

Contents

3 Papers

- 5 **Holistic computational design framework**
Elisabeth Korff
- 17 **Translating Architectural Knowledge into Short-Format Social Media: The Case of Nikola Dobrović**
Veronica Chencheva
- 25 **Finding the Best Restroom: Planning Algorithms for Real-Time Crowd Distribution in Public Venues**
Mariia Pykhacheva
- 37 **Introducing Multi-Objective Algorithmic Spatial Planning for Charging Accessibility in Contemporary Public Spaces**
Aslı Yılmaz
- 43 **A Rule-Based Comfort Algorithm for Passenger Distribution in Vienna's Metro System**
Diego Pando
- 49 **A Data-Driven Framework for the Qualitative Assessment and Algorithmic Integration of Recycled Concrete in Circular Construction**
Anna Stalzer
- 61 **Decision Logic for Occupant Behavioural Freedom in Building Energy Performance**
Bükre Öksüz
- 67 **Algorithmic Support for Post-Disaster Temporary Living Area Planning**
Bircan Kömürcü
- 73 **Generative Design System and Evolutionary Optimization for Architectural Layout Planning**
Francesca Iaconis
- 79 **Covering the Lot: Budget-Constrained Placement of EV Chargers in Parking Lots**
Jinsan Ryu
- 85 **Algorithmic Optimization of Vaulted Floor Slabs for Structural Performance and CO₂ Reduction**
Mohamad mahdi Kazemi
- 95 **Bridging the Gap: Parametric design model for social housing**
Esmeralda Torres Perez
- 101 **Algorithmic Compliance Checking in BIM: A Rule-Based Approach for Austrian Building Regulations**
Rineta Sinani
- 111 **Translating Urban Air Quality Data into Planning Knowledge: Algorithmic Approaches in Urban Planning**
Ermira Sejdiu
- 121 **Introducing KPIs for Sustainable Development Goals**
Utku Arslan
- 131 **Forecasting Building Futures: An Algorithm for Measuring Transformation Diversity (TDI)**
Enkeljetë Ademi
- 137 **Beyond Geometric Efficiency: Integrating Social Constraints into Multi-Objective Zoning Algorithms**
Aikhomu Evans Onokevbagbe

PAPERS

Abstract

Computational Design is a method to produce efficient design solutions.

However the approach to it remains a top down logic.

This paper proposes a holistic bottom up approach that grounds computational design in biological principles and philosophical teachings before parametric computation is introduced.

This repositions computational design as a emergent and relational process and will therefore reframe design intent.

Grounding Computational Design in Biological and Philosophical Principles: Towards a Holistic, Bottom-Up Framework Drawing on Computational Design Thinking and the ICD Stuttgart

By Elisabeth Korff

Computational design has emerged as a powerful methodology for generating efficient, data-driven design solutions across architecture, engineering, and construction. Pioneering institutions, such as the Institute for Computational Design and Construction (ICD) at the University of Stuttgart, have demonstrated their capacity to produce formally and materially innovative outcomes by integrating simulation, fabrication, and biological precedents within a single design framework.

Despite these advances, computational design remains predominantly grounded in a top-down logic: algorithmic scripts, performance targets, and formal grammars are imposed upon design problems from the outset, with limited regard for the emergent, relational, and philosophical dimensions of built environments. Even within research-led practice, the generative substrate of computation is rarely interrogated before parameters are set, leaving the deeper orientation of design intent unexamined.

This paper proposes a holistic, bottom-up framework that repositions computational design by grounding it first in biological principles like self-organisation, morphogenesis, material behaviour and in philosophical teachings on relationality and systems thinking, before parametric computation is

introduced. The framework draws critically and productively on Achim Menges' theory of Computational Design Thinking and on exemplary ICD Stuttgart projects as concrete instantiations of biologically and materially informed computation.

Adopting this framework repositions computational design as an emergent and relational process rather than a tool of formal optimisation. It is argued that this reframing will expand design intent, deepen the integration of material and biological intelligence into generative workflows, and provide a replicable methodology for practice and pedagogy aligned with the trajectory established by the ICD.

Keywords: computational design, bottom-up design, biological principles, emergence, morphogenesis, Achim Menges, ICD Stuttgart, relational design, material computation

1. Introduction

Computational design occupies a central and rapidly evolving position in contemporary architectural discourse. Over the past three decades, the integration of parametric modelling, simulation, and digital fabrication into design workflows has fundamentally altered what designers can produce, how they reason about material and form, and what counts as architectural knowledge. Research institutions have been at the forefront of this transformation. Foremost among them is the Institute for Computational Design and Construction (ICD) at the University of Stuttgart, directed by Achim Menges, whose work has consistently demonstrated that computation, when coupled with deep biological and material intelligence, is capable of

Abstract

producing structural and spatial outcomes of exceptional performance and formal innovation. The pavilion projects, fibre-wound structures, and bio-inspired timber systems that have emerged from the ICD represent a sustained argument for the productive alignment of algorithmic process and natural logic. Yet even within this advanced research context, a fundamental tension persists. Computational design—as it is practised across both research and professional settings—remains largely structured around a top-down logic: designers specify

objectives, constraints, and formal grammars, and the algorithm searches for solutions within those pre-defined boundaries. This structure presupposes that the relevant variables of a design problem can be fully articulated before computation begins. In practice, this assumption is epistemologically problematic. The most generative properties of living systems—emergence, adaptability, relational sensitivity—arise precisely from processes that resist prior specification. When computational design imports the optimisation paradigm wholesale, it risks producing outputs that are locally efficient yet globally disconnected from the biological and philosophical realities of inhabited environments (see **Problem**).

This paper addresses these tensions through the following contributions:

- **Overview of the proposed framework.** A layered, bottom-up methodology is introduced in which biological principles and philosophical teachings constitute the foundational stratum upon which parametric computation is subsequently applied. The theoretical grounding for this framework is developed in relation to existing scholarship on computational design, material behaviour, and biological morphogenesis (see **Background**).
- **Identification of the top-down problem.** The structural limitations of prevailing computational design practice are examined through quantitative and qualitative evidence, including post-occupancy assessments and critiques drawn from the literature on algorithmic design (see **Problem**).
- **Engagement with Computational Design Thinking and ICD Stuttgart.** The theoretical framework advanced by Achim Menges—particularly his concept of Computational Design Thinking as a mode of integrating material, biological, and computational intelligence—is critically examined and extended as the conceptual core of the proposed bottom-up methodology (see Computational Design Thinking & ICD Stuttgart).

The outcome anticipated from this framework is a fundamental reframing of computational design intent. Rather than treating the algorithm as a problem-solving engine applied to a pre-specified brief, this paper argues for a mode of practice in which computation serves as a medium through which emergent, biologically and philosophically grounded design intelligence is expressed. The ICD Stuttgart, and Menges' theoretical work in particular, provides both an intellectual precedent and a practical demonstration that such a reorientation is not only possible but generative.

2. Background

The history of computational design is one of progressive formalisation. Early parametric systems, developed in the 1960s and 1970s in the work of Nicholas Negroponte and the Architecture Machine Group at MIT, sought to encode functional and spatial relationships as mathematical expressions, enabling designers to explore families of solutions rather than singular artefacts (Woodbury, 2010). The subsequent development of generative and evolutionary computation extended this capacity to include stochastic search and fitness-based selection, embedding optimisation logic at the core of the computational design paradigm. Contemporary environments—Grasshopper, Dynamo, scripting interfaces in Python and C#—have democratised these methods while reinforcing their underlying epistemological orientation: the designer specifies; the algorithm optimises. In parallel, research in developmental biology and complexity science has articulated a fundamentally different model of how form arises. Biological morphogenesis—the process by which organisms develop differentiated structure through the interaction of genetic programmes and environmental signals—produces forms of extraordinary structural efficiency and adaptive integration without recourse to top-down

specification (Thompson, 1917; Turing, 1952). Self-organising systems, from slime mould networks to trabecular bone architecture to the branching geometry of vascular systems, generate order through local interactions that aggregate into globally coherent patterns (Ball, 2009). These biological precedents suggest that the most robust and ecologically integrated design solutions arise not from imposed optimisation but from co-evolutionary processes in which form, material, and environment mutually condition one another. Philosophical traditions provide complementary frameworks. Process philosophy, as articulated by Alfred North Whitehead (1929), conceives of reality as constituted by events and relations rather than static objects or fixed geometries—a conception directly at odds with the object-centred ontology implicit in most parametric design environments. Gregory Bateson's systems epistemology (1972) argues that intelligence is not a property of individual agents but of relational systems, implying that design intelligence cannot be fully located in the algorithm or the designer, but emerges from the interaction of computational processes, material behaviour, and ecological context. These philosophical resources, taken together, articulate an alternative ontological ground for computational design—one that is relational, processual, and ecologically embedded. It is within this dual context—the biological sciences and philosophical process thought—that the work of the ICD Stuttgart becomes theoretically significant. The ICD's research programme is not simply an application of computational tools to

architectural problems; it represents a sustained investigation into the conditions under which computation, material, and biology can be made to think together. The pavilion series, the research on fibre composite structures, and the collaborative work with the Institute of Building Structures and Structural Design (ITKE) collectively constitute an empirical body of evidence for the propositions advanced in this paper.

