metric. Daylight metrics depends more on the combination of density and the geometric design of the building typology (i.e., orientation and design choices in relation to surrounding context). This review finally highlighted that in the last decade, efforts have been devoted to establish a systematic workflow to implement metrics in dense city urban block development. Ranging from simplified metrics (VSC, VDF, SBI, H/V, S/V) at EDP level, to more detailed metrics (GFR, DA, UDI, heat load density) at later stages. However, the amount of research efforts focusing specifically on Nordic climates is still scarce, and further research is required to analyse basic benchmarks and measures for correlating such metrics effectively.

The main findings of this review are summarised below:

- Presently, the most prevalent workflow strategy is the one using parametric and performance-based design, relying heavily on the Grasshopper software package.
- At EDP, urban density, urban canyon H/W ratio and basic building geometry constraints are most relevant parameters as they will impact the building block's overall energy use and daylighting at later stage.
- At EDP, simplified metrics such as VSC can be powerful predictors of daylight performance.
- At EDP, SBI is a promessing metric for future evaluation.
- At building block concept design phase, architectural typologies, building form, GFR, WWR, urban canyons, façade reflectivity and orientation parameters play a key role to be able to achieve good daylight distribution and energy balance design.
- At building block concept design phase, FAR, is a good control variable to describe density.
- At detailed building block design phase, DA and UDI displayed the strongest association with urban density. These metrics associated significantly with mean building height of surroundings and heat load.
- Solar heat gains correlates strongly to DA and does not change proportionally to density (plot ratio).

In addition of findings about methodology (workflow, modelling, software packages, analysis,), parameters, and metrics, the information from the included articles provided other findings which are summerized below:

- Density and compactness of a building block decrease the energy use of a building block. However with a density plot ratio over 250% will decrease daylight and not bring any more energy benefit (heatload).
- Combining building typologies within same block can be a solution to balance daylighting and density
- Heatload for residential buildings is the main energy metric to take into consideration.
- Urban density [$m^3/m^2$] correlates to room daylight factor criterion

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# Steady-State Calculation versus Dynamic Energy Simulations during the Early Design Phase

Emanuele Pepe[1,2*], Marie-Claude Dubois[1]
[1] Division of Energy and Building Design, Department of Building and Environmental Technology, Lund University, Lund, Sweden
[2]Skanska Sverige AB, Stockholm, Sweden
** corresponding author: emanuele.pepe@ebd.lth.se*

## Abstract

This article uses the steady-state calculation, based on the heating degree-day method, to verify dynamic energy simulations and estimate a building's heating energy use in early design phases. Utilizing Climate Studio through Rhinoceros/Grasshopper, this method acts as a control, ensuring reliability of the dynamic model's input/output. The simulations were conducted on a single building block with increasing density. Heating demand considerations included conduction, air leakage, and ventilation. Employing Copenhagen, Denmark (55.7° N, 12.6° E) climate file, the heating demands was assessed both with and without solar radiation. The results show a near alignment between the steady-state and dynamic results with differences ranging from 2.2% to 5.4% when solar radiation is omitted and a control constant outdoor temperature of 0°C is applied. However, a discrepancy exceeding 36% is observed when including solar radiation and an average outdoor temperature of 10°C, attributable to solar radiation combined with the building's thermal mass lag absent in steady-state calculations. While the steady-state approach has limitations, it offers a simplified yet reliable method to estimate energy use in early stages.

Keywords: Dynamic energy simulations, steady-state calculations, urban densification, early-stage building design, heating demand, control method

## 1. Introduction

Global climate change and limited resources are among the most significant issues challenging the world today [1-2]. The building sector is responsible for approximately 30% of global energy use and significant greenhouse gas (GHG) emissions [3]. To address this issue, many countries are implementing policies and regulations to improve building energy efficiency. The EU's revised Energy Performance of Buildings Directive (EPBD) aims to transform buildings into energy-efficient and decarbonized buildings by 2050 [4].

In the Nordic countries, where the climate is cold and heating needs are high, energy-efficient buildings are particularly important. Nordic countries have therefore established ambitious energy regulations. For instance, Sweden has one of the most ambitious energy regulations in the world, which currently sets a limit of 75 kWh/m², per year for primary energy use in multi-family residential buildings [5]. This primary energy threshold includes all end-uses i.e., heating, cooling, ventilation, domestic hot water (DHW), and collective electricity use. The only part that is excluded is individual electricity use, such as plug loads, electric lighting, etc.

Reliable methods are essential for designers and architects to estimate energy use during the early design phase (EDP), to meet building regulations and ensure energy-efficient design at a later stage in the design. Building energy modelling (BEM) is the most common approach for verifying compliance at more advanced design phases. It involves dynamic energy simulations using programs such as e.g., EnergyPlus [6], IDA-ICE [7], IES-VE [8], ClimateStudio [9], etc. However, Stendahl and Dubois [10] have shown that a simple static energy calculation can also be useful for estimating heating energy demand at the EDP.

According to Ballarini et al. [11], simplified simulation methods offer benefits by using easily obtainable and understandable inputs, with outputs that can be understood and verified. Static models assume a steady-state environment, where both internal and external conditions remain constant [12]. Although they are simple and rapid in execution, their precision is limited since they do not account for time-varying factors such as passive solar heat gains, thermal inertia, dynamic internal heat loads and varying environmental conditions. Corrado et al. [13] emphasized the importance of considering factors such as heat transfer determination and zoning detail. On the other hand, dynamic models, although more time-consuming, provide a more accurate prediction of energy flows by incorporating dynamic variables over time. These variables include thermal mass, external environmental conditions (e.g., air temperature, solar radiation, etc.), and variable internal heat gains [14].

While dynamic models offer more accurate building energy predictions, their complexity necessitates a robust verification mechanism of the input/output used in the 3D model. This study explores the potential of steady-state calculations, based on the heating degree-day (HDD) method, as a verification method at EDP. In examining this comparative approach, the goal is to not only verify dynamic simulations but also to understand the strengths and limitations of steady-state calculations. This study highlights the value of steady-state calculations as a verification method, equipping professionals with a reliable method to optimize input/outputs in dynamic models at EDP.

## 2. Methodology

The following paragraphs present the case study and describe the geometry, input data and calculation methods used in the analysis.

### 2.1 Geometries and simulation settings

The Level of Development (LOD) system was used in this study to determine the appropriate level of detail required for each simulation. This system, widely used in the Architecture, Engineering, and Construction (AEC) industry, establishes the necessary level of detail for Building Information Modeling (BIM) at different stages [15]. For this study, the building models were specifically developed using LOD 200, which provides sufficient detail for heating demand estimates (kWh/m$^2$, year).

The steady-state analysis used Microsoft Excel spreadsheets [16] with HDD calculation formulas [17] to determine the annual energy use for heating. The dynamic geometrical modelling was built using Rhinoceros 7 software [18] and Grasshopper [19]. Energy simulation employed EnergyPlus as the engine, with the ClimateStudio plugin integrated within the Grasshopper/Rhinoceros 3D environment [9].

This study focused on analysing a single residential building block, A18 (Figure 1), which served as the common structure for both the static and dynamic models. The analysis approach was the only differentiating factor between these models. The A18 series included three variations for the steady-state analysis: A18-3s, A18-6s, and A18-9s, as well as three variations for the dynamic analysis: A18-3d, A18-6d, and A18-9d (Figure 1). An overview of the input for the steady-state and dynamic models can be found in Table 1.

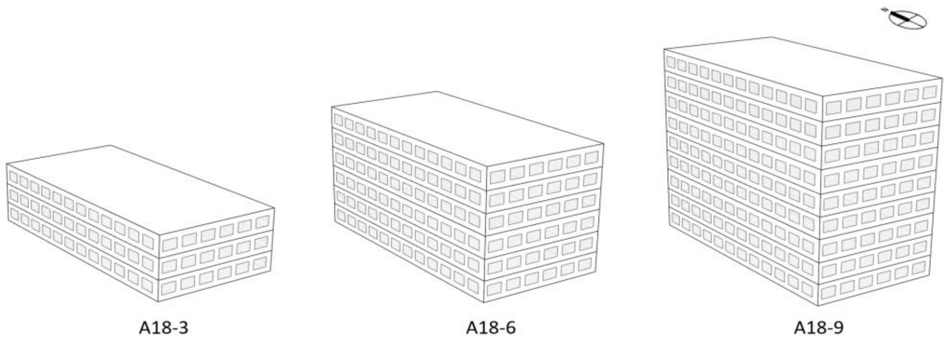


*Figure 1. Building model A18 with 3 floors (A18-3), 6 floors (A18-6) and 9 floors (A18-9).*

In all models, the window-to-wall ratio (WWR) was constant at 30%, which is a typical value found in residential buildings. Each floor had a floor-to-floor height of 3 m, with an external wall thickness of 0.4 m, a slab thickness of 0.3 m, and a roof thickness of 0.45 m. Internal walls, roof details, facade elements, balconies, urban infrastructure, external obstructions, or vegetation, were excluded in this analysis. It is important to note that this study focused on a low level of detail in EDP stage (LOD 200), and therefore, other architectural and contextual details were not taken into account in the simulations.

