# FROM MACRO TO MICRO

*An integrated algorithmic approach towards sustainable cities*

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**Abstract.** As urbanization rapidly increases towards concerning levels, new methodologies and approaches are required to shape future cities. This research combines passive design approaches with building performance simulation in the same algorithmic description, to highlight the bidirectional impact of the building and the urban context in which it is inserted. To that end, the proposed workflow employs an algorithmic design tool along with validated analysis engines, to assess incident solar radiation and comfort metrics. We apply this methodology in a case study, exploring alternative building geometries to mitigate the consequences of uninformed design decisions in the environment. Results show that the application of passive design strategies can be done within early design stages, allowing a continuous workflow from project to construction while minimizing time and labour requirements regarding building efficiency.

**Keywords.** Algorithmic design; Building analysis; Passive design; Urban comfort.

## 1. Introduction

Buildings are responsible for 60-80% of the energy consumption and 75% of the carbon emissions at a global level (United Nations 2019). With 68% of the world's population predicted to live in urban areas by 2050 (UN DESA 2019), an excessive and unplanned increase in urban density can significantly impact cities' comfort levels, as well as their overall energy demand. Buildings are increasingly expected to fulfil a series of environmental and efficiency requirements, and the concern over the ecological footprint of new urban areas reflects a ubiquitous need for new decision-making strategies regarding project conception and design.

The evaluation of building energy efficiency is typically postponed to a later design stage, where the building form is already definite. This happens because (1) in early design stages there is considerable uncertainty in simulation inputs and, thus, large parameter ranges need to be used (Samuelson et al. 2016), and

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(2) architects and engineers tend to approach the design process in discrepant manners, emphasizing either design exploration or the optimization of building systems (Yang and Yan 2016).

Parametric design approaches can provide new form-finding and communication methodologies for urban planning and architecture, promoting design understanding and learning outcomes from the user's perspective (Schnabel 2008). These approaches can potentially expand the design exploration space, allowing for the generation of multiple design outcomes that respond to specific objectives and needs. When combined with building performance simulation (BPS), parametric design approaches establish a bridge between urban design and environmental requirements, allowing the evaluation of the impact of the physical properties of buildings, urban density, and the use of renewable energy sources in the project's site (Tereci and Kesten 2014).

### 1.1. RELATED WORK

Considering the diversity of parametric design approaches and their disciplinary connections, informed decision-making processes in urban design involve the contemplation of trade-offs. Delmas et al. (2018) implements the concept of integrated design through a platform that incorporates accurate physics with parametric modelling for data exchange, design exploration, and performance-driven optimisation. The usability and appropriateness of this platform are investigated through a workshop, highlighting the need to improve the fluidity of modelling within different phases, along with the transparency of assumptions and calculations. Following this line, the design workflow developed by De Luca (2019) comprises several integrated algorithms to generate building cluster variations and perform daylight analysis, as well as wind and urban comfort simulations. Fink and Koenig (2019), alternatively, focus on the analysis of designs in different disciplines such as climate, usage, and spatial quality, emphasizing the need for automated processes and the development of a strategy for interdisciplinary data exchange.

Integrating multi-software approaches denotes a comprehension of the required balance between investments and achievements, as the project process is divided into a series of smaller tasks - ranging from the creation of an initial shape to the making of a 3D model and, subsequently, one or more analytic models. The back-and-forth communication between different programs and software experts is not direct: in most of the cases, the analysis tools require a simplified version of the original 3D model that needs to be created manually, turning the task of performance evaluation into a process that is more susceptible to user mistakes which cause delays in the project's timeline (Leitão et al. 2017).

### 1.2. OBJECTIVES

There are two key perspectives to be considered in urban design: (1) the impact of the building in the urban context, and (2) the impact of the urban context in the building. Changing quantitative variables regarding geometry, building systems, and site morphology contributes to the adaptation of a project to different climatic and urban contexts. The presented research develops an integrated approach for urban design, combining algorithmic design (AD) and BPS. The goal is to reduce the time required by the separate tasks, as well as to avoid information losses caused by moving the building model between different tools.

Section 2 defines the workflow of the presented work. This methodology is applied to a case study, described in Section 3. Section 4 discusses the results of the proposed study, outlining the final remarks and future work in Section 5.

## 2. Workflow

To achieve an integrated urban design approach, we present an AD strategy that merges the design and analysis modelling into a single task. We use a new AD tool, Khepri, to automate the generation of equivalent models in several CAD, BIM, and analysis tools, as well as game engines. An abstraction layer is used to translate the operations for geometric modelling into the corresponding operations of each specific tool, commonly known as *backends*. Although based on a textual programming language, Julia, Khepri has a smooth learning curve so that architects can develop large-scale projects in a short time span (Leitão et al. 2019; Sammer et al. 2019).