3. Problem

The central problem addressed in this paper is the structural disconnect between the operational logic of computational design as broadly practised and the relational, biological, and philosophical dimensions of the environments it produces. This disconnect manifests across three interrelated registers.

3.1 The Epistemology of Top-Down Specification

Top-down computational design proceeds from a reductionist epistemology in which the complexity of real environments is collapsed into a set of computable variables. This epistemology is not merely a technical convenience; it actively structures what designers pay attention to, what counts as a performance criterion, and what remains outside the model. Emergent properties—social vitality, material resilience over time, ecological responsiveness—cannot be specified as input variables because they are precisely those properties that arise from interactions the model cannot anticipate. When computational design treats these properties as secondary outputs rather than primary generative inputs, it systematically underperforms in producing environments that sustain living systems. Quantitative evidence of this underperformance is accumulating. Post-occupancy evaluations of algorithmically optimised buildings have consistently found that energy efficiency targets, while met in

formal terms, frequently coincide with occupant wellbeing deficits and diminished spatial adaptability (Leaman & Bordass, 2007). The gap between predicted and actual performance—well documented across simulation-led design processes—points to a modelling horizon beyond which the complexity of inhabited environments exceeds the representational capacity of the computational framework.

3.2 Material Intelligence and Its Suppression

A second dimension of the problem concerns the treatment of material. In conventional computational design workflows, material is assigned to a pre-determined geometry as a property rather than engaged as an active participant

in form generation. This suppresses what Menges (2012) describes as material computation: the capacity of physical matter to process environmental information and to generate differentiated structural behaviour without external specification. Biological structures—bone, shell, wood—are not uniform materials applied to pre-designed geometries but heterogeneous, gradient organisations in which material distribution, orientation, and density are co-extensive with structural logic. When computational design treats material as a passive substrate, it forfeits the generative and structural intelligence embedded in material behaviour itself.

3.3 The Absence of a Bottom-Up Generative Substrate

The third dimension of the problem is the absence, in most computational design practice, of a generative substrate that precedes formal specification. Designers typically enter computational environments with a design brief already structured around programmatic, regulatory, and aesthetic criteria that encode particular assumptions about what design is for and what counts as a good outcome. These assumptions are rarely made explicit or subjected to critical examination before the algorithmic process begins. The result is a computational design practice that is technically sophisticated but philosophically unreflective—capable of generating formally complex solutions but unable to question the criteria by which those solutions are evaluated. The framework proposed in this paper addresses this absence by insisting that biological and philosophical grounding must precede the introduction of parametric tools.

4. Computational Design Thinking & ICD Stuttgart

Achim Menges introduced the concept of Computational Design Thinking as a theoretical reorientation of how designers understand and engage with computation. In his edited volume of the same title (Menges & Ahlquist, 2011), and in subsequent theoretical writings, Menges argues that computation in architecture has been predominantly understood as a representational and optimisation tool—a means of making pre-conceived designs more precise or efficient. Against this, he proposes that computation be understood as a mode of thinking: a cognitive and generative process through which designers explore, negotiate, and co-produce design intelligence in relation to material, environment, and biological precedent. This shift from computation-as-tool to computation-as-thinking is foundational to the framework advanced in the present paper.

4.1 Biological Analogues and Material Systems

A central strand of Menges' theoretical work concerns the relationship between biological morphogenesis and computational form-finding. Drawing on the developmental biology of organisms whose structural performance arises from heterogeneous material organisation—sea urchin shells, beetle elytra, plant stems—Menges argues that architectural computation can be reoriented around the logic of material systems rather than the logic of geometric specification (Menges, 2012). In this view, the algorithm does not impose form upon material but rather simulates the differentiation processes through which biological materials self-organise in response to structural and environmental loads. The formal outcomes of such processes are not predetermined but emerge from the interaction of computational rules and material constraints. The ICD/ITKE Research Pavilions, produced annually between 2010 and the present, constitute the most sustained empirical demonstration of this principle. The 2011 pavilion, for example, was informed by the structural geometry of the sea urchin's plate skeleton—a biological system in which triangulated plate arrangements produce global structural rigidity from locally thin elements. The computational workflow developed to realise this pavilion did not begin with a geometric target but with a biological structural logic, which was then translated into fabrication constraints and robotic assembly sequences (Fleischmann et al., 2012). The result was a structure whose formal character emerged from the computational negotiation of biological precedent, material behaviour, and fabrication constraint—precisely the bottom-up generative dynamic that this paper proposes as a foundational methodology.

4.2 Integrative Computational Design

Menges develops the concept of Integrative Computational Design to describe workflows in which multiple performance domains—structural, environmental, material, spatial—are co-processed within a single generative model rather than addressed sequentially in separate specialist analyses (Menges, 2015). This integration is not merely technical but epistemic: it requires that the designer hold multiple, potentially incommensurable performance logics in productive tension throughout the generative process. The ICD's work on hygroscopic wood composite structures illustrates this integrative logic particularly clearly. In the HygroSkin pavilion (2013), the differential swelling behaviour of wood veneer in response to atmospheric humidity was engaged as an active actuating mechanism, with the computational design process modelling material response rather than specifying geometric outcome. The pavilion's aperture system—responsive, material-based, without mechanical actuation—emerged from

computational engagement with biological material intelligence rather than from geometric design intent.

4.3 Implications for a Bottom-Up Framework

The theoretical and practical contributions of Menges and the ICD demonstrate that a bottom-up, biologically grounded approach to computational design is not a speculative proposition but a research-validated methodology. However, the present paper argues that the ICD's framework, while exemplary, requires extension in one critical respect: it has not yet systematically integrated the philosophical dimension of relational and ecological thinking as a generative precondition. Menges' work operates with biological analogues and material intelligence as its primary conceptual substrate; the framework proposed here augments this with the processual and relational philosophies of Whitehead and Bateson, arguing that a fully bottom-up computational design practice must be grounded in both biological and philosophical intelligence before computation begins. In this sense, the proposed framework represents not a critique of the ICD's work but its philosophical extension.

5. Discussion

Viewed from an external vantage point, the framework proposed here occupies a productive but contested position within the broader field of architectural computation. It aligns itself with the most intellectually ambitious strand of computational design research—as represented by the ICD—while arguing that even this strand requires a more explicit philosophical grounding. This positioning is deliberate: the framework is not proposed as a rejection of algorithmic sophistication but as its conceptual deepening. The question is not whether to compute, but from what epistemic and ontological ground computation should proceed. The relationship between the proposed framework and Menges' Computational Design Thinking deserves careful articulation. Menges argues that computation enables designers to engage with biological complexity at a level of resolution and integration that manual design methods cannot achieve. This paper accepts that argument and builds upon it. Where it departs from Menges is in the insistence that the biological analogues operative in computational design must be accompanied by an explicit philosophical account of what it means to design relationally and processually—an account that Menges' empirically-oriented research programme does not fully develop. The philosophical resources of Whitehead and Bateson, introduced in the Background, provide this account and constitute the theoretical supplement that the proposed framework contributes. From a pedagogical perspective, the

framework has significant implications for architectural education. Computational design pedagogy has tended to prioritise technical proficiency—scripting, simulation, fabrication—over conceptual depth. The introduction of biological principles and philosophical teachings as prerequisites to parametric instruction would represent a substantial curricular reorientation. Precedent exists for such an approach: the ICD's own teaching programme integrates material research, biological investigation, and computational exploration within a single design studio, demonstrating that technical and conceptual learning are not sequential but mutually constitutive. The framework proposed here scales this pedagogical logic into a replicable structure applicable beyond Stuttgart. Several challenges to the framework's implementation merit acknowledgement. First, the translation of biological and philosophical principles into computational parameters is not straightforward. The richness of biological morphogenetic processes and the relational complexity of philosophical process thought exceed what any parametric model can fully represent. This is not a deficiency to be overcome but a productive tension to be maintained: the gap between biological reality and computational representation should function as a generative irritant rather than an engineering problem to be solved. Second, the institutional contexts within which most computational design is practised—professional offices, procurement frameworks, accreditation systems—are structured around deliverable outputs rather than generative processes. Advocating for a process-centred, bottom-up methodology requires engagement with these institutional structures as well as with design theory.