| Name | Model type | Plot size (m) | LOD | N, of floors | Plot Area (m²) | Floor area (m²) | Facade area (m²) | Window area (m²) |
|---|---|---|---|---|---|---|---|---|
| A18-3s A18-3d | Static and Dynamic | 18x36 | 200 | 3 | 648 | 605 | 972 | 291 |
| A18-6s A18-6d | Static and Dynamic | 18x36 | 200 | 6 | 648 | 605 | 1944 | 583 |
| A18-9s A18-9d | Static and Dynamic | 18x36 | 200 | 9 | 648 | 605 | 2916 | 875 |

*Table 1. Building type and variables for each model.*

## 2.2 Input data

The simulations used weather data from the EPW (EnergyPlus Weather Format) for Copenhagen, Denmark, obtained from OneBuilding's ClimateStudio [20]. The specific dataset used was DNK_HS_Copenhagen-Kastrup.AP.061800_TMYx.2007-2021. The study followed two simulation series: the "control method" and the "full weather method." Details of this data can be found in Table 2.

| | | Static | Dynamic |
|---|---|---|---|
| U-value, external walls | W/m²·K | 0.13 | 0.13 |
| U-value, roof | W/m²·K | 0.15 | 0.15 |
| U-value for ground slab | W/m²·K | 0.15 | 0.15 |
| U-value, windows incl. frames | W/m²·K | 1.05 | 1.05 |
| Glazing g-value | | 0.5 | 0.5 |
| Thermal bridges | % | 30 | 30 |
| Infiltrations | l/s/m²) | 0.4[a] | 0.4[a] |
| Occupancy rate | person/m² | 0 | 0 |
| Ventilation per area | l/s/m² | 0.35 | 0.35 |
| Heating set point with “control method” | °C | 21 | 21 |
| Heating set point with “full weather method” | °C | 18[b] | 21 |
| Heating COP | | 1 | 1 |
| Heat recovery on ventilation | % | 0.75 | 0.75 |
| Internal loads people | W/p at h/d/w | 0 | 0 |
| Internal loads equipment and lighting | kWh/m² | 0 | 0 |

[a] *Enclosing envelope leakage at 50 Pa (q50) (m³/(m²·s))*
[b] *As a rule-of-thumb, passive solar heat gains contribute to a reduction in heating demand equivalent to about 3°C below the indoor temperature set point.*

*Table 2. Input data.*

In the pursuit to verify the results of dynamic energy simulations, the "control method" used the Copenhagen EPW data adjusted in a specific manner. It set the yearly outdoor temperature to a constant through the day of 0°C and eliminated solar radiation. The objective was to develop a control baseline, against which dynamic simulations could be benchmarked. By stripping down the solar radiations variable, it is easier to outline discrepancies between steady-state and dynamic calculations. A heating set point of 21°C was adopted for both static and dynamic calculations in the control method.

In the 'full weather method', the actual solar radiation data from the EPW file was considered, which also included an average outdoor temperature of 10°C. The objective behind this comprehensive method is to thoroughly evaluate the adaptability of both static and dynamic models in the face of typical environmental variations, highlighting their robustness and precision when introducing solar radiation, thermal mass, etc. For the steady-state calculations, Microsoft Excel was used, considering the 10°C value, while ClimateStudio employed the hour-by-hour temperatures derived from the EPW data. Due to the limitations of the static model in capturing the effects of passive solar heat gains, an 18°C heating set point was used for the full weather methods.

## 2.3 Calculation and simulation methods

### 2.3.1 Static model calculation with “control method”

The static calculation was employed in this section to determine the annual heating demand based on the heat losses of the building envelope. Building upon the previously mentioned "control method," the Heating Degree-Days (HDD) were calculated from the modified Copenhagen EPW weather file. This adaptation, which centered on the absence of solar radiation data and a constant 0°C annual outdoor temperature, allowed the extraction of HDD. The extrapolated HDD represents the cumulative temperature difference between the reference indoor temperature ($T_{ref}$ = 21°C) and the outdoor temperature, which in the controm method is a constant ($T_{out}$ = 0°C) over a year. This resulted in a total of 7665 HDD for temperatures below 21 °C, equivalent to 183960 Heating Degree Hours (HDH) when multiplied by 24.

| Equation | |
|---|---|
| (1) | $Q_{cond} = 1.3(U \cdot A)\ HDH$ |
| (2) | $Q_{vent} = [\rho \cdot cp \cdot q_{vent} \cdot (1 - \eta) + \rho \cdot cp \cdot q_{leakage}]\ HDH$ |

*Where:*
- *$T_{ref}$: Reference temperature (℃)*
- *$T_{out}$: Average annual outdoor temperature (℃)*
- *U: Thermal conductance of specific building components (W/m²·°C)*
- *A: Surface area of specific building components (m²)*
- *HDH: Heating Degree-Hour (℃h)*
- *$Q_{cond}$: Annual heat loss through conduction (kWh/m² year)*
- *$Q_{vent}$: Annual heat losses resulting from air leakage and ventilation (kWh/m² year)*
- *ρ: Air density at room temperature (1.2 kg/m³)*
- *cp: Specific heat capacity for air (1000 J/kg·℃)*
- *$q_{vent}$: Ventilation rate according to Swedish standards (L/s, m²)*
- *η: Heat exchanger efficiency (0.75)*
- *$q_{leakage}$: Leakage at 50 Pa overpressure (m³/m², s)*

*Table 3. Equations to estimate heat losses.*

The conduction heat losses ($Q_{cond}$) through the building envelope were then determined by multiplying the HDH by the thermal conductance (U-value) and other relevant factors, such as thermal bridges 30%, as described in Equation (1), see Table 3. Thermal conductance (U) reflects the rate of specific building components, including windows, external walls, roof, and ground, in transferring heat.

The heat losses resulting from air leakage and ventilation ($Q_{vent}$) were calculated using Equation (2), see Table 3. $Q_{vent}$ accounts for energy losses due to outdoor air infiltration and mechanical ventilation within the building. Equation (2) was applied to compute $Q_{vent}$, considering parameters such as air density (ρ), specific heat capacity for air (cp), ventilation rate ($q_{vent}$), heat exchanger efficiency (η), and leakage ($q_{leakage}$). Notably, the influence of building internal heat gains and occupancy on ventilation requirements was excluded from this analysis.

Finally, the total annual energy requirement for heating, considering heat recovery on the ventilation system, was obtained by combining the heat losses from $Q_{vent}$ and $Q_{cond}$ denoted as $Q_{total}$. Dividing the HDH value by the total building area ($A_{temp}$) provided the annual heating energy intensity with heat recovery on the ventilation system, expressed in kWh/m².

### 2.3.2 Static model calculation with “full weather method”

Similar to the previous analysis, the static model calculation with solar radiation and an outdoor annual average temperature of 10°C employed the same equations as described in Table 3. The process began by extrapolating the Heating Degree-Days (HDD) from the Copenhagen EPW weather file (DNK_HS_Copenhagen-Kastrup.AP.061800_TMYx.2007-2021). The original weather file yielded a total of 3132 HDD for temperatures below 18°C, resulting in 75168 HDH when multiplied by 24.

It is important to note that this steady-state calculation does not account for the thermal inertia of heat gain accumulation in the building structure, which is considered in dynamic analyses. The 18°C set point in the static model compensates for an approximate 3°C difference attributed to passive solar heat gains, which is an accepted method in this field.

### 2.3.3 Dynamic calculation

The dynamic energy simulations were performed using the ClimateStudio plugin in the Grasshopper/Rhinoceros 3D environment [9], based on the same input data as for the static calculations (see Table 2).

The thermal analysis results represent the total annual energy use across all thermal zones of the building, with each floor representing a separate thermal zone. It includes the annual heating demand, which measures the energy required to heat the building per year in kilowatt-hours per square meter per year (kWh/m²y). Combining these measures provides insights into the energy required for heating and the energy gained from solar radiation.

For assessing the solar radiation on a facade, a 1-meter sensor spacing was judged sufficient. This study focuses solely on heating energy demand, intentionally excluding other factors such as internal heat gains, equipment, overheating, and thermal comfort. This streamlined approach allows for a targeted analysis and reduces the number of factors affecting the predicted annual heating demand; their omission in this study enables a more focused assessment.