Our AD approach is illustrated in Figure 1. Along with the building design component, it comprises radiation analysis to assess the impact of a building on the adjacent urban fabric, and comfort analysis of buildings within different urban contexts. OpenStreeMap (OSM) and weather data are retrieved through Khepri from a previously selected location site. The building geometry is described parametrically, along with the required operations for each *backend*. The user can directly visualise the 3D model or, instead, run simulations and visualise the attained results in a chosen platform. This workflow is applied to a case study, to ponder upon the performance of a building design when compared to other design variations.

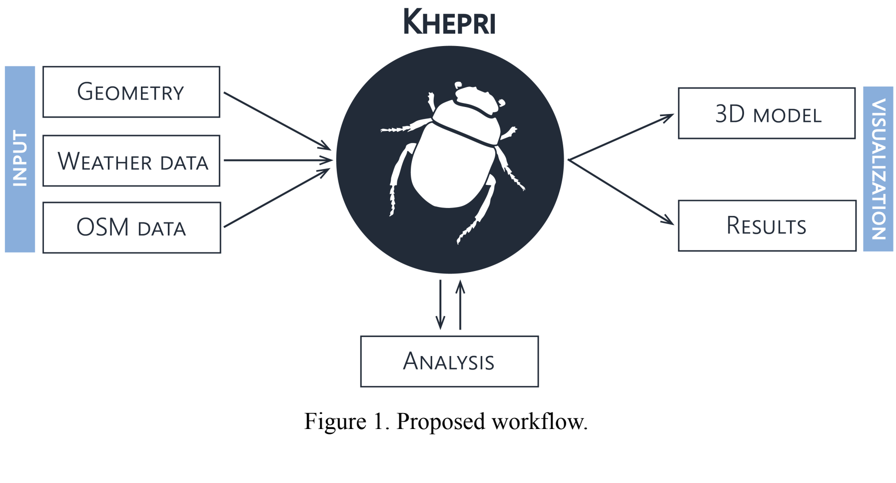



Figure 1. Proposed workflow.

## 3. Case Study

To evaluate the applicability of the proposed workflow, a case study is modelled and analysed to observe the interrelation between a building and its surroundings. The building design is inspired by Rafael Viñoly's 20 Fenchurch Street in London, often called the *Walkie Talkie*. Since its construction, the concave shape of the Southern façade raised multiple concerns regarding the creation of a lens effect, concentrating sunlight towards Eastcheap Street and, consequently, severely increasing temperature and glare levels in the area. Viñoly argued that a lack of tools to accurately analyse the problem in a design stage was responsible for this fault (Wainwright, 2013). The presented work uses this case study to show that incorporating AD and BPS into the design workflow can significantly help to identify issues before the building's construction, ultimately preventing additional costs to the project.

### 3.1. DESIGN STAGE

The first step of our workflow encompasses the generation of building geometry through an algorithmic description. The modelled elements have specified design constraints, which can be manipulated throughout the design process. In this case, we explore passive building design variables such as building height, glazing ratio, and the shape of the building envelope, namely its concavity/convexity. Afterwards, the user selects the location of the urban environment to be tested alongside the building, as well as the tool in which the model will be generated (Figure 2). The possibility of using various *backends* allows the user to take advantage of the multiple capabilities of each tool, transitioning effortlessly from one to another without having to import or reproduce the model from scratch.

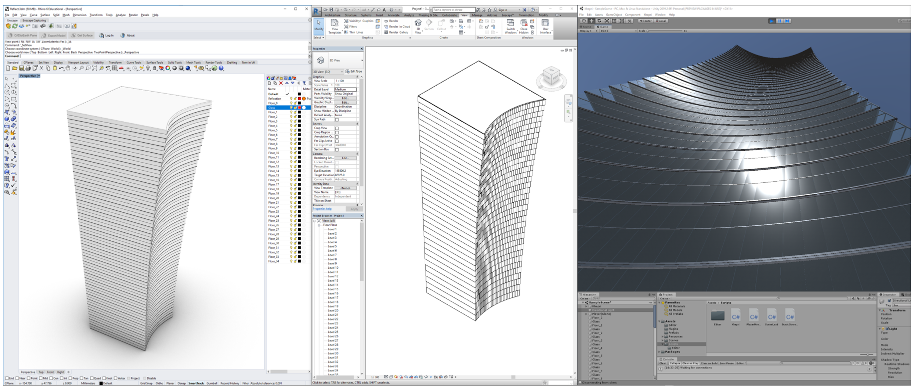
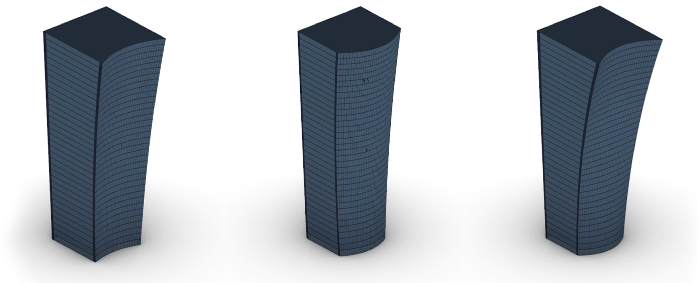