6. Conclusion

Computational design emerged as a powerful methodology for generating efficient design solutions across architecture, engineering, and construction. Pioneering institutions such as the ICD Stuttgart, under the direction of Achim Menges, demonstrated its capacity to produce formally and materially innovative outcomes by integrating simulation, fabrication, and biological precedent within a single design framework. Despite these advances, computational design remained predominantly grounded in a top-down logic in which algorithmic scripts and performance targets were imposed upon design problems from the outset, with limited regard for the emergent, relational, and philosophical dimensions of built environments. Even within research-led practice, the generative substrate of computation was rarely interrogated before parameters were set. This paper proposed a holistic, bottom-up framework that repositioned computational design by grounding it first in biological principles—self-organisation, morphogenesis, material behaviour—and in philosophical teachings on relationality and systems thinking, before parametric computation

was introduced. The framework drew critically and productively on Menges' theory of Computational Design Thinking and on exemplary ICD Stuttgart projects as concrete instantiations of biologically and materially informed computation. It extended this body of work by arguing that a fully bottom-up methodology required the explicit integration of philosophical grounding as a generative precondition—a dimension not yet systematically developed within the ICD's empirically-oriented research programme. The adoption of this framework repositioned computational design as an emergent and relational process rather than a tool of formal optimisation. It was argued that this reframing expanded design intent, deepened the integration of material and biological intelligence into generative workflows, and provided a replicable methodology for practice and pedagogy aligned with—and extending beyond—the trajectory established by the ICD. Future research was identified in the empirical validation of the bottom-up methodology across diverse project types and institutional contexts.

References

- [1] Ball, P. (2009). *Shapes: Nature's Patterns — A Tapestry in Three Parts*. Oxford University Press.
- [2] Bateson, G. (1972). *Steps to an Ecology of Mind*. Chandler Publishing.
- [3] Fleischmann, M., Knippers, J., Lienhard, J., Menges, A., & Schleicher, S. (2012). Material behaviour: Embedding physical properties in computational design processes. *Architectural Design*, 82(2), 44–51.
- [4] Knippers, J., & Menges, A. (2013). Advancing wood architecture: A computational approach. *Architectural Design*, 83(2), 60–65.
- [5] Leaman, A., & Bordass, B. (2007). Are users more tolerant of 'green' buildings? *Building Research & Information*, 35(6), 662–673.
-
- [6] Menges, A. (2012). Material computation: Higher integration in morphogenetic design. *Architectural Design*, 82(2), 14–21.
- [7] Menges, A. (2015). Integrative design computation: Integrating material behaviour and robotic manufacturing processes in computational design for performative wood constructions. *Proceedings of the 35th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)*, 170–177.
- [8] Menges, A., & Ahlquist, S. (Eds.). (2011). *Computational Design Thinking*. Wiley.
- [9] Thompson, D. W. (1917). *On Growth and Form*. Cambridge University Press.
- [10] Turing, A. M. (1952). The chemical basis of morphogenesis. *Philosophical Transactions of the Royal Society B*, 237(641), 37–72.
- [11] Whitehead, A. N. (1929). *Process and Reality: An Essay in Cosmology*. Macmillan.
- [12] Woodbury, R. (2010). *Elements of Parametric Design*. Routledge.

Translating Architectural Knowledge into Short-Form Social Media: The Case of Nikola Dobrović

Abstract

Nowadays, social media platforms such as Instagram and TikTok are among the most dominant channels for public communication. However, high-quality architectural content is rarely presented in this medium, especially in an accessible way. We propose a method for translating architectural knowledge into short-format videos, tested through the case of Nikola Dobrović's Grand Hotel and Generalštab buildings, without reducing it to purely visual entertainment. This approach can make architecture more visible, understandable, and relevant in today's social media culture.

Introduction

In the last two decades, social media has become one of the most dominant platforms for presenting contemporary culture, information, and visual material. Platforms such as Instagram and TikTok are no longer used only for entertainment; they also host channels for topics like education, professional development, opinions, politics, and controversial issues. The fact that these platforms are highly visual and cater to short attention spans means they can not only communicate but also influence how information is selected, filtered, and presented.

This new way to deliver information also affects the architecture field. Usually, architectural knowledge is communicated through drawings, models, photographs, exhibitions, lectures, books, competitions, and professional publications. These formats allow architecture to be understood through spatial concepts, context, materiality, function, and design process. On social media, however, architecture is often presented through its immediate visual qualities, such as attractive façades, spectacular interiors, lifestyle images, or short inspirational clips (Lindsay, Sawyer, & Alaily-Mattar, 2025). Most of this content is produced for broad public engagement and therefore tends to privilege visual appeal, speed, and entertainment value over architectural analysis. As a result, deeper layers of architectural knowledge, such as historical context, materiality, spatial experience, and social meaning, can remain underrepresented.

This environment presents a significant challenge for architectural communication. When architecture is primarily presented as visual content, public understanding of the discipline risks becoming simplified or distorted. Buildings of historical or technical significance may be overlooked online if they are not immediately visually striking. Nevertheless, the increasing use of short-form video also offers new opportunities to give knowledge and generate public interest. Rather than dismissing social media as superficial, architects can treat it as a communication tool, translating their expertise into formats appropriate to these platforms while maintaining the depth and integrity of their content.

This paper proposes a method for sharing architectural knowledge through short-format videos on social media. It looks at how architectural topics can be visualized and structured for platforms like Instagram and TikTok. The goal is to make architecture more accessible and relevant in social media culture, without reducing it to just visual entertainment. To test this approach, the paper uses the figure of Nikola Dobrović and his buildings, the Grand Hotel and the Generalštab, as case

studies. The team project involved creating a social media account to produce short videos about his work.

Architectural Representation and Social Media

Architectural representation has always depended on different tools. Since buildings cannot always be experienced directly, especially in the early stages of planning, architecture is often communicated through sketches, plans (such as floor plans, sections, elevations), physical models at a given scale, photographs, texts, exhibitions, lectures, and, in some cases, even professional publications. Each of these formats presents a different side of the architecture's qualities. Plans represent spatial organization and technical structures. Photographs and models can show atmosphere and materiality, helping to better understand the building. Written and spoken formats, such as books, lectures, and articles, enable the transportation of historical context, theoretical ideas, the design process, and social meaning. Architectural knowledge is built from many layers that combine visual, textual, and spatial information.

Therefore, architecture is not only a visual discipline. A building may be perceptibly interesting, but its architectural value is also connected to its function, construction, context, history, material use, and the experience of space. These aspects often require time and explanation and are not intuitive. For example, the meaning of a building cannot always be inferred from a single image of its façade. Its meaning may depend on urban factors or even on the historical period in which it was created. Also, while looking at a concrete project, one may not know the political meanings coded in the concept. That's why using the traditional architectural media usually allows these layers to be explained in more detail.

Social media introduces a different way of working with information. Platforms such as Instagram and TikTok are built for fast visual consumption, meaning the videos on those platforms are usually less than or around 60 seconds. Content on these platforms must often attract attention within only a few seconds (the first 3 to 5 are the most important). As a result, the information is usually simplified and presented in a visually direct way. While social media can still present knowledge, the information needs to be adapted to fit the platform's format. The short-format video combines image, movement, text, sound, and narration, which makes it possible to explain complex topics in an accessible way.

For architecture, this situation brings both challenges and opportunities. The challenge is that content can easily be reduced to attractive images or lifestyle aesthetics, ignoring the complexity behind the surface. The opportunity is that short-format videos can serve as tools for architectural education and building preservation. If knowledge is carefully selected and presented, social media can help architects, students, researchers, and cultural institutions reach a wider audience.

This is important in the case of Nikola Dobrović, because his buildings cannot be fully understood only from their current visual appearance, especially given their poor condition. The Grand Hotel and Generalštab have architectural and historical meanings that require explanation, as their value lies not only in form but also in context, memory, urban position, and political history. For this reason, they are useful examples for testing how architectural knowledge can be transformed into short-format social media content.

The Challenge of Translating Architectural Knowledge into Social Media

The main research question of this paper is: how can complex architectural knowledge be translated into short-form social media content while still preserving historical, spatial, and

theoretical meaning? The central problem appears in the difference between architectural communication and the logic of social media. Architecture usually requires time, context, and explanation to be understood, while platforms such as Instagram and TikTok are built on visual appeal, short attention spans, and immediate engagement. This creates a tension between the complexity of architectural knowledge and the simplified form in which information is often consumed online.

Because of this, architecture on social media can easily be reduced to its most visible qualities. Buildings are often presented through aesthetics, atmosphere, or impressive images, while less visible layers such as historical context, spatial organization, materiality, construction logic, social meaning, and political background remain unexplained. This is especially problematic for buildings that are historically or culturally important but not immediately photogenic in their current condition. Their architectural value may become invisible to a broader public because online visibility often depends more on visual attractiveness than on historical or theoretical significance. (Alaily-Mattar, Ponzini, & Thierstein, 2023).

Nikola Dobrović's work clearly shows this difficulty. The Grand Hotel and the Generalštab cannot be understood only through their external appearance (Milošević, 2015). Their importance is connected to historical circumstances, urban position, spatial ideas, political meanings, and architectural concepts. If they are presented only as images, many of these layers remain hidden. Therefore, the problem is not simply that architecture is missing from social media, but that architectural knowledge is difficult to translate into a format that is short, accessible, and still meaningful.

This context underscores the necessity for a method that adapts architectural knowledge to social media without reducing it to mere visual entertainment. The central challenge lies in selecting relevant information, determining suitable simplifications, and effectively visualizing content in a short-form video format. The following section presents the case study and methodological approach adopted in this project, which involved creating a social media account to test how knowledge about Nikola Dobrović's Grand Hotel and Generalštab could be communicated via short videos.