## 3. Results

The results of this study are presented in Table 5 and 6, which include the findings for the heating demand with the "control method" and with the "full weather method". The A18 building blocks, representing static and dynamic models, were analysed in two simulation series. In the first series ("control method"), the static calculations showed reasonable accuracy, with differences ranging from 2.2% to 5.4%. However, in the second series ("full weather method"), the steady-state calculations deviated significantly from the dynamic method, with differences ranging from 36.7% to 39.5%.

| Static Model (s) | Dynamic Model (d) | Static (kWh/m²y) | Dynamic (kWh/m²y) | Relative difference (%) |
|---|---|---|---|---|
| A18-3s | A18-3d | 92 | 90 | 2.2 |
| A18-6s | A18-6d | 79 | 82 | 3.8 |
| A18-9s | A18-9d | 74 | 78 | 5.4 |

*Table 5. Results for the heating demand with modified "control method".*

| Static Model (s) | Dynamic Model (d) | Static (kWh/m²y) | Dynamic (kWh/m²y) | Relative difference (%) |
|---|---|---|---|---|
| A18-3s | A18-3d | 38 | 23 | 39.5 |
| A18-6s | A18-6d | 32 | 20 | 37.5 |
| A18-9s | A18-9d | 30 | 19 | 36.7 |

*Table 6. Results for the heating demand with "full weather method".*

Examining the heating demand for the "control method" analysis, Model A18-3s, A18-6s, and A18-9s exhibited demands of 92 kWh/m²y, 79 kWh/m²y, and 74 kWh/m²y, respectively. The dynamic models, A18-3d, A18-6d, and A18-9d had similar annual heating demands at 90 kWh/m²y, 82 kWh/m²y, and 78 kWh/m²y, respectively. The percentage differences between the static and dynamic models ranged from 2.2% to 5.4%.

However, when simulating the "full weather method" analysis, the heating demands decreased significantly when including the effect of solar radiation and a 10°C average outdoor temperature, which was expected.

Model A18-3s had a demand of 38 $kWh/m^2y$, while A18-3d obtained a demand of 23 $kWh/m^2y$, resulting in a percentage difference of 39.5%. Similarly, Model A18-6s had a demand of 32 $kWh/m^2y$, while A18-6d exhibited a demand of 20 $kWh/m^2y$, resulting in a percentage difference of 37.5%. For Model A18-9s, the demand was 30 $kWh/m^2y$, while A18-9d showed a demand of 19 $kWh/m^2y$, resulting in a percentage difference of 36.7%.

This relative difference between the static and dynamic methods can be attributed to the omission of solar radiation and thermal mass lag in the steady-state calculations, causing a delay in the building's response to solar radiation and temperature. What happens effectively is that heat is accumulated in the concrete slab during the day and passively heats the building at night when outdoor temperatures are dropping, which reduces the heating demand significantly. The comparison between the static and dynamic models revealed that dynamic simulations more accurately captured the effect of solar radiation and thermal mass lag, resulting in lower heating demands.

## 4. Discussion

The results of the analysis provide valuable insights into the comparison between static and dynamic calculation methods for estimating building energy use at the EDP. This type of verification is encouraged to make sure that the dynamic energy simulation are verified and do not become a “black box”. The static calculations based on the heating degree-day method offer a practical and straightforward approach, providing reasonably accurate estimates especially when solar radiation, thermal mass and internal heat gains are excluded. When adding the solar gains afterwards, the estimation also returned expected results in this case, which gives confidence in the dynamic simulation results. These calculations serve as a useful tool in the EDP, enabling architects and designers to assess initial heating energy needs and verify inputs/outputs towards more advanced dynamic simulations.

However, when the “full weather method” is introduced into the analysis, the static calculations reveal a limitation. They do not account for solar radiation and thermal mass lag, leading to larger deviations when compared to dynamic simulations. Dynamic simulations, which consider variables like thermal capacity, environmental conditions, and internal heat gains, offer a more precise prediction of energy flows in the building. This suggests that a combined approach, harnessing the benefits of both static and dynamic methods, might be the most effective way to estimate energy use during the EDP. Additionally, the real-time capability of static calculations within the BIM environment is interesting for immediate energy demand estimation at EDP. Investigating this further, particularly its relationship with dynamic simulations and in different climate scenarios could be a focus for future studies.

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*Article*

# Effect of urban density on heating demand and daylighting in Nordic residential buildings

**Emanuele Pepe[1,2]*, Niko Gentile[1], Marie-Claude Dubois[1]**

[1] Division of Energy and Building Design, Department of Building and Environmental Technology, Lund University, Lund, Sweden
[2] Skanska Sverige AB, Stockholm, Sweden
* Correspondence: emanuele.pepe@ebd.lth.se, emanuele.pepe@skanska.se

**Abstract:** This research examines the impact of density on heating demand and daylighting in multi-dwelling residential buildings in Copenhagen, Denmark (55.7° N, 12.6° E) by increasing density through additional floors and deeper building depth on a simplified courtyard typology. The study then compares the 16-m deep courtyard typology (C16) to two other building types of the same density: 16-m deep U-shaped and 16-m deep mixed typologies"U16" and "M16". The findings show that taller and deeper buildings yield a reduction in both heating demand and daylighting. The decrease in heating demand shows a significant drop from low to medium density levels (floor area ratio, FAR 1-3). Both "U16" and "M16" consistently outperform C16, which suggests that a compact building form with greater solar access can achieve better thermal and daylighting performance. The optimal building depth and height can vary depending on the size of the plot. Nonetheless, a FAR of up to 3 ensures that the building has access to daylight while maintaining a balanced level of heating demand. In summary, this study highlights the significance of incorporating daylight access in the initial building design stages to reach a balance, between urban density and energy efficiency especially in northern Europe where daylight is limited during winter.

**Keywords:** Urban planning, urban density, building form, heating demand, daylighting, solar access, floor area ratio, early design stages, residential, building block, Northern Europe

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## 1. Introduction

According to projections, the worldwide urban population is expected to rise from 4.2 billion in 2018 to 6.7 billion in 2050 (UN Population Division, 2019) which denotes a growth of 50% or an additional 2.5 billion people over a span of thirty years. This rapid urbanization is resulting in cities becoming increasingly congested and putting pressure on resources such as electricity, water, air circulation, heat management, and food availability. Other projections predict that the global urban footprint will triple by 2030, and therefore, the most significant potential for energy optimization lies in cities where master planning and urban density are not yet "locked-in" (Creutzig et al., 2015). Given this context, it is thus critically important, at this moment, to investigate how urban form and density affect the overall energy use of cities, since it will have a great impact on global energy demand for years to come (Papa et al, 2014; Young et al, 2013).

Densifying cities holds the potential to enhance energy conservation; however, the specific strategies to achieve this goal remain unclear, particularly when considering multiple factors and measures (Larivière & Lafrance, 1999). The impact of densification on society and the economy varies from country to country. According to Burton (2000) higher urban densities can have both negative and positive effects on social equity. On one side, increased density can enhance public transportation systems and improve access to facilities. However, there is also a downside as it may lead to reduced living space and a lack of affordable housing options. Similarly, Duranton and Puga (2020) highlight the advantages of density, such, as greater productivity, innovation and improved availability of goods and services.

Strømann Andersen and Sattrup (2013) emphasize the importance of considering solar access during the early stages of urban planning, especially in Nordic countries, characterized by high latitudes and low solar altitudes. In these regions, urban densification significantly impacts solar access and overshadowing. Moreover, the prevalence of overcast sky conditions compounds the already limited natural lighting available during winter (Strømann Andersen & Sattrup 2013). Thus, it is crucial to incorporate daylighting into design considerations as it directly impacts both electric lighting use and the well-being of residents (Bournas, 2021; Nagare et al., 2021). Several studies have demonstrated that access to daylight brings about psychological benefits such as improved cognitive function, better sleep quality and overall health (Figueiro et al., 2019; Heschong, 2018; Lee & Boubekri 2010; Veitch et al., 2010). For instance, Lee and Boubekri (2010) conducted a field study examining how exposure to daylight affects office workers sleep patterns, their findings revealed a correlation between increased exposure to daylight and enhanced sleep quality well as overall well-being.

According to a study by Norman et al. (2006) optimizing building operations such as heating, cooling, ventilation, and lighting is important for achieving energy savings. Taller buildings tend to have higher embodied energy highlighting the need to consider the energy intensity associated with increased building height (Foraboschi et al., 2014). Therefore, it becomes crucial to address the energy implications of densification development of sustainable urban environments and the mitigation of environmental impacts associated with increased building height and density. To make the most of densification while minimizing building impacts, it is essential to adopt an approach that integrates energy efficient building operations and sustainable design practices.

Considering factors such as solar access, daylighting, and heating demand, it becomes crucial to evaluate the different types of building typologies in the context of urban densification. At the building block level, increasing compactness can help reduce energy consumption for heating since it decreases the envelope-to-volume ratio. This is important as space heating represents the primary energy end-use in residential buildings. However, it is essential to explore how heating requirements and daylighting availability are interconnected during the Early Design Phase (EDP), as compact buildings may also lead to reduced daylighting and increased reliance on electric lighting (Strømann-Andersen & Sattrup, 2011).

One of the most prevalent Nordic multi-family building typologies is the courtyard or 'perimeter block' typology (Czachura et al., 2022a; Rådberg & Friberg, 2001). If well planned, this typology offers an effective compromise solution in terms of daylighting and energy use compared to denser building typologies or detached buildings (Ahmadian et al., 2021; Strømann-Andersen & Sattrup, 2013). However, recent research highlights that the courtyard typology may create dark corners on the courtyard side, leading to reduced daylighting in several rooms close to the inner corners (Bournas, 2021).

