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

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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.

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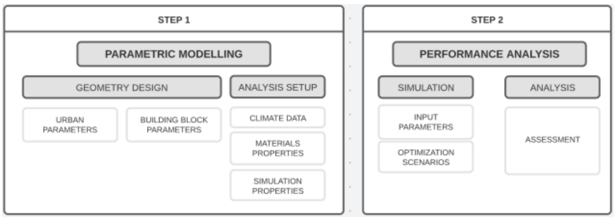
Table 1: Illustration of key findings by previous articles

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 Urban Design	Geometry of urban canyons (H/W ratio) had a relative impact on total energy use and solar distribution
Ko (2013)	Parameters / Metrics Urban Design	Urban canyon height/width ratio (H/W) and envelope “surface-to-volume’ ratio (S/V) used for analysing urban density and its influence on energy use and solar potential
Vartholomaios (2017)	Parameters / Metrics Urban Design	S/V ratio most connection to the heatload H/W ratio most connection to solar provision
Bournas and Dubois (2019)	Parameters / Metrics Urban Design	Urban density [m³/m^2] correlates to room daylight factor criterion
Li et al. (2009)	Parameters / Metrics Building Block Concept Design	Vertical Daylight Factor (VDF) - daylight is significantly reduced in a heavily obstructed dense building block
Mardaljevic and Roy (2016)	Parameters / Metrics Building Block Concept Design	Sunlight Beam Index (SBI) - daylight is significantly reduced in a heavily obstructed dense building block
Sattrup and Strømann-Andersen (2013), ŠPrah & Košir (2019)	Parameters / Metrics Building Block Concept Design	Floor Area Ratio (FAR), and overall plot ratio density, are used as control variables to regulate maximum density
Chatzipoulka et al. (2018), Bournas (2020)	Parameters / Metrics Building Block Concept Design	Vertical Sky Component (VSC) can be a powerful predictor of daylight performance
Bournas (2021)	Parameters / Metrics Building Block Concept Design	Combining building typologies within same block can be a solution to balance daylighting and density
Sattrup and Strømann-Andersen (2013)	Parameters / Metrics Detailed building block design	-Nordic countries are heating energy use dominated -Density above 250%, there is a reduction in daylighting, without any major energy benefit -Daylight Autonomy (DA) highly correlates passive solar gain levels -Specific building typology with same density effect up to 48% DA , and up to 16% of the total energy performance
Bournas (2020)	Parameters / Metrics 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 [m^3/m^2] correlated with room daylight factor (DF) criterion using Grasshopper with Honeybee plugin. They found that density above 2 m^3/m^2 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/m^2, 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/m^2), 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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References

Aksamija, A. (2012, September). BIM-Based Building Performance Analysis: Evaluation and Simulation of Design Decisions. Proceedings of the 17th ACEEE Summer Study on Energy Efficiency in Buildings, Online Event.

Aksamija, A. (2018). Methods for Integrating Parametric Design with Building Performance Analysis. Proceedings of the EAAE/ARCC International 2018 Conference, Philadelphia, PA, May 16–18.

Ayoub, M. (2019). 100 Years of daylighting: A chronological review of daylight prediction and calculation methods. Solar Energy, 194, 360–390. https://doi.org/10.1016/j.solener.2019.10.072

Berge, B. (2009). The ecology of building materials (2nd ed.). Oxford, UK: Architectural Press.