Case Study and Method: Nikola Dobrović on Social Media and the *gameofparallels* Account

To test how architectural knowledge can be adapted to short-format social media, this paper uses Nikola Dobrović and two of his buildings, the Grand Hotel on Lopud and Generalštab in Belgrade, as a case study. These two works were selected because they contain several layers of architectural meaning that cannot be fully understood from their visual appearance alone. The Grand Hotel is connected to tourism, the Adriatic and Yugoslav context, architecture and landscape, and the question of abandonment. Generalštab, on the other hand, is connected to political meaning, war damage, memory, monumentality, and state power.

The project started within a university design studio focused on Nikola Dobrović. Through lectures, exercises, and workshops, the team was introduced to his architectural work and to different ways of reading his buildings. One important exercise was based on Vladimir Kulić's text "Architecture and the Politics of Reading: The Case of the Generalštab Building in Belgrade," which helped define interpretative layers such as history, theory, void, and future. These layers later served as the basis for the social media project's structure and the "parallel series" developed for the account.

Before creating the videos, the team investigated whether Nikola Dobrović and his buildings were already present on social media. This showed that Dobrović himself and the Grand Hotel were almost absent from the platforms, while information about Lopud was mostly connected to tourism and rarely mentioned the hotel. Generalštab had greater online visibility, mainly due to its political status, war damage, and current public debate. From this observation, the research question became clearer: can social media be used to make architectural knowledge about Dobrović's work more understandable and accessible?

As a response, the team created a public Instagram and TikTok account called *gameofparallels*. The name refers to the layered reading of Dobrović's work and to the parallel comparison between different time periods, buildings, and meanings. Although the project was present on both Instagram and TikTok, engagement on Instagram was stronger, partly because the team and its wider network were already more active there.

The content strategy was organized around a clear posting structure. Starting on 11 May, the account published introductory posts about the team, the project's mission, Nikola Dobrović, and the two selected buildings. After this phase, the team began the "parallel series." Each week followed a thematic structure: Monday was dedicated to theory, Wednesday to the void, Thursday to the history of the place, and Friday to the future of the buildings. This structure allowed the project to break complex architectural knowledge into smaller thematic units rather than trying to explain everything in one video.

The videos were mostly produced as reels of about 60 seconds each. They combined spoken explanation, low-volume background music, text, archival material, maps, plans, basic animation, and footage collected during site visits. The team traveled to Lopud Island and Belgrade to film directly in front of the buildings and to collect visual material of their spatial, structural, and contextual qualities. In the case of the Grand Hotel, this also included drone footage of the hotel and its landscape context. In the case of Generalštab, filming was more limited because of the military character of the surrounding area. The team also conducted five interviews, which are planned to be edited and posted as part of the project.

The workflow followed several main steps: research, topic selection, script writing, selection of visual materials, editing, and posting. Although individual tasks existed during the process, the project functioned mainly as a group work of three people, with decisions discussed and refined collectively.

The account was also used to observe how audiences react to architectural content on social media. Since the Instagram account was set up as a business account, it provided access to statistics such as views, interactions, and audience data. By the time of writing, the account had reached 30.4 thousand views in the last thirty days. The most successful videos had between 1,500 and 3,500 views, while the introductory video about Generalštab reached around 8,300. The average watch time for the more successful videos was around 15-19 seconds. These numbers do not prove that viewers fully understood the architectural content, but they do show a visible level of public interest and engagement with this type of material.

The method therefore tested how complex architectural knowledge can be selected, simplified, visualized, and distributed within the limits of short-format social media. The case of Dobrović's Grand Hotel and Generalštab showed that a single video is not enough to explain all the historical, spatial, and political layers of a building. For this reason, the project used a series-based structure,

where different videos could focus on different layers. This became the main methodological response to the problem of simplification.

Discussion

The case study showed that short-format social media can be used as a tool for architectural communication, but only under certain conditions. Architectural content can attract public attention when it is structured in a clear, visual, and accessible way. The account reached a visible audience, especially through Instagram, and the response to some videos showed that there is interest in architectural topics beyond purely aesthetic images. The introductory video about Generalštab was especially successful, suggesting that architectural content can attract more attention when it is linked to a building that already carries public debate, political meaning, or collective memory.

One aspect that worked well was the use of different types of visual material. Site footage, archival images, plans, maps, drone footage, and basic animations helped translate architectural information into a format suitable for short videos (Rogers, 2021). This was important because architecture is difficult to explain only through speech. Visual material allowed the videos to convey context, condition, atmosphere, and spatial qualities, while narration and text guided the viewer through the main argument.

Another important result was the usefulness of the series-based structure. Since the Grand Hotel and the Generalštab contain many historical, spatial, political, and theoretical layers, a single video could not convey the full meaning of each building. The “parallel series” responded to this problem by dividing the architectural knowledge into smaller themes such as theory, void, history, and future. This allowed each video to remain short while still creating a broader narrative across several posts.

However, the project also revealed several limitations. The first is the issue of simplification. To fit architectural knowledge into a video of approximately sixty seconds, it was necessary to prioritize the most essential information and overlook many details. This challenge was particularly obvious when addressing interview material and complex historical or political contexts, as with Generalštab. While the format enhances accessibility, it also risks oversimplifying nuanced concepts (Chiossi et al., 2023).

Another limitation is not knowing what the audience understands. Statistics such as views and watch time are useful, but they cannot fully show whether viewers understood the architectural argument. A video may receive many views because of its visual appeal or topical relevance, rather than because viewers understood its deeper architectural meaning. The average watch time of 15 to 19 seconds indicates that many viewers drop off before finishing.

A third challenge is the extent to which visibility relies on the platform’s logic. Generalštab attracted more attention, partly because of its location in Belgrade and its ties to political debates. The Grand Hotel, while architecturally significant, generated less visible discussion. This shows that visibility on social media depends not only on a building’s architectural value, but also on where it is, what people are talking about, and how algorithms work.

The current physical condition of a building also influences how it can be communicated. Abandoned, damaged, or neglected buildings can be visually powerful, but they are difficult to present without reducing them to ruin aesthetics. In the case of the Grand Hotel, the abandoned condition could become more visible than the architectural concept. In the case of Generalštab,

filming restrictions, military surroundings, and political sensitivity affected both production and representation.

Overall, the experiment showed that social media can support architectural communication if the content is carefully researched, structured, and visually translated. However, it cannot replace traditional forms of architectural representation. Instead, it can function as an entry point. A short video can create interest, introduce a concept, or make a building visible to a broader public, but deeper understanding still requires additional formats, longer explanations, and further research.

Conclusion

This paper examined how architectural knowledge can be adapted to short-form social media without being reduced to mere visual entertainment. It began with the problem that architecture requires context, time, and explanation, while platforms such as Instagram and TikTok are based on speed, visual attraction, and short attention spans. This difference creates a challenge for architectural communication, especially when buildings contain historical, spatial, political, and theoretical meanings that are not immediately visible.

The paper used Nikola Dobrović's Grand Hotel and Generalštab as case studies to test this problem in practice. Through the creation of the public social media account *gameofparallels*, the project explored how knowledge about these buildings could be selected, simplified, visualized, and presented through short videos. The method was based on research, thematic structuring, script writing, collection of visual material, editing, posting, and observation of audience reactions.

The project showed that short-format video can make architectural topics more accessible and visible to a wider audience. Visual material, narration, text, maps, archival images, and site footage can work together to explain selected aspects of a building. The series-based structure was especially useful because it allowed complex knowledge to be divided into smaller thematic parts rather than compressed into a single explanation.

At the same time, the project also showed the limitations of this medium. Complex architectural and historical information must be strongly simplified, and social media statistics cannot conclusively demonstrate that viewers understood the content. The visibility of a video also depends on factors such as location, public debate, visual appeal, and platform algorithms. Therefore, social media should not be seen as a replacement for deeper architectural research, but as a communication tool that can introduce architectural knowledge to a broader public.

In conclusion, the experiment demonstrated that architectural knowledge can be translated into short-form social media content when carefully selected, structured, and visually supported. The case of Nikola Dobrović showed that even buildings with complex historical and political meanings can become more present in contemporary digital culture. However, this is only possible when social media is used critically, not as a space for simple visual consumption, but as a tool for creating access, interest, and further discussion.

References

- Alaily-Mattar, N., Ponzini, D., & Thierstein, A. (2023). *The performance of exceptional public buildings on social media*. PLOS ONE.
- Chiossi, F., Haliburton, L., Ou, C., Butz, A., & Schmidt, A. (2023). *Short-Form Videos Degrade Our Capacity to Retain Intentions: Effect of Context Switching on Prospective Memory*. Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems.

Kulić, Vladimir. "Architecture and the Politics of Reading: The Case of the Generalštab Building in Belgrade."

Lindsay, G., Sawyer, M., & Alaily-Mattar, N. (2025). *Architecture in the age of social media: introduction to the special issue*. Archnet-IJAR: International Journal of Architectural Research.

Milošević, S. (2015). *The concept of otherness in architecture: the case of the Army Headquarters in Belgrade, Serbia*. Journal of Architecture and Urbanism.