This article investigates the impact of urban density and building form on daylighting and energy use intensity (EUI) for heating, since heating is the predominant energy use in the Nordic countries (Strømann-Andersen & Sattrup, 2013). The goal is to study how building typology and density may affect building performance. The following research questions were articulated:

- For a typical Nordic residential building block, what is the effect of increasing urban density on the heating energy demand and daylighting?
- Focusing on the courtyard building typology, how does increasing density (by changing building depth and height) affect heating energy demand and daylighting?
- Could the implementation of a “U-shaped” or “M-shaped” (mixed with tower) derivative of the courtyard type result in a more energy-efficient building block offering a compromise between heating demand and daylighting?

The scope of this study is limited to high density residential multi-family building blocks located in a Scandinavian city (Copenhagen). The results provide valuable insights about the effect of different building typologies and density levels, confirming the importance of an appropriate density and solar access design in urban areas.

## 2. Materials and Methods

The study is based on parametric 3D modelling, simulations, and analyses. A comparison of heating energy demand and daylighting performance was conducted on twelve generic models representing the common Nordic courtyard building typology as defined by Rådberg & Friberg (2001), and eight generic courtyard type derivative models. Previous research indicated that implementing a mixed typology is a possible solution to improve the building performance for daylighting (Bournas, 2021; Ferreira et al., 2019). Although generic, these models still allow drawing key conclusions regarding building density, energy demand, and daylighting.

### *2.1 Simulation settings and analysis*

To identify the appropriate level of detail required for each simulation, the Level of Development (LOD) system was used as a basis for model definition in the simulations. LOD is a system used in the Architecture, Engineering, and Construction (AEC) industry to determine the level of detail required for Building Information Modelling (BIM) at various stages (Sacks et al., 2018). Aksamija (2012) suggests that for EDP analyses, a minimum LOD of 100-200 is required, while for more detailed analysis, such as energy use and lighting within a building block, a minimum LOD of 300-400 is necessary. In this study, the building models were created with LOD 100 for solar radiation and vertical sky component (VSC), LOD 200 for energy use (heating), and LOD 300 for spatial daylight autonomy (sDA) simulations (Table 2).

The geometrical parametric modelling was generated using the software Rhinoceros 7 (Robert McNeel & Associates, 2022) and Grasshopper (Grasshopper, 2022). These simulation engines are based on the Energy+ software and on the Radiance Lighting Simulation System (Larson & Shakespeare, 1998). The following plugins were used via Grasshopper/Rhinoceros 3D environment: ClimateStudio for heating simulation, radiation, and daylighting (Solemma, 2022), and Honeybee for VSC (Ladybug Tools, Honeybee, 2022). The weather EPW (EnergyPlus Weather Format) data was obtained from OneBuilding (OB) (OneBuilding Climate, 2023) and the file used for the simulations was set to Copenhagen (DNK_HS_Copenhagen-Kastrup.AP.061800_TMYx.2004-2018). The properties used in the research (see Table 1) reflect commonly used values adopted in Nordic countries for newer buildings, according to Sveby (2015).

**Table 1.** Simulation parameters.

| Parameter | Value |
|---|---|
| **Construction** | |
| Exterior walls U-value | 0.13 W/m²·K |
| Roofs U-value | 0.15 W/m²·K |
| Ground/exposed floors U-value | 0.15 W/m²·K |
| Internal walls U-value | 0.30 W/m²·K |
| Internal ceilings/floor U-value | 0.30 W/m²·K |
| Envelope thermal bridge | 30% |
| Windows U-value | 1.05 W/m²·K |
| Windows g-value | 0.50 |
| Visible light normal properties | 0.68 |
| **Air Exchanges** | |
| Infiltration | 0.4 l/m²/s |

| | |
|---|---|
| Variation profile | on continuously |
| Mechanical ventilation | |
| Minimum flow | 0.35 l/s/m² |
| Variation profile | on continuously |
| Heat-recovery efficiency | 75% |
| **Natural ventilation** | |
| Ventilation rate | 0.3 l/s/m², t > 26°C |
| Variation profile | on continuously |
| **Heating** | |
| Heating set point, winter | 21°C (on continuously) |
| Heating COP | 1 |
| **Loads** | |
| People ASHRAE55 | |
| People density | 0.033 P/m² |
| Metabolic rate | 1 met |
| Variation profile | 100% occupancy: 18pm – 08am<br>40% occupancy: 08am-18pm |
| Equipment | 0.35 W/m² |
| Variation profile | on continuously |
| **Surface Reflectance** | |
| Ground (Albedo) | 0.20% |
| Surrounding | 0.30% |
| External wall | 0.30% |
| Interior wall | 0.80% |
| Interior ceiling | 0.80% |
| Windows frame | 0.80% |
| Floor | 0.30% |

The results regarding the heating demand comprise the sum of the annual energy use for all thermal zones of the building, where each floor was represented by a single thermal zone. The simulations focused on the heating demand, as Scandinavian homes do not normally have cooling systems. However, note that mechanical ventilation was considered as part of the heating demand calculation (i.e., the energy needed to heat up the incoming air) since mechanical ventilation with heat recovery is common in Scandinavian residential buildings. While domestic hot water (DHW) is often the second largest energy end-use in residential buildings in the Nordic countries (Strømann-Andersen & Sattrup, 2013), similarly to property electricity, these end-uses are independent of urban density, hence they were not considered in the simulation.

*2.3 Target metric*

The Floor Area Ratio (FAR) is a simple metric used in urban planning for regulating building construction density; it compares the gross floor area of buildings to their site area (Metropolitan Council, 2021; Czachura et al., 2022b). It is expressed as a decimal, such as FAR 1.5, which indicates that the building's total floor area is 1.5 times larger than the plot of land on which it is built. The same 1.5 FAR is called "plot ratio" when given as a percentage e.g., 150%. Adding floors and increasing building depth increases the FAR. Therefore, this independent variable was used to assess the effect of density on heating energy use and daylighting.

*2.3 Performance metrics*

The present study is based on a previous literature review about energy use and daylighting in dense urban environments (Pepe et al., 2022), which provided the foundation for selecting relevant metrics for the analysis presented in Table 2.

**Table 2.** List of metrics selected for analysis.

| Name | Threshold | LOD | Calculation or Simulation method |
|---|---|---|---|
| Solar radiation | - | 100 | Cumulative annual solar radiation per façade area [kWh/m²] |
| Vertical sky component (VSC) | 27 % | 100 | Amount of sky illuminance on a vertical surface (façade) compared to horizontal global illuminance from an unobstructed sky based on the CIE overcast sky distribution [%] |
| Heating demand | 20 kWh/m² | 200 | Annual heating demand per floor area [kWh/m²] |
| Spatial daylight autonomy ($sDA_{300/50\%}$) | 50 % | 300 | Percent floor area [%] where 300 lux of illumination are achieved for 50% of the operating time |

2.3.1. Vertical Sky Component (VSC) and Spatial Daylight Autonomy (sDA300/50%)

The Vertical Sky Component (VSC) measures the amount of diffuse skylight received at a point, divided by the global diffuse illuminance from an unobstructed CIE overcast sky (Littlefair, 2011). In contrast to the vertical daylight factor (VDF), the VSC does not consider any reflection from the ground or facing buildings. The VSC only considers the incident diffuse illumination with the CIE overcast sky distribution and does not consider the window properties, internal layout of a building, or materials reflectance (Chatzipoulka et al., 2018). VSC is a good "outdoor" predictor of daylighting indoors (Czachura et al., 2022a). The VSC has been shown to have a linear relation to the Daylight Factor (DF) measured indoors, according to Littlefair (2010) and it is thus included as a predictor of daylight in the Building Research Establishment (BRE) daylighting handbook (BRE Group, 2022). Littlefair (2011) states that a VSC greater than 27% is desirable for achieving good daylighting within a building. The maximum façade VSC with an unobstructed view of 90° in all directions is estimated to be 39.6%, as reported by Littlefair (1998) due to framing and setbacks of the window glass. In this study, the VSC is used to evaluate the potential for daylighting through a building façade at EDP, given the relatively low level of model complexity required. In this study, the sensor grid spacing was set to 1m by 1m for VSC analysis, which was considered a sufficiently detailed grid urban scale decision.