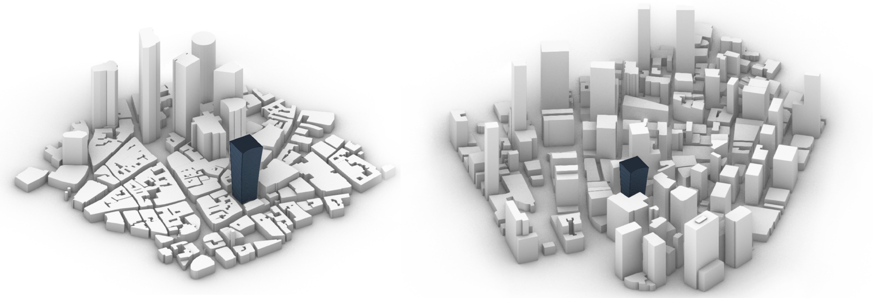
Figure 2. Visualization of the algorithmic model in different Khepri backends. From left to right: Rhinoceros 3D; Revit; Unity.



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

Figure 3. Design variations for the case study geometry: (a) original design, with a concave façade; (b) convex façade; (c) concave and convex façade.

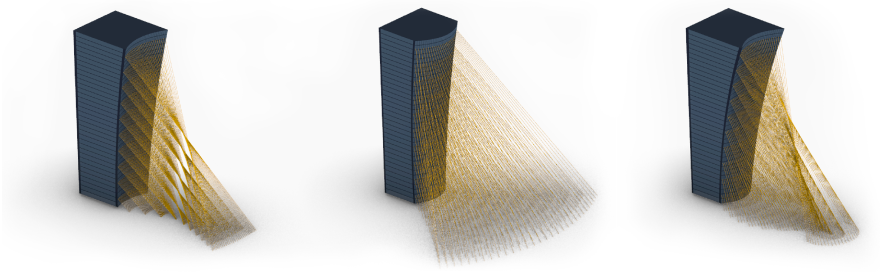
The urban context is incorporated into the algorithmic definition using the previously retrieved and converted OSM data. Two contrasting environments are modelled, to understand how different urban fabrics can impact the same building. For this work, apart from London, we integrate our building into the city of New York. The built environment of Lower Manhattan, shown in Figure 4b, has an average building height that can, hypothetically, accommodate a structure as the *Walkie Talkie* more adequately. Therefore, it is predicted that the incident solar radiation in our case study is significantly smaller in this location than in the building's original site, hence enhancing the comfort level in interior spaces.



*(a)* *(b)*

Figure 4. Urban models for the cities of (a) London and (b) New York.

Before transitioning to the analysis stage, we can already discern the effects of each design variation in terms of the reflection of sun rays. By observing the light reflection at the centre of each glazed surface, it is possible to foresee the areas of impact in the surrounding environment (Figure 5). As seen in (a), there is a high concentration of sun rays at the ground level and along with the building height, contrasting with (b) which shows the higher radiation dispersion of the three. As a compromise between the two scenarios, the inflection point in (c) where the façade turns from convex to concave may be revised, so that its reflection does not focus on any building or public space in the urban fabric.



(a) (b) (c)

Figure 5. Preliminary feedback for the reflection of sun rays in the three building variations.

## 3.2. ANALYSIS STAGE

Two distinct simulations are contemplated in the analysis stage. Firstly, a grid-based daylight simulation is performed, where the impact of the case study, as well as its geometrical variations, on the nearby buildings and public space is evaluated through a radiation map. Secondly, we observe the influence of the urban fabric in the interior comfort of our case study, comparing its performance in the two selected sites. To perform the required analysis, we use validated simulation tools, namely Radiance (McNeil and Lee 2012) and EnergyPlus (Witte et al. 2001).