Rogers, R. (2021). *Visual media analysis for Instagram and other online platforms*. Big Data & Society.

Finding the Best Restroom: Planning Algorithms for Real-Time Crowd Distribution in Public Venues

Mariia Pykhacheva

Faculty of Architecture and Planning, TU Wien, Vienna, Austria

Abstract

Large public venues such as airports, stadiums and train stations experience uneven restroom usage due to chaotic crowd flows and limited real-time information. Users tend to select the nearest visible restroom, which often leads to congestion, longer waiting times and inefficient distribution of demand across facilities. This paper proposes a real-time restroom recommendation framework that combines occupancy sensing, short-term prediction and planning algorithms to recommend the most efficient restroom option based on walking time, waiting time and predicted congestion. The proposed approach demonstrates how data-driven routing and crowd-aware optimization can improve restroom utilization, reduce queue intensity and support smarter operational management in public venues.

Keywords

real-time planning, crowd management, occupancy prediction, queue optimization, restroom recommendation systems

Introduction

Large public facilities such as airports, stadiums or railway stations rely not only on architectural design but also on the effective organization of human movement within shared and service areas. The distribution of visitors across security checkpoints, corridors, retail zones and, in particular, restroom facilities has a direct impact on overall performance of a venue. The National Academies of Sciences, Engineering and Medicine (2015) consider restroom planning an integral component of airport terminal design rather than a secondary concern. Consequently, access to restroom facilities represents a relevant issue in planning and operational management.

In practice, users typically select the nearest or most visible restroom. The decision is mainly influenced by visibility, distance and surrounding conditions (Moussaïd et al., 2011). While this choice appears rational from an individual perspective, it often leads to system inefficiencies. Certain facilities become congested, whereas nearby alternatives remain underutilized. In high-traffic environments such imbalance contributes to longer queues, increased waiting times and higher levels of congestion. Recent research on crowd management emphasizes the role of real-time sensing, short-term forecasting and adaptive decision-making in transportation hubs and other public environments (Darsena et al., 2021). These technologies are already used for monitoring passenger flows and improving operational management, but they have rarely been applied specifically to restroom selection.

From a planning perspective, the restroom navigation problem combines several factors. There are: large number of users, multiple restroom options, changing demand over time and different walking distances between locations. In addition, decisions influence one another: if too many users are redirected to the same restroom, that restroom may quickly become overloaded as well. This creates a dynamic resource-allocation problem in which real-time information is important for maintaining balanced usage across the system.

This paper therefore approaches restroom selection as a real-time planning and optimization problem. First, it reviews previous work on crowd management, occupancy sensing and passenger-flow analysis. Then it explains why reliance on proximity-based choice and static signage frequently results in uneven distribution. Next, the paper proposes a privacy-aware framework that integrates occupancy sensing, short-term congestion prediction and algorithmic recommendation mechanisms based on walking time, expected waiting time and the risk of overload. Finally, it discusses the system's advantages alongside with possible limitations and future work direction.

The goal of the proposed framework is not to remove queues completely, but to distribute users more efficiently across existing restroom capacity. Better routing and flow organization can reduce waiting times and improve user experience without requiring expensive reconstruction of the facility itself. In this sense, a restroom recommendation system can be understood as a small but practical example of smart infrastructure: a system that uses real-time data and short-term prediction to support faster and more efficient operational decisions.

Background and Problem

Background and Related Work

The literature specifically focused on restrooms is still relatively limited, but it already provides two important starting points. First, airport planning research treats restrooms as part of terminal capacity, passenger comfort, accessibility and overall service quality. The National Academies guide was created because airports needed a more structured approach to restroom planning and design. Second, Gwynne et al. (2019) collected restroom dwell-time data from 502 users in a North American airport and showed that restroom usage is not unpredictable and can be measured and analyzed for planning purposes. This is important for the present paper because any recommendation system requires assumptions about service time, while dwell-time data provide a useful basis for estimating them.

Another major line of research is airport passenger flow management and crowd management systems. ACI EUROPE's manual emphasizes live monitoring, short-term forecasting, real-time passenger information and dynamic distribution of waiting time and crowding data. It also connects restroom demand to predicted passenger flows in sanitation planning, which suggests that restroom usage can be forecasted and managed operationally. In related research Anagnostopoulou et al. (2024) developed a simulation-based tool for airports that helps reduce waiting times and help to minimize overcrowding. Similarly, Zhang et al. (2024) showed in a metro transfer station case-study that better flow organization can reduce queue length, average travel time and crowd density. Although these studies do not specifically focus on restroom recommendation, they show that better routing and flow management can improve public infrastructure operation and help redistribute demand more evenly in general.

Another important research area is occupancy sensing and prediction. Recent studies point out that single sensing technologies do not work equally well in every environment (Ding et al., 2022; Caballero-Peña et al., 2024). Wang et al. (2018) showed that combining environmental sensing with Wi-Fi data can improve occupancy prediction in buildings and also proposed a Markov-based recurrent neural network using Wi-Fi probe data. At the sensing level Lu et al. (2021) demonstrated that low-resolution ToF (time-of-flight) systems can achieve highly accurate occupancy counting. Meanwhile Li and Hishiyama (2023) reported strong indoor people-counting performance using mmWave radar and additional sensors. More recently Zeleny et al. (2024) showed that Wi-Fi probe requests combined with GRU models can support room-level occupancy classification. Together these studies show both the potential and the limitations of wireless sensing systems for real-time occupancy estimation.

The next crucial methodological area is real-time crowd prediction and agent-based simulation. Yasufuku and Takahashi (2024) developed a platform that combines pedestrian-flow sensing, short-term prediction and agent-based simulation for congestion forecasting around a stadium. Their system was able to predict congestion at a nearby station up to ten minutes in advance while running almost real-time simulations for thousands of agents. However, Senanayake et al. (2024) note that agent-based systems still face challenges such as computational cost, validation and realistic human behavior modeling. Malleson et al. (2020) make a similar argument, explaining that integrating real-time data into crowd simulation becomes difficult as the number of agents grows. These limitations are directly relevant to restroom recommendation systems, which must remain both responsive and computationally efficient.

Finally, privacy is an important design requirement. For restroom-related sensing systems one of the key issues is minimizing the amount of personal data collected. The European Data Protection Board's Article 25 guidelines state that systems should collect only the minimum amount of personal data necessary for a specific purpose. In practice, this supports the use of privacy-preserving occupancy sensing in sensitive environments such as restrooms.

Problem

The operational gap can now be stated precisely. Restroom navigation in public venues is still mostly static. Signs can show where restrooms are located, but they do not tell users whether a restroom is crowded, how long the queue is, or whether another option nearby would actually be faster overall. Because of this, people usually choose the closest or most visible restroom even when that choice increases their total waiting time. As a result, some facilities become overloaded, while others remain underused. Although operators may already monitor passenger flows at a larger scale, this information is not transformed into direct recommendations for users.

This issue becomes especially important in venues with high traffic and predictable demand peaks, such as airports, train stations, stadiums and event halls. Boarding waves, train arrivals, intermissions, etc. can quickly create temporary overcrowding. In these situations restroom routing becomes a dynamic problem rather than a static one. A recommendation that is useful one minute may become ineffective a few minutes later as crowd conditions change. In addition, if too many users receive the same recommendation, the suggested restroom may quickly become overcrowded as well. This means that the problem is not only about prediction, but also about balancing demand across multiple facilities.

Another limitation of current systems is that they focus mainly on present conditions instead of future ones. Choosing the restroom with the shortest queue right now is often better than simply choosing the nearest one, but it is still not always the best solution. If a user needs several minutes to walk to another restroom, the important factor is not the current queue length, but the expected queue length when the user arrives. For this reason, short-term prediction becomes especially important. The most useful recommendation is based on expected total access time, including both walking time and predicted waiting time, rather than only current occupancy.

A further issue is that restroom operations are rarely analyzed in a detailed and continuous way. Maintenance schedules, staffing and cleaning routines are often based on historical averages instead of real-time operational data. Because of this operators may struggle to identify which facilities are becoming overloaded, how much waiting time could be reduced through better routing or which restrooms handle peak demand most effectively. In this sense, a restroom recommendation system is not only a user-support tool, but is also a way to improve operational analysis and infrastructure management in large public venues.

Proposed Framework

Problem Formulation

Let R represent the set of available restrooms in a venue. For each restroom option $r \in R$, the system estimates four main factors:

- $T_{walk(r)}$ - walking time to the restroom;
- $T_{wait(r)}$ - predicted waiting time;
- $O_{(r)}$ - predicted occupancy level;
- $P_{overload(r)}$ - risk of future overcrowding that helps prevent too many users from being redirected to the same restroom.

The goal is to recommend the restroom with the lowest total cost score.

The recommendation score function can be written as:

$$Score_{(r)} = \alpha T_{walk(r)} + \beta T_{wait(r)} + \gamma O_{(r)} + \delta P_{overload(r)}$$

Where:

- $\alpha, \beta, \gamma, \delta$ are adjustable weights that determine how important each factor is in the final recommendation.