The Spatial Daylight Autonomy (sDA) returns the percentage of space that receives enough daylighting on a work plane during typical operating hours. Normally, the target illuminance considered is 300 lux for 50% of the operation time ($sDA_{300/50\%}$) (Reinhart et al., 2006). This method was chosen as an improvement to the daylight factor (DF) method, since it considers all sky types (overcast, sunny and intermediate) on an annual basis through climate-based daylight modelling (CBDM). The advantage of this metric is its connection to the same climate data file as the one used in energy simulations. This study considers as threshold a minimum acceptable value of sDA 50% for the total area achieving 300 lux for 50% of the operating time ($sDA_{300/50\%}$), which reflects similar suggestions from European and Nordic standards (CEN, 2018; Boverket, 2023). For the $sDA_{300/50\%}$ analysis in this study, the work plane offset was set to 0.8m between the floor surface and sensor plane, while the grid spacing was set to 1m by 1m within the room area, as recommended by the European Standards EN 17037 (CEN, 2018); no offset from the walls was considered. The operation time was set from 06:00 to 18:00 hours (equivalent to sunrise to sunset on the equinox), without the use of any shading devices.

2.3.2. Heating demand and solar radiation

The annual heating demand is a measure of the amount of energy required to heat a building each year, expressed in kilowatt-hours per square meter per year (kWh/m²y). For this study, the threshold of 20 kWh/m²y heating demand was considered as a low value for Nordic countries, considering the actual limit in primary energy use of 75 kWh/m²y for multi-family residential buildings in current building regulations (Boverket, 2022). This threshold leaves room for other energy end-uses (DHW is normally roughly 20 kWh/m²y or more depending on household size and usage, property electricity 10 kWh/m²y, etc.) (Sveby, 2015).

The solar radiation analyzed here is the cumulative solar radiation received by all building facades surfaces each year, expressed in kilowatt-hours per square meter per year (kWh/m²y). The main assumption for solar radiation is that it is desirable most of the time in residential buildings for the passive solar heat gains. This study used a 1m-by-1m sensor grid, which is sufficient for assessing facade solar radiation at the urban scale.

*2.4 Geometrical parametric modelling*

For all models in this study (table 3), a homogeneous building block district with a 5 m by 5 m unit grid was used to include contextual obstructions, but only the central plot was analyzed (Figure 1). The basic urban plot was defined as a rectangular plot measuring 100 m by 80 m, with 15 m-wide streets, measured from the buildings' outer façade, despite the absence of continuous uniform grid layouts in Nordic city centers, this specific street width was chosen to exemplify a typical block dimension commonly found in such areas. The window-to-wall ratio (WWR) was set to 30%, which is a typical average value found in residential buildings and a sufficient WWR for good daylighting in peripheral rooms (Dubois & Flodberg, 2013). No detailing of the roof, façade, balconies, urban infrastructure, or vegetation was included in the simulations. Each floor had a 3 m floor-to-floor height, with an external wall thickness of 0.4 m and a slab thickness of 0.3 m in all models. It is important to note that the focus of this study was on urban density at EDP from LOD 100 to 300, thus other architectural and contextual details were not considered in the simulations.

The courtyard building typology (C) was first investigated with depths of 10 m (building type C10), 13 m (building type C13), and 16 m (building type C16). For each of these models, four floor number alternatives were studied: 3 floors (e.g. C10-3), 5 floors (e.g. C10-5), 10 floors (e.g. C10-10), and 15 floors (e.g. C10-15), summing up to a total of 12 models (Figure 2). Living spaces of 5 m in depth were assumed on the courtyard side; while on the street side, living spaces were assumed with depths of 5 m for building C10, which is a common room depth size in Nordic residential buildings (Strømann-Andersen & Sattrup, 2013), 6.5 m for building C13, and 8 m for building C16, as worst case scenatio, see Figure 3. The second step consisted of comparing the worst case for daylighting with the courtyard typologies (C16 series) to a U-shaped (U16) and Mixed with tower (M16) typologies, with the same building depth of 16 m, while varying the number of floors but keeping the same FAR, see Figure 2. A total of eight models were built as indicated in Table 3. Living spaces of 5 m in depth were assumed on the courtyard side, while 8 m deep rooms were assumed on the street side, see Figure 4.

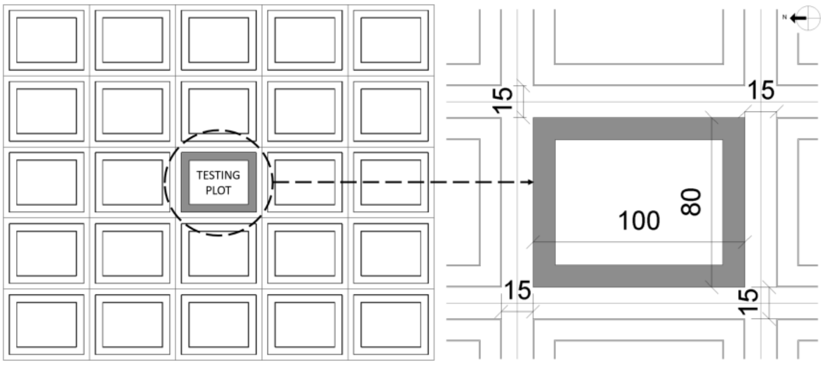
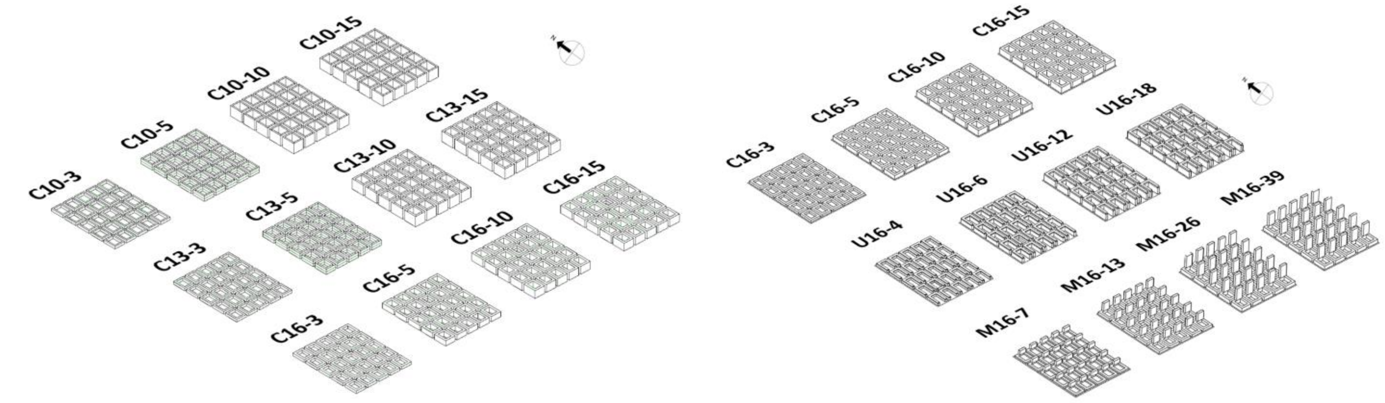



**Figure 1.** Urban building district block uniform grid 5-by-5 unit with testing plot of 100m by 80m.




(**a**) (**b**)

**Figure 2.** Urban district for all simulation variation. (a) Courtyard typologies comparison. (b) Courtyard, U-shape and Mixed typologies comparison.