Bournas, I. (2020). Daylight compliance of residential spaces: Comparison of different performance criteria and association with room geometry and urban density. Building and Environment, 185, 107276. https://doi.org/10.1016/j.buildenv.2020.107276

Bournas, I. (2021). Swedish daylight regulation throughout the 20th century and considerations regarding current assessment methods for residential spaces. Building and Environment, 191, 107594. https://doi.org/10.1016/j.buildenv.2021.107594

Bournas, I., & Dubois, M. C. (2019). Daylight regulation compliance of existing multi-family apartment blocks in Sweden. Building and Environment, 150, 254–265. https://doi.org/10.1016/j.buildenv.2019.01.013

Chatzipoulka, C., Compagnon, R., Kaempf, J., & Nikolopoulou, M. (2018). Sky view factor as predictor of solar availability on building façades. Solar Energy, 170, 1026–1038. https://doi.org/10.1016/j.solener.2018.06.028

Ko, Y. (2013). Urban Form and Residential Energy Use. Journal of Planning Literature, 28(4), 327–351. https://doi.org/10.1177/0885412213491499

Larivière, I., & Lafrance, G. (1999). Modelling the electricity consumption of cities: effect of urban density. Energy Economics, 21(1), 53–66. https://doi.org/10.1016/s0140-9883(98)00007-3

Li, D. H., Cheung, G. H., Cheung, K., & Lam, J. C. (2009). Simple method for determining daylight illuminance in a heavily obstructed environment. Building and Environment, 44(5), 1074–1080. https://doi.org/10.1016/j.buildenv.2008.07.011

Littlefair, P. (2001). Daylight, sunlight and solar gain in the urban environment. Solar Energy, 70(3), 177–185. https://doi.org/10.1016/s0038-092x(00)00099-2

Mardaljevic, J., & Roy, N. (2016). The sunlight beam index. Lighting Research & Technology, 48(1), 55–69. https://doi.org/10.1177/1477153515621486

Natanian, J., & Auer, T. (2020). Beyond nearly zero energy urban design: A holistic microclimatic energy and environmental quality evaluation workflow. Sustainable Cities and Society, 56, 102094. https://doi.org/10.1016/j.scs.2020.102094

Ratti, C., Baker, N., & Steemers, K. (2005). Energy consumption and urban texture. Energy and Buildings, 37(7), 762–776. https://doi.org/10.1016/j.enbuild.2004.10.010

Sacks, R., Eastman, C., Lee, G., & Teicholz, P. (2018). BIM Handbook. A Guide to Building Information Modeling for Owners, Designers, Engineers, Contractors, and Facility Managers. 3rd Edition, Wiley, Hoboken. https://doi.org/10.1002/9781119287568

Saelens, B. E., Sallis, J. F., & Frank, L. D. (2003). Environmental correlates of walking and cycling: Findings from the transportation, urban design, and planning literatures. Annals of Behavioral Medicine, 25(2), 80–91. https://doi.org/10.1207/s15324796abm2502_03

Sattrup, P., & Strømann-Andersen, J. (2013). Building typologies in Northern European cities: Daylight, solar access, and building energy use. Journal of Architectural and Planning Research, 30(1), 56–76. https://www.jstor.org/stable/43030993

Sorrell, S. (2015). Reducing energy demand: A review of issues, challenges and approaches. Renewable and Sustainable Energy Reviews, 47, 74–82. https://doi.org/10.1016/j.rser.2015.03.002

ŠPrah, N., & Košir, M. (2019). Daylight Provision Requirements According to EN 17037 as a Restriction for Sustainable Urban Planning of Residential Developments. Sustainability, 12(1), 315. https://doi.org/10.3390/su12010315

Steemers, K. (2003). Energy and the city: density, buildings and transport. Energy and Buildings, 35(1), 3–14. https://doi.org/10.1016/s0378-7788(02)00075-0

Strømann-Andersen, J., & Sattrup, P. (2011). The urban canyon and building energy use: Urban density versus daylight and passive solar gains. Energy and Buildings, 43(8), 2011–2020. https://doi.org/10.1016/j.enbuild.2011.04.007

Vartholomaios, A. (2017). A parametric sensitivity analysis of the influence of urban form on domestic energy consumption for heating and cooling in a Mediterranean city. Sustainable Cities and Society, 28, 135–145. https://doi.org/10.1016/j.scs.2016.09.006