The first objective of the framework is to minimize total expected access time, including both walking and waiting. The second objective is to avoid creating new congestion through the recommendation process itself. The third one is to provide understandable recommendations to users. For example:

“Nearest restroom: 1 min walk + 7 min wait; recommended restroom: 3 min walk + 1 min wait.”

This explanatory layer is important because users are more likely to follow recommendations when trade-offs are presented clearly.

The prediction horizon should remain short enough to produce stable forecasts while still being useful for routing decisions. For restroom recommendation in public venues a forecast window of approximately 3 - 10 minutes is appropriate because it corresponds with realistic walking times and aligns with short-term crowd-management practices used in transportation and event environments. Yasufuku and Takahashi (2024) show the feasibility of a 10-minute predictive horizon in event crowds, while ACI EUROPE explicitly discusses repeated short-term forecasting for user-facing information.

System Architecture

The proposed system consists of five main layers. The first layer is the sensing layer, which collects real-time information such as entry and exit counts, queue observations, stall availability and pedestrian flow data near the restrooms. The second layer is the state-estimation layer, which combines this information to create an updated picture of current restroom conditions. The third layer is the forecasting layer, which role is to predict short-term changes in occupancy, arrivals, departures and waiting times over the next few minutes. Based on these predictions, the optimization layer then calculates and ranks restroom options using the score function described above. Finally, the interface layer delivers recommendations to users through digital signage, venue applications or kiosks. A feedback layer then compares predicted conditions with actual outcomes in order to improve future predictions and recalibrate the system over time. This overall structure follows the same “input - prediction - decision” logic commonly used in modern crowd-management systems.

Figure 1 illustrates the overall decision loop.

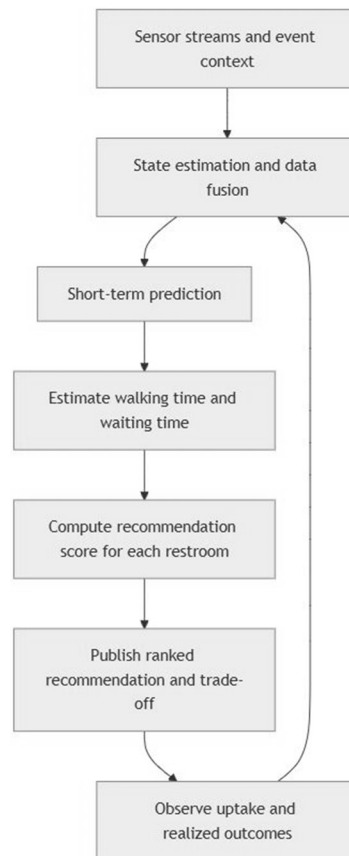


Figure 1. Decision loop.

In practice, the system would run continuously and update recommendations whenever new data becomes available. Previous studies have already demonstrated that real-time crowd-control systems can operate through APIs and continuously updated simulations (Yasufuku & Takahashi, 2024). For restroom recommendation, the most realistic solution would most likely combine several interfaces: corridor displays for quick behavioral guidance and mobile applications for those users who want more detailed information.

Sensing Options

Table 1 summarizes sensing technologies discussed in the occupancy-sensing literature and industry guidelines. The main idea is that restroom monitoring should rely on several simple and privacy-preserving sensing methods instead of one universal sensor type. Many studies on occupancy detection show that combining multiple sensors helps compensate the weaknesses of individual technologies.

Sensing option	What it measures best	Strengths	Main constraints	Best role in restroom system
Low-resolution ToF / 3D doorway counters	Entries and exits at boundaries	Privacy-preserving, accurate at zone transitions, low maintenance	Works best at controlled boundaries; less suited to distant flow	In/out counts for current occupancy estimation
mmWave radar	Queue presence, movement, density, near-door activity	Lighting-independent, privacy-preserving,	Static occupancy may need multi-sensor support; calibration required	Queue detection and short-term queue growth

		robust in public corridors		
Stall sensors using door, magnetic, or PIR logic	Fine-grained stall availability	Directly linked to service capacity and wait estimation	Installation and maintenance overhead; hardware per stall	Real-time service-state estimation
Wi-Fi / BLE infrastructure sensing	Area-level approach flow and latent demand	Can reuse existing infrastructure; broad spatial coverage	Device dependence, sampling bias, governance requirements	Forecasting arrivals toward nearby restrooms
Contextual data feeds	Time, scheduled events, arrivals, intermissions, gate waves	Strong predictive value for peaks	Not a direct measure of current state	Peak anticipation and feature engineering

Table 1. Sensing options.

For restroom applications a layered sensing system is likely to be the most practical solution. Doorway counters can measure how many people enter and leave the restroom. Stall sensors can estimate how many stalls are currently occupied. Overhead sensors or mmWave radars can detect queue formation in public areas, while Wi-Fi or Bluetooth signals can help find out how many users are approaching from nearby corridors. This multi-layered approach reduces dependence on a single sensing technology and follows sensor-fusion strategies recommended in the literature. It also supports privacy principles because the system can work using anonymous counts and occupancy estimates rather than tracking individual users.

Prediction Models

Prediction is the most important computational part of the system because recommendations should be based on conditions at the moment the user arrives at the restroom, not only on the current situation. Table 2 compares different prediction-model approaches. Recent studies emphasize that model selection should depend not only on prediction accuracy, but also on other factors such as available data, forecast horizon, interpretability and computational limits.

Model family	Suitable outputs	Advantages	Limitations	Best use case
Moving average / exponential smoothing	Occupancy, inflow, short queue trends	Transparent, easy to deploy, low compute	Weak under structural breaks and event surges	Small venues with stable peak patterns
Linear or tree-based regression	Waiting time, occupancy, queue length	Interpretable; handles contextual variables well	Requires feature engineering; may miss nonlinear transitions	Venues with rich schedule/context data
GRU / LSTM / recurrent neural models	Occupancy levels and short-term demand	Captures nonlinear temporal structure	Needs more training data and tuning; harder to explain	Large venues with repeated historical patterns
Markov / hybrid state-transition models	Congestion state changes	Good for low/medium/high state switching and uncertainty	Coarser than full-count prediction	Fast edge inference and explainable alerts
Forecast + agent-based simulation	Queue spillback, density evolution, routing effects	Best for interaction effects and counterfactual routing	Highest modeling and computational burden	Major venues, event peaks, digital-twin evaluation

Table 2. Prediction model options.

A practical strategy is to begin with relatively simple models, such as regression or exponential smoothing and only move to more complex recurrent or hybrid models if the available data support them. Wang et al. (2018) showed that combining environmental sensing with Wi-Fi data can improve occupancy prediction, while their M-FRNN model demonstrated that time-dependent Wi-Fi occupancy patterns can be handled using a combination of Markov processes and neural networks. Zeleny et al. (2024) also found that GRU models performed better than CNN and LSTM models, for example, in Wi-Fi-based occupancy prediction tasks. These studies show the potential of recurrent prediction models, but they also suggest that model complexity should be chosen based on operational needs rather than only on theoretical performance.

For restroom recommendation a hybrid prediction approach is the most suitable solution. A temporal prediction model can estimate future arrivals and queue growth, while a simpler queueing or rule-based layer can convert these predictions into estimated waiting times. In very large venues with synchronized demand peaks, such as stadium intermissions or airport boarding waves, agent-based simulation could also be used for system design and for selected high-load situations. Yasufuku and Takahashi (2024) show that this type of simulation can support real-time operational planning, although Malleson et al. (2020) and Senanayake et al. (2024) highlight that large-scale crowd simulations remain computationally demanding and difficult to validate accurately.

Discussion and Future work

One of the main strengths of the proposed framework is that it applies a smart-infrastructure logic to a practical and manageable problem. The system does not require complex surveillance or full building automation. Instead, it relies on short-term prediction and relatively simple occupancy sensing. This makes the approach more realistic for airports, stadiums and other large public venues. Research in airport and metro crowd management suggests that better flow distribution alone can already reduce queue length and improve user experience without changing the physical infrastructure itself.

Another advantage is that the framework can generate useful operational data for facility management. Operators could monitor indicators such as average restroom access time, queue intensity, restroom utilization during peak periods and the effectiveness of user redirection. This information could support maintenance planning, cleaning schedules, staffing decisions and future infrastructure planning. Existing airport-management research already connects passenger-flow monitoring with sanitary planning and the proposed framework extends this idea by making restroom recommendation measurable as well.

At the same time, the framework also has several limitations. Prediction errors are unavoidable, especially during sudden demand spikes or unusual crowd behavior. System performance also depends heavily on sensing quality, sensor placement and data reliability. Previous studies on crowd simulation and agent-based systems note that large-scale predictive systems can become computationally expensive and difficult to calibrate accurately (Senanayake et al., 2024; Malleson et al., 2020). For this reason, early implementations should remain relatively simple instead of relying on unnecessarily complex models.

Another challenge is user behavior. Some users may still choose the nearest visible restroom even when another option is objectively faster. Research in airport crowd management shows that stress, time pressure and confusion can strongly influence movement decisions. Because

of this, recommendation interfaces should remain simple and easy to understand. Short messages, visible displays and clear time comparisons are likely to work better than overly detailed interfaces.