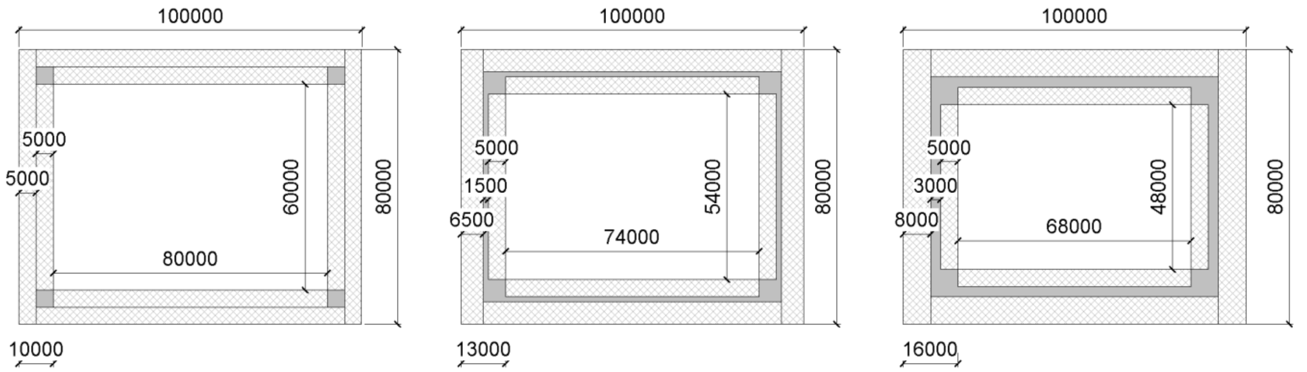



**Figure 3**. Courtyard 10 m- (building C10), 13 m- (building C13), and16 m-deep (building C16) comparison.

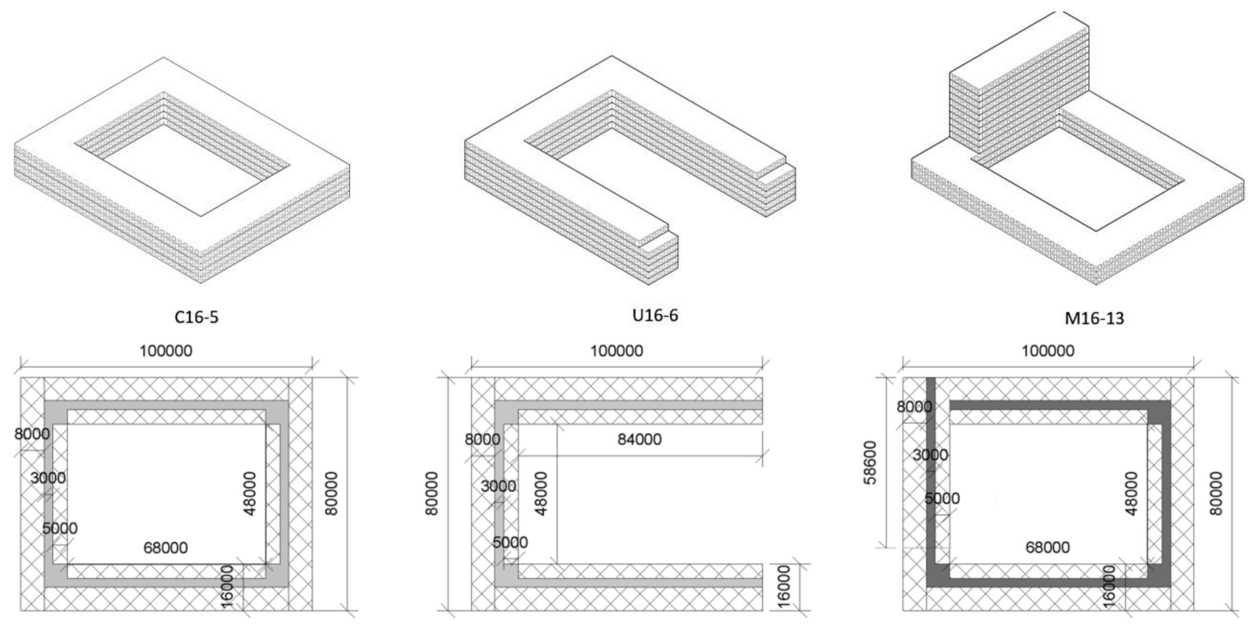



**Figure 4**. Courtyard typologies (C16) with a U-shaped (U16) and Mixed-tower (M16).

**Table 3.** Building type and variables for each typology.

| Name | Depth (m) | N, of floors | Plot Area (m²) | Floor area (m²) | FAR |
|---|---|---|---|---|---|
| **C10-3** | 10 | 3 | 8000 | 9600 | 1.2 |
| **C10-5** | 10 | 5 | 8000 | 16000 | 2.0 |
| **C10-10** | 10 | 10 | 8000 | 32000 | 4.0 |
| **C10-15** | 10 | 15 | 8000 | 48000 | 6.0 |
| **C13-3** | 13 | 3 | 8000 | 12012 | 1.5 |
| **C13-5** | 13 | 5 | 8000 | 20020 | 2.5 |
| **C13-10** | 13 | 10 | 8000 | 40040 | 5.0 |
| **C13-15** | 13 | 15 | 8000 | 60060 | 7.5 |
| **C16-3** | 16 | 3 | 8000 | 14164 | 1.8 |
| **C16-5** | 16 | 5 | 8000 | 23680 | 3.0 |
| **C16-10** | 16 | 10 | 8000 | 47360 | 5.9 |
| **C16-15** | 16 | 15 | 8000 | 71040 | 8.9 |
| **M16-7** | 16 | 7 | 8000 | 14164 | 1.8 |
| **M16-13** | 16 | 13 | 8000 | 23680 | 3.0 |
| **M16-26** | 16 | 26 | 8000 | 47360 | 5.9 |
| **M16-39** | 16 | 39 | 8000 | 71040 | 8.9 |
| **U16-4** | 16 | 4 | 8000 | 14164 | 1.8 |
| **U16-6** | 16 | 6 | 8000 | 23680 | 3.0 |
| **U16-12** | 16 | 12 | 8000 | 47360 | 5.9 |
| U16-18 | 16 | 18 | 8000 | 71040 | 8.9 |

## 3. Results

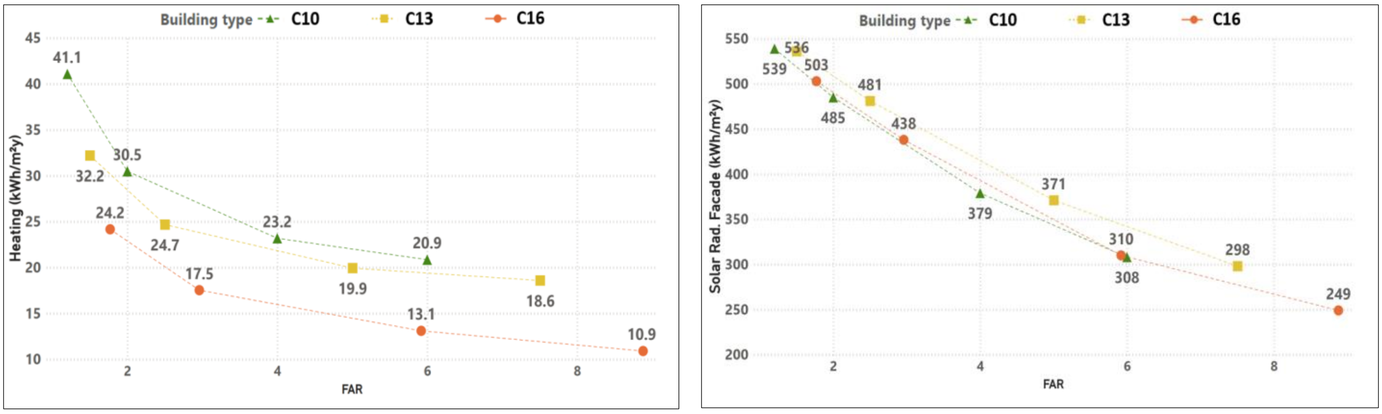
### *3.1. Courtyard typology: effect of density on heating demand and solar radiation.*

The results of the first series of simulations for heating demand and solar radiation are presented in Table 4 and Figure 5. Table 4 shows that while both heating demand and solar radiation decrease for all buildings by increasing the FAR, the 16 m-deep series (C16) exhibits the most significant reduction of 54.9% (from 24.2 to 10.9 kWh/m²y) in heating demand and 50.5% (from 503 to 249 kWh/m²y) in solar radiation for C16-5. The results indicate that building type C16 is generally more energy-efficient compared to building types C10 and C13, looking only at the heating demand, which is an expected result given the more compactness of the building, with less facade per volume. The solar radiation reduction shows a nearly linear reduction with increasing FAR, in comparison to the reduction in heating demand, which exhibits an exponential decay, i.e. increasing FAR from 1 to 3 yields an acute drop, but this trend stabilizes for FAR larger than 3 (Figure 5).

**Table 4.** Effect of courtyard typology density on heating demand and solar radiation.

| Name | FAR | Heating (kWh/m²y) | Heating Δ (%) | Solar Radiation (kWh/m²y) | Solar Radiation Δ (%) |
|---|---|---|---|---|---|
| **C10-3** | 1.2 | 41.1 | Base case | 539 | Base case |
| **C10-5** | 2.0 | 30.5 | -25.8 | 485 | -10.0 |
| **C10-10** | 4.0 | 23.2 | -43.6 | 379 | -29.7 |
| **C10-15** | 6.0 | 20.8 | -49.2 | 308 | -42.9 |
| **C13-3** | 1.5 | 32.2 | Base case | 536 | Base case |
| **C13-5** | 2.5 | 24.7 | -23.4 | 481 | -10.3 |
| **C13-10** | 5.0 | 19.9 | -38.1 | 371 | -30.8 |
| **C13-15** | 7.5 | 18.6 | -42.3 | 298 | -44.4 |
| **C16-3** | 1.8 | 24.2 | Base case | 503 | Base case |

| | | | | | |
|---|---|---|---|---|---|
| **C16-5** | 3.0 | 17.5 | -27.4 | 438 | -12.9 |
| **C16-10** | 5.9 | 13.1 | -45.8 | 310 | -38.4 |
| **C16-15** | 8.9 | 10.9 | -54.9 | 249 | -50.5 |




(**a**) (**b**)

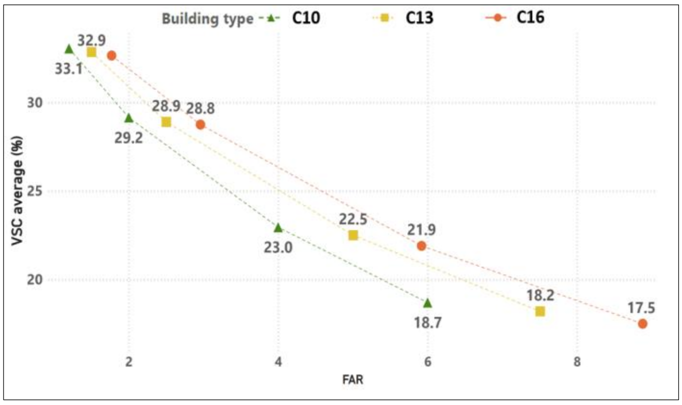
**Figure 5.** Courtyard (C10, C13, C16) typologies density effect on heating demand (a) and solar radiation (b).