### *3.2.1. Radiation Analysis*

Prior to running the simulation, the building materials need to be defined. For this case study, we use a plastic material with a 30% reflectance for the façade and context, and a mirror material for the glazing to replicate the highly reflective glass panes of the *Walkie Talkie*. An analysis grid is positioned in the ground geometry and surrounding environment, with three meters between each analysis node. The simulation runs from August to September, between 11 AM and 1 PM, in the urban fabric of London, using the correspondent weather file for this location.

We test the cumulative incident solar radiation per area caused by the three geometric variations shown in Figure 2. The purpose of these analyses is to grasp if the issues concerning the original construction of the *Walkie Talkie* could have been avoided. Changing the façade concavity to convexity along the building height should show better results than the original, highlighting the importance of including BPS in early design developments.

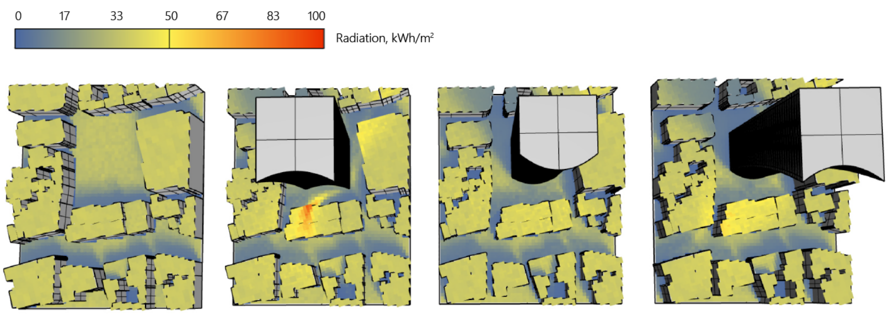
### *3.2.2. Comfort Analysis*

In this stage, we change from a day-long to a year-long analysis period to contemplate the cumulative effect of the urban fabric in our building. Weather variables (e.g., outdoor dry bulb temperature, and wind speed) and building performance variables (e.g., mean radiant and operative temperatures) are joined to compose an adaptive comfort chart based on the ANSI/ASHRAE Standard 55. The percentage of comfort hours for each floor is calculated for the locations shown in Figure 4, and their performance is compared for two contrasting climates. Afterwards, we assess the impact of the urban fabric on a smaller scale to observe the relation between the outdoor and indoor temperatures on an average floor.

## 4. Results and Discussion

The radiation analysis results are illustrated in Figure 6, comprising the incident radiation in both the public space and in the building envelopes that surround our case study. We compare the performance of the design variations with a scenario in which no building is inserted, which showed a significant distinction regarding the impact of a building with this height and glazing in a low-height urban fabric such as the one of London. The maximum values for the cumulative incident radiation reach 39, 87, 45, and 56 kWh/m2 for (a), (b), (c) and (d), respectively.

The first design option, with a fully concave façade, was intended to roughly reproduce the effects caused by the *Walkie Talkie* building in Eastcheap Street. A higher density of incident radiation is clearly identified in the adjacent public space and buildings, which will negatively affect their indoor operative temperature and energy needs due to the increased heat transfer. This effect is reduced to nearly half when the tested geometry has a fully convex façade, as the output of the second design option is approximate to scenario (a). The third design option portrays a more flexible compromise, as the convex shape at the building ground level diffuses the radiation in the immediate surroundings. However, as the top portion of the façade is still concave, it is evident that the effects caused by the glazed parabola will occur out of the simulated bounds. By increasing the analysed site area, it would be possible to discern the area that might be affected by this phenomenon.




(a) (b) (c) (d)

Figure 6. Incident radiation per area for the empty site and the three building variations.

The comfort simulation output provides an overview of how different urban fabrics and climates can affect the same building. The annual percentage of comfort ranges between 64 and 70% in a warm climate (Figure 7) and between 49 and 61% in a cold climate (Figure 8). Results show that the overall indoor comfort levels are lower in the urban fabric of London than in the one of New York, from the 8th floor until the top floor. Considering the average building height of the two sites, it is logical that the case study performs at a higher level in the latter, given the increased amount of shading produced by the surrounding buildings.

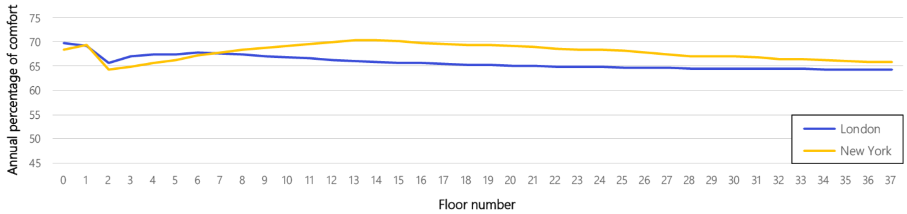



Figure 7. Annual percentage of comfort for a warm climate.