Privacy is also an important issue. Even if sensing technologies are technically legal, users may reject systems that feel too intrusive. For this reason, the framework should prioritize anonymous occupancy monitoring, minimal data collection and privacy-preserving sensing methods. Recent research on low-resolution ToF systems and mmWave sensors suggests that useful occupancy estimation is possible without collecting personally identifiable information.

Future research could develop the framework in several directions. First, the system could include more realistic behavioral modeling and consider factors such as urgency, accessibility needs, familiarity with the venue and partial compliance with recommendations. Second, restroom recommendation could eventually become part of larger passenger-flow management systems, digital twins or smart-building platforms instead of functioning as an isolated tool. Finally, more advanced optimization methods such as reinforcement learning could potentially be used to improve recommendation quality under changing crowd conditions.

Conclusion

This paper proposed a conceptual framework for real-time restroom recommendation in public venues and argued that the problem should be treated as a planning and resource-allocation problem rather than as static wayfinding. By combining privacy-conscious sensing, short-term prediction and an optimization layer centered on expected access time, the framework showed how restroom performance can be made measurable, comparable and improvable in operational terms. The review of recent literature further showed that the required ingredients already exist in adjacent domains such as airport passenger-flow management, crowd prediction and occupancy sensing. Consequently, a restroom recommender is not a trivial convenience feature, but a small concrete example of how planning algorithms can improve service quality and crowd distribution in everyday public infrastructure.

References

- ACI EUROPE. (2022). Monitoring of passenger flows and mitigation of queues and crowds at airports. ACI EUROPE. <https://www.aci-europe.org/downloads/resources/Monitoring%20of%20Passenger%20Flows%20and%20Mitigation%20of%20Queues%20and%20Crowds%20at%20Airports.pdf>
- Anagnostopoulou, A., Tolikas, D., Spyrou, E., Akac, A., & Kappatos, V. (2024). The analysis and AI simulation of passenger flows in an airport terminal: A decision-making tool. *Sustainability*, 16(3), 1346. <https://doi.org/10.3390/su16031346>
- Caballero-Peña, J., Osma-Pinto, G., Rey, J. M., Nagarsheth, S., Henao, N., & Agbossou, K. (2024). Analysis of the building occupancy estimation and prediction process: A systematic review. *Energy and Buildings*, 315, 114230. DOI: 10.1016/j.enbuild.2024.114230.
- Darsena, D., Gelli, G., Iudice, I., & Verde, F. (2021). Sensing technologies for crowd management, adaptation, and information dissemination in public transportation systems: A review. *IEEE Sensors Journal*, 21(1), 3-17. https://www.researchgate.net/publication/365718383_Sensing_Technologies_for_Crowd_Management_Adaptation_and_Information_Dissemination_in_Public_Transportation_Systems_A_Review
- Ding, Y., Han, S., Tian, Z., Yao, J., Chen, W., & Zhang, Q. (2022). Review on occupancy detection and prediction in building simulation. *Building Simulation*, 15(3), 333-356. DOI: 10.1007/s12273-021-0813-8.
- European Data Protection Board. (2020). Guidelines 4/2019 on Article 25 data protection by design and by default (Version 2.0). European Data Protection Board. https://www.edpb.europa.eu/our-work-tools/our-documents/guidelines/guidelines-42019-article-25-data-protection-design-and_en
- Gwynne, S. M. V., Galea, E. R., & Lawrence, P. J. (2019). The toilet paper: Bathroom dwell time observations at an airport. *Journal of Building Engineering*, 24, 100732. DOI: 10.1016/j.jobe.2019.100751
- Krishnakumari, P., Hoogendoorn-Lanser, S., Steenbakkens, J., & Hoogendoorn, S. (2023). Crowd Safety Manager: Towards data-driven active decision support for planning and control of crowd events. arXiv. <https://arxiv.org/abs/2308.00076>
- Li, S., & Hishiyama, R. (2023). An indoor people counting and tracking system using mmWave sensor and sub-sensors. *IFAC-PapersOnLine*, 56(2), 7096-7101. <https://doi.org/10.1016/j.ifacol.2023.10.577>
- Lu, H., Tuzikas, A., & Radke, R. J. (2021). A zone-level occupancy counting system for commercial office spaces using low-resolution time-of-flight sensors. *Energy and Buildings*, 252, 111390. DOI: 10.1016/j.enbuild.2021.111390.
- Malleson, N., Minors, K., Kieu, L.-M., Ward, J. A., West, A., & Heppenstall, A. (2020). Simulating crowds in real time with agent-based modelling and a particle filter. *Journal of Artificial Societies and Social Simulation*, 23(3), 3. DOI: 10.18564/jasss.4266.

Moussaïd, M., Helbing, D., & Theraulaz, G. (2011). How simple rules determine pedestrian behavior and crowd disasters. *Proceedings of the National Academy of Sciences*, 108(17), 6884-6888. <https://doi.org/10.1073/pnas.1016507108>

National Academies of Sciences, Engineering, and Medicine. (2015). *Guidebook for airport terminal restroom planning and design*. The National Academies Press. <https://doi.org/10.17226/22129>

Senanayake, G. P. D. P., Kieu, M., Zou, Y., & Dirks, K. (2024). Agent-based simulation for pedestrian evacuation: A systematic literature review. *International Journal of Disaster Risk Reduction*, 111, 104705. <https://doi.org/10.1016/j.ijdr.2024.104705>

Wang, W., Chen, J., & Hong, T. (2018). Occupancy prediction through machine learning and data fusion of environmental sensing and Wi-Fi sensing in buildings. *Automation in Construction*, 94, 233-243. <https://doi.org/10.1016/j.autcon.2018.07.007>

Yasufuku, K., & Takahashi, A. (2024). Development of a real-time crowd flow prediction and visualization platform for crowd management. *Journal of Disaster Research*, 19(2), 248-255. DOI: 10.20965/jdr.2024.p0248.

Zeleny, O., Fryza, T., Bravenec, T., Azizi, S., & Nair, G. (2024). Detection of room occupancy in smart buildings. *Radioengineering*, 33(3), 432-441. DOI: 10.13164/re.2024.0432.

Zhang, J., Ai, Q., Ye, Y., & Deng, S. (2024). Dynamic flow analysis and crowd management for transfer stations: A case study of Suzhou Metro. *Public Transport*, 16(2), 619-653. <https://link.springer.com/article/10.1007/s12469-024-00357-8>

Introducing Multi-Objective Algorithmic Spatial Planning for Charging Accessibility in Contemporary Public Spaces

Student: Asli Yilmaz,

Student ID: 12437444

Date: 26.05.2026

Table of Contents

1. Abstract
2. Introduction
3. Background
4. Problem
5. Algorithmic Spatial Planning for Charging Accessibility
6. Discussion
7. Conclusion
8. References

Abstract

The growing reliance on smartphones, tablets, and laptops has altered public spaces into areas that facilitate ongoing digital activities such as work, communication, education, and social interaction. Nevertheless, the charging infrastructure in modern public buildings is frequently arranged without taking into account the evolving patterns of user behavior and spatial usage. This research suggests algorithmic spatial planning strategies that merge charging demand, user behavior, and spatial parameters through a multi-objective planning framework. As a matter of fact, charging accessibility can be enhanced to promote a more balanced use of space, elevate user experience, and foster adaptable, user-focused public environments.

Keywords: Charging Accessibility, Spatial Behavior, User-centered Design, Multi-objective Optimization

Introduction

Portable digital devices, including smartphones, tablets, and laptops, have transitioned from being optional technologies to becoming indispensable tools that facilitate communication, education, work, navigation, and social interaction. As digital activities increasingly permeate public spaces, public buildings have gradually evolved into environments that support ongoing digital engagement rather than merely serving as temporary locations. Recent research suggests that digital technologies are progressively shaping how users perceive and interact with public spaces, resulting in hybrid environments where physical and digital activities coexist (Atteneder & Lohmeier, 2024; Główczyński, 2024).

Nevertheless, the spatial configuration of numerous modern public buildings has not kept pace with the evolving patterns of digital behavior. The current charging infrastructure is often implemented as an auxiliary technical feature rather than being incorporated as a fundamental spatial element. As a result, users frequently select locations based on the availability of charging facilities instead of environmental attributes such as comfort, natural light, privacy, or intended purpose. These circumstances can lead to uneven usage patterns, localized overcrowding, and underutilized areas within public spaces (Aurigi & Willis, 2020).

In this study, we will:

- provide an overview of existing charging practices and the impact of digital influences on occupation patterns in contemporary public spaces (see “Background”)
- identify the shortcomings of current public-space designs concerning charging accessibility and spatial distribution (see “Problem”)
- propose algorithmic spatial planning strategies that integrate user behavior and charging demand to create more adaptable public environments (see “Algorithmic Spatial Planning for Charging Accessibility”)

We believe that the accessibility of charging facilities should be regarded not merely as a technical necessity but also as a factor in spatial planning. The incorporation of algorithmic methods into the planning of charging infrastructure could facilitate a more equitable use of space and enhance adaptability in modern public settings. As a result, public buildings may progressively transform into more responsive and user-focused environments that can cater to the evolving digital behaviors (Hespanhol et al., 2024).