## *3.2. Courtyard typology: effect of density on VSC and sDA300/50%*

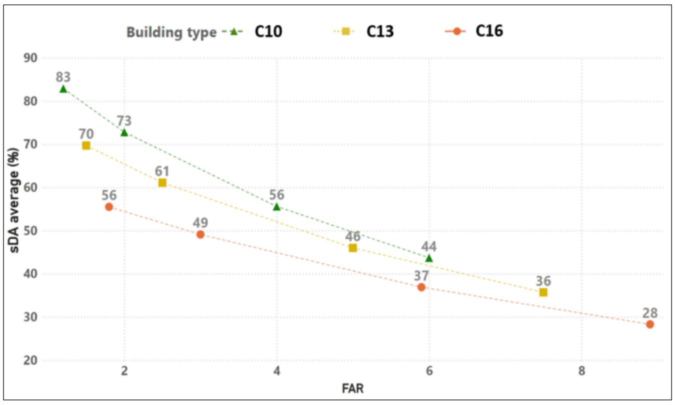
The results of the first series of simulations for VSC and sDA300/50% are presented in Table 5 and Figure 6. As the depth of the building increases from 10 m for building C10, to 13 m for building C13, and 16 m-deep for building C16, daylighting drops significantly, as shown by a reduction in sDA300/50% values, which was an expected result. Figure 6 shows that among all buildings, C16 has sDA300/50% and VSC values decreasing the most in percentage as the number of floors and FAR increase, with the highest reduction of 46.4% (from 32.6 to 17.5) for the VSC (%) and 49% (from 55.5 to 28.3) sDA300/50% for C16-15.

**Table 5.** Effect of courtyard typologies and density on VSC and sDA300/50%.

| Name | FAR | VSC (%) | VSC Δ (%) | sDA300/50% (%) | sDA300/50% Δ (%) |
|---|---|---|---|---|---|
| **C10-3** | 1.2 | 33.0 | Base case | 82.9 | Base case |
| **C10-5** | 2.0 | 29.1 | -11.8 | 72.8 | -12.2% |
| **C10-10** | 4.0 | 22.9 | -30.6 | 55.6 | -32.9% |
| **C10-15** | 6.0 | 18,7 | -43.4 | 43.7 | -47.3% |
| **C13-3** | 1.5 | 32.8 | Base case | 69.7 | Base case |
| **C13-5** | 2.5 | 28.9 | -12.0 | 61.1 | -12.3% |
| **C13-10** | 5.0 | 22.5 | -31.5 | 46.0 | -34.0% |
| **C13-15** | 7.5 | 18.2 | -44.6 | 35.7 | -48.8% |
| **C16-3** | 1.8 | 32.6 | Base case | 55.5 | Base case |
| **C16-5** | 3.0 | 28.7 | -11.9 | 49.1 | -11.5% |
| **C16-10** | 5.9 | 21.9 | -32.9 | 36.9 | -33.5% |
| **C16-15** | 8.9 | 17.5 | -46.4 | 28.3 | -49.0% |




(**a**)




(**b**)

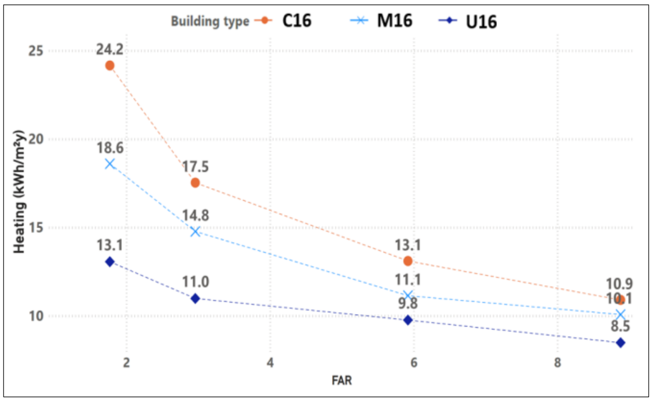
**Figure 6.** Courtyard (C10, C13, C16) typologies density effect on VSC (a) and sDA300/50% (b).

### *3.3. Effect of courtyard, U-shaped and Mixed typologies, on heating demand and solar radiation*

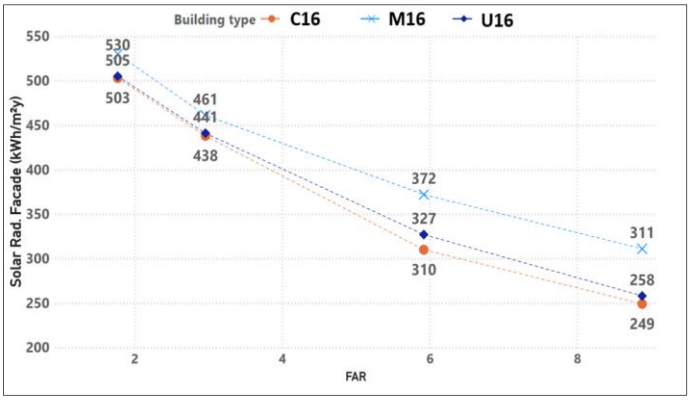
The results of the second series of simulations for heating demand and solar radiation are presented in Table 6 and Figure 7. Based on the heating demand results (Table 6), it is apparent that with the same FAR, a more compact building form with less sky obstruction led to a lower heating demand, see Figure 7. The "U-shape" typology resulted in the lowest heating demand with a reduction of 35.1% (from 13.1 to 8.5 kWh/m²y). Overall, solar radiation values are similar for buildings C16, U16 and M16. Building M16 receives more solar radiation due to the tower, which is well exposed to skylight. Similar to the first analysis, the reduction in heating demand shows an exponential decay, with an acute reduction up to FAR 3, which stabilizes beyond this point.

**Table 6.** Courtyard, U-shaped and Mixed-tower typologies density, on heating demand and solar radiation.

| **Name** | **FAR** | **Heating (kWh/m²-y)** | **Heating Δ (%)** | **Solar Radiation (kWh/m²-y)** | **Solar Radiation Δ (%)** |
|---|---|---|---|---|---|
| **C16-3** | 1.8 | 24.2 | Base case | 503 | Base case |
| **C16-5** | 3.0 | 17.5 | -27.4 | 438 | -12.9 |
| **C16-10** | 5.9 | 13.1 | -45.8 | 310 | -38.4 |
| **C16-15** | 8.9 | 10.9 | -54.9 | 249 | -50.5 |
| **M16-7** | 1.8 | 18.6 | Base case | 530 | Base case |
| **M16-13** | 3.0 | 14.8 | -20.6 | 461 | -13.0 |
| **M16-26** | 5.9 | 11.1 | -40.1 | 372 | -29.8 |
| **M16-39** | 8.9 | 10.1 | -45.9 | 311 | -41.3 |
| **U16-4** | 1.8 | 13.1 | Base case | 505 | Base case |
| **U16-6** | 3.0 | 10.9 | -15.9 | 441 | -12.7 |
| **U16-12** | 5.9 | 9.8 | -25.3 | 327 | -35.2 |
| **U16-18** | 8.9 | 8.5 | -35.1 | 258 | -48.9 |




(**a**)




(**b**)

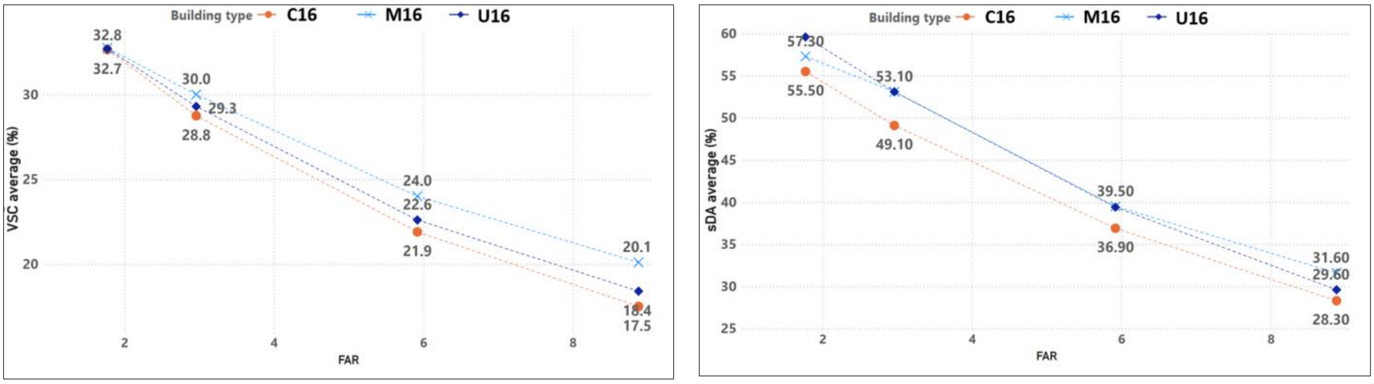
**Figure 7.** Courtyard (C16), U-shaped (U16) and Mixed with tower (M16) typologies form and density effect on heating demand (a) and solar radiation (b).