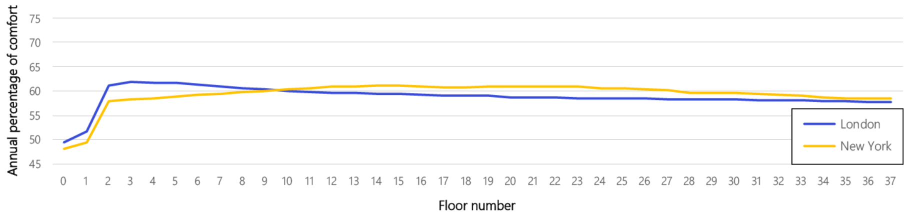



Figure 8. Annual percentage of comfort for a cold climate.

Figure 9 shows the adaptive comfort chart for an average floor, comprising an agglomeration of the hours in which an occupant would feel comfortable in the interior space. For the sake of simplification, this simulation uses only the weather file of the cold climate. New York shows at least 500 hours where occupants are slightly cold, with indoor temperatures of 16 to 18ºC contrasting with an 8ºC outdoor temperature. Moreover, this location shows a reduced thermal amplitude when compared to the same floor inserted into London's context, particularly when temperatures are higher. In this specific case, we see a variation of only 3% between the comfort hours of both locations. However, on some floors, this variation can reach up to 10%. Ultimately, this form of output is valuable to discern how climate and urban fabric affects the building shape, allowing the user to adjust the project in a passive way (e.g., building height, glazing ratio, number of floors) to ensure maximum comfort levels for occupants.

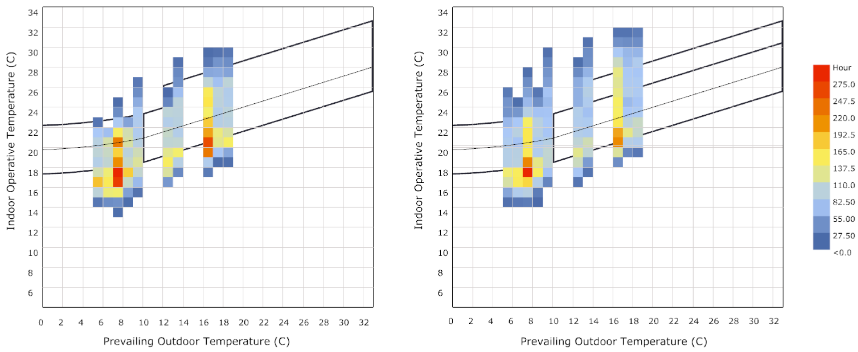



Figure 9. Adaptive comfort chart for an average floor. Left: New York; Right: London.

Although BPS is a relevant component of this workflow, it is important to consider that these analyses are to be applied in early design stages. Hence, the selected material properties, as well as the project orientation and scale, can be a source of uncertainty for the radiation analysis output. However, we can discern design heuristics from this case study, quickly identifying high impact parameters in the shape's algorithmic description, which can affect incident radiation and consequent decrease in urban space indoor comfort levels. This work does not consider parameters such as metabolic rates, occupancy levels and light density, which are often only considered in later design stages when the requirements regarding building systems are stricter.

## 5. Conclusions and Future Work

This work merges AD and BPS into an integrated approach for architectural and urban design to facilitate the application of passive design strategies. Using AD, the implementation of design changes is significantly less time-consuming than the manual adjustment of a model (Leitão et al. 2013), while at the same time allowing for several levels of information regarding BPS inputs, creating a continuous process with an incremental level of detail as we move along design stages. Although the presented AD tool, Khepri, is used specifically for radiation and comfort analysis in this research, it encompasses several other kinds of building simulation and visualization methods.

Considering the building that inspired our case study, one can argue the urgency of incorporating this workflow into project conception. Applied in early stages, it helps the architect to predict and prevent severe damage and discomfort in the surrounding context of the modelled building, while maintaining the creative freedom to explore design variations.

One limitation of the presented workflow is that it does not yet involve optimization processes based on iteration, where analysis results are used to improve building and urban design. We are currently working on incorporating this feature. Moreover, future developments in our methodology aim to include an analysis component based on computational fluid dynamics, which will allow further extension of the analysis scope to wind tunnel and air flow simulations.

## Acknowledgements

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