*3.4. Effect of courtyard, U-shaped and Mixed with tower typologies on VSC and sDA300/50%*

The results of the second series of simulations, which compares C16 to M16 and U16, for VSC and sDA300/50% are presented in Table 7 and Figure 8. For buildings C16, M16 and U16, the trend shows a similar pattern of reduction in sDA300/50% and VSC as the number of floors and FAR increase, see Figure 8. Building type M16 and U16 always outperform C16. Building C16 shows the most significant reduction of 49.0% (from 55.5 to 28.3) in sDA300/50% for C16-15. The VSC values follow a similar trend, with a 46.4% reduction (from 32.7 to 17.5) for C16-15.

**Table 7.** Courtyard, U-shape and Mixed-tower typologies density, VSC and sDA300/50%.

| Name | FAR | VSC (%) | VSC Δ (%) | sDA300/50% (%) | sDA300/50% Δ (%) |
|---|---|---|---|---|---|
| **C16-3** | 1.8 | 32.7 | Base case | 55.5 | Base case |
| **C16-5** | 3.0 | 28.7 | -11.9 | 49.1 | -11.5 |
| **C16-10** | 5.9 | 21.9 | -32.9 | 36.9 | -33.5 |
| **C16-15** | 8.9 | 17.5 | -46.4 | 28.3 | -49.0 |
| **M16-7** | 1.8 | 32.7 | Base case | 57.3 | Base case |
| **M16-13** | 3.0 | 30.0 | -8.4 | 53.1 | -7.3 |
| **M16-26** | 5.9 | 24.0 | -26.7 | 39.5 | -31.1 |
| **M16-39** | 8.9 | 20.1 | -38.6 | 31.6 | -44.9 |
| **U16-4** | 1.8 | 32.8 | Base case | 59.6 | Base case |
| **U16-6** | 3.0 | 29.3 | -10.4 | 53.1 | -10.9 |
| **U16-12** | 5.9 | 22.6 | -30.9 | 39.4 | -33.9 |
| **U16-18** | 8.9 | 18.4 | -43.7 | 29.6 | -50.3 |




(**a**) (**b**)

**Figure 8** Courtyard (C16), U-shaped (U16) and Mixed with tower (M16) typologies form and density effect on VSC (a) and sDA300/50% (b).

*3.5. Comparison between heating demand and VSC*

Since VSC provides good prediction of daylighting while being a low LOD 100, it is beneficial, at EDP, to compare VSC to Heating demand.

Figure 9 puts in relation heating demand, and VSC with different urban densities. The results are contrasted to two key thresholds used in practice i.e., 20 kWh/m²y for heating, and 27% for VSC.

Considering the external façade and surrounding obstructions of the building, the VSC graphs in Figure 9 indicate that the density reaches a turning point at a FAR 3. The advantage of a mixed typology is illustrated in Figure 9, where the U-shaped typology results in a lower heating demand, while providing good solar access as indicated by the VSC. This figure reveals that when FAR drops from 3 to 1.8, there is a considerable increase in heating demand, indicating that there is a significant benefit to increase the FAR from low (1.8) to intermediate (3) values. Beyond FAR 3 the advantages of reduced heating demand are offset by a drastic decrease in VSC for all building typologies.

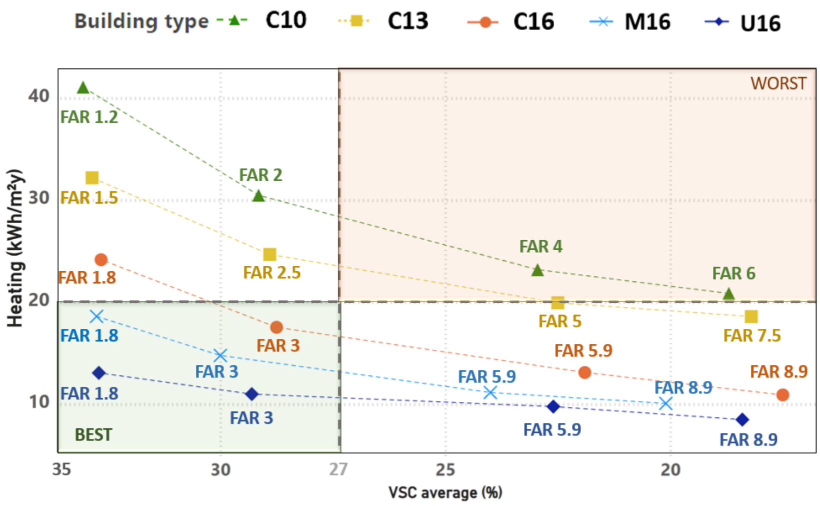



**Figure 9.** Relation between heating demand, and VSC for C10, C13, C16, M16 and U16.

## 4. Discussion

This study confirms that VSC is a good indicator for determining building density, depth, and plot size at EDP, when the focus in on daylighting only. This is due to its ability to quantify the amount of skylight incident on a particular point, which directly impacts the daylight availability in a building. When VSC is linked to Heating demand (Figure 9), with thresholds 20 kWh/m$^2$y for heating and 27% for VSC, it allows to identify the best FAR and building form solution for both daylighting and heating.

The results also indicate that none of the designs investigated here meet the VSC 27% thresholds and daylighting compliance level (sDA300/50% ≥ 50%) for any configuration with FAR greater than 3, when considering a 30% WWR and a street width of 15 meters. This suggests a densification limit for Nordic countries.

Previous studies have shown that a plot ratio of up to 300% (FAR = 3) in a five-story building with a depth of 10 meters is a good compromise between energy use and daylighting (Ahmadian et al., 2021; Strømann Andersen & Sattrup 2013) which is further supported by this study.

In regions characterized by cold and temperate climates, compactness plays an important role in limiting the heating demand. Deeper and taller buildings help minimize air leakage and heat losses through walls and roofs. Solar radiations results shows that there is a correlation between urban density and passive solar gain, where solar gains decrease with the increase of density, however, the compactness and building form design have a higher impact on the total heating energy demands and solar access.

Buildings such as M16 or U16 have the potential to enhance solar access providing solar heating gains and daylighting. In this research, the U16 type returned better performance in terms of heating demand, solar radiation and daylighting compared to the C16 and M16 types. This is because the U16 type has an optimized building design that combines compactness with exposure to sunlight on the courtyard side.

To achieve high density while ensuring daylighting and managing heating demand, it is crucial to also consider factors such as street width, plot size and window dimensions.

This study highlights the significance of considering both solar access and building types when planning dense urban areas. Neglecting solar access at EDP stages, may result in increased reliance on electric lighting, particularly on lower floors of the buildings. Combining VSC and heating demand analysis at the EDP can help to preserve solar access while optimizing density for lower energy use.

## 5. Conclusions

This study offers insights into how density, building types, heating demand, solar radiation, and daylighting interact with each other. The findings suggest that while increasing density can reduce heating energy consumption, it also has an impact on solar access and daylighting. Additionally, this research gives new insights on the potential of using different building depths and heights, while maintaining the same FAR, and incorporating different typologies with well-designed building forms to increase density while ensuring solar access. However, further investigation is needed to understand the complexities of optimal building block design at EDP in the Nordic climate, also accounting for potential seasonal weather shifts.

Based on the results presented, the main findings are summarized below:

- FAR 3 can be identified as a densification limit for Nordic countries, which provides a compromise between heating demand and daylighting, when considering a 30% WWR and 15 m street width;
- The U16 typology resulted in significant improvements in heating demand, solar radiation, VSC, and sDA300/50% compared to the C16 and M16 typologies;
- New building forms and mixed typologies that are more "solar access conscious" from the EDP, can have equivalent heating demand while improving daylighting, compared to more traditional courtyard typology;

- VSC linked to Heating demand is a valuable analysis for indicating optimal building form and density threshold at EDP;
- Solar radiations results shows that there is a correlation between urban density and passive solar gain, however, the compactness and building form have a higher impact on the total heating energy demands and solar access.

Future research in this field could focus on refining simulation models and incorporating additional variables. These variables could include novel building forms and construction solutions, thermal comfort and overheating considerations, energy generation possibilities, and future climatic conditions. It is important to note some limitations of this study, for instance, we did not account for overheating and thermal comfort. Furthermore, the study employed a city design simplification with a generic typology applied around the test block, which may limit its representation of the complexities observed in real-world urban environments. The findings of this study offer valuable insights that can inform policy decisions and standards, particularly in the development of innovative building forms that prioritize solar and daylight access within Nordic urban developments.

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