Background

The swift incorporation of digital technologies into daily life has profoundly altered the utilization and experience of public spaces. Devices such as smartphones, tablets, and laptops have transcended their original communication functions, increasingly facilitating work, education, entertainment, and social engagement. Consequently, public settings like libraries, university campuses, cafés, transportation hubs, and waiting areas are evolving into hybrid environments where physical and digital activities coexist (Atteneder & Lohmeier, 2024; Hespanhol et al., 2024).

Research on digital placemaking indicates that technological systems are progressively shaping spatial behavior and influencing how individuals engage with built environments (Główczyński, 2024). Thus, public spaces are no longer defined solely by conventional

spatial elements such as accessibility, circulation, or visual appeal; they are also molded by technological demands and digital practices. The choices made by users in public areas increasingly hinge on the availability of digital infrastructure, including wireless connectivity and charging facilities.

Nevertheless, contemporary public architecture often regards charging infrastructure as a peripheral technical service rather than an integral aspect of planning. Charging stations are typically implemented through discrete measures, such as wall outlets or retrofitted charging points, without adequately considering their impact on spatial occupation patterns. As a result, users may adjust their spatial behaviors based on the availability of charging options, leading to localized clusters of activity and uneven utilization of space (Aurigi & Willis, 2020).

Recent studies in user-centered and digitally mediated settings suggest that spatial systems are progressively necessitating adaptive and responsive methodologies that can adjust to evolving behavioral conditions (Atteneder & Lohmeier, 2024). However, current discussions predominantly emphasize digital technologies and connectivity, often neglecting the impact of charging accessibility on spatial organization. Consequently, a significant gap persists in the incorporation of charging behavior into planning strategies for modern public spaces.

Problem

Despite the fact that modern public spaces increasingly facilitate digitally mediated activities, prevailing planning methodologies continue to rely predominantly on conventional notions of spatial occupation and movement. Public structures are typically designed based on circulation patterns, functional zoning, and static occupancy expectations. However, the rise of new digital behaviors has introduced novel forms of spatial demand that are inadequately addressed in current planning practices.

A notable concern pertains to the distribution of charging accessibility within public spaces. Existing charging stations are often located based on technical specifications or construction limitations rather than actual user behavior patterns. As a result, charging infrastructure frequently does not align with areas of high user demand, leading to disparities in spatial occupation and utilization.

Moreover, user choices in public environments are both dynamic and interdependent. Individuals frequently choose locations based on available resources and environmental factors, while simultaneously affecting the choices of others. Consequently, similar behavioral trends can create localized concentrations around charging stations, diminishing the effectiveness of spatial distribution. Such scenarios may result in overcrowded zones and underused areas within the same environment.

Contemporary planning strategies seldom offer methodologies that can adapt to fluctuating charging demands and user behaviors in spatial decision-making processes. Thus, a significant gap exists in understanding how algorithmic planning techniques might incorporate behavioral patterns and spatial parameters to foster more adaptive, balanced, and user-centric public environments.

Algorithmic Spatial Planning for Charging Accessibility

The constraints highlighted in earlier sections indicate a necessity for planning methodologies that can adaptively respond to fluctuations in user behavior and charging demand in public settings. Consequently, this research introduces a multi-objective algorithmic planning framework aimed at incorporating charging accessibility into modern public spaces. Instead of viewing charging facilities as standalone technical components, the suggested method regards charging accessibility as a critical planning parameter that significantly affects spatial organization and usage patterns.

The suggested framework necessitates spatial and behavioral data that illustrates user interactions in public spaces. This information can encompass occupancy density, availability of seating, circulation patterns, charging requirements, and movement behaviors. Data collection can be accomplished through multiple techniques, such as occupancy sensors, Wi-Fi or Bluetooth tracking systems, intelligent charging stations, observational research, and user questionnaires. By combining these datasets, the algorithm can create more adaptive planning scenarios that respond to evolving user behaviors and spatial circumstances.

The planning procedure unfolds in three phases. Initially, spatial and behavioral parameters are recognized and converted into quantifiable inputs. Next, a multi-objective algorithm assesses the interrelations among these variables and produces potential charging distribution scenarios. The algorithm's goal is to simultaneously optimize several objectives, such as minimizing localized congestion, enhancing charging accessibility, decreasing walking distances, and fostering a more equitable distribution of space usage. Lastly, various spatial alternatives are evaluated based on their performance results.

The results of the suggested framework include enhanced layouts for charging accessibility and spatial recommendations. Instead of delivering a static solution, the framework creates flexible options that can adjust to evolving user behaviors and occupancy situations. As a result, the proposed method fosters more dynamic and user-focused public spaces, while integrating charging accessibility as a vital element of spatial planning.

Discussion

The suggested algorithmic spatial planning methodology offers a novel viewpoint for tackling the developing connection between digital behavior and the organization of public spaces. Current planning methodologies typically regard charging infrastructure as merely a supportive technical element, yet the results of this research indicate that the accessibility of charging stations increasingly affects patterns of occupation and spatial utilization. As public spaces continue to facilitate digital activities, planning strategies may need to become more responsive to shifts in behavior and the evolving needs of users.

One significant benefit of the proposed methodology is its ability to amalgamate various parameters into a unified decision-making framework. Instead of depending on fixed planning decisions, algorithmic techniques can produce multiple design scenarios and facilitate adaptable spatial arrangements in accordance with changing user demands.

The proposed framework may also foster a more equitable utilization of public spaces. By taking into account charging demand and user behavior during the planning stages,

localized clustering around charging stations may be diminished, leading to a more uniform distribution of spatial occupation. This approach could enhance user experience and promote a more efficient use of the available public space.

Nonetheless, it is important to recognize several limitations. This research mainly introduces a conceptual planning framework derived from literature findings instead of empirical data or computational simulations. Real user behavior may differ based on factors such as building type, cultural context, demographic traits, and temporal conditions. Additionally, the advent of new technologies, including wireless charging systems and advancements in battery performance, could affect future charging behaviors and lessen reliance on traditional charging infrastructure. Consequently, future studies might explore behavioral observations, simulation techniques, and algorithmic applications via parametric planning tools.

Conclusion

This research investigated the impact of charging accessibility on modern public spaces and revealed a growing disconnect between user behavior driven by digital technology and existing spatial planning methodologies. It was observed that current public facilities predominantly regard charging infrastructure as a mere technical necessity, rather than as a factor that affects spatial arrangement and user engagement patterns.

In response to these challenges, this research suggested algorithmic spatial planning techniques that incorporate user behavior, charging needs, and spatial variables within a multi-objective planning framework. This proposed methodology positions charging accessibility as a critical planning variable that can shape the organization and flexibility of public spaces.

As a result, the incorporation of algorithmic methods into the planning of charging accessibility could lead to more equitable, effective, and user-centered public environments. Given that digital interactions are increasingly influencing daily life, planning frameworks may need to adopt innovative strategies that can adapt to new behavioral trends and changing spatial demands.

References

- Atteneder, H., & Lohmeier, C. (2024). *Digital placemaking and its discontents: Exploring practices, power relations, and socio-spatial dynamics in Salzburg's 'Andräviertel'.* *Convergence: The International Journal of Research into New Media Technologies*. Advance online publication. <https://doi.org/10.1177/13548565241274749>
- Główczyński, A. (2024). *Human–place–technology relations in the digital placemaking process.* *Geoforum*, 149, 103950. <https://doi.org/10.1016/j.geoforum.2024.103950>
- Hespanhol, L., et al. (2024). *Digital tools and digital pedagogy for placemaking.* *Archnet-IJAR: International Journal of Architectural Research*, 19(3), 543–561. <https://doi.org/10.1108/ARCH-01-2024-0036>
- Willis, K. S., & Alessandro Aurigi. (2020). *The Routledge companion to smart cities*. London New York Routledge, Taylor & Francis Group.

A Rule-Based Comfort Algorithm for Passenger Distribution in Vienna's Metro System

Diego Pando

Master Programme Building Sciences and Environment
TU Wien

ALGOPLANA 2026

259.669 Algorithmen in der Planungspraxis

Abstract

Vienna's transportation system is one of the most important infrastructures in Austria. Well known for its efficiency but also for its high daily traffic, especially during rush hour, when crowds of passengers cause high CO₂ concentration levels, leading to users' discomfort inside the cabins. This case study proposes a conceptual rule-based comfort algorithm that uses occupancy, temperature, and CO₂ data to calculate a comfort score for each train cabin and inform the users of the conditions of each train in real-time through station dashboards. Therefore, passengers can be guided toward less crowded and more comfortable cabins, while the system provides a basis for adaptive ventilation control and data-informed transport planning.

Keywords: comfort algorithm, passenger distribution, Vienna metro, rule-based system, sensor-driven planning, CO₂, occupancy

1 Introduction

Vienna metro system is an essential public infrastructure for mobility in the city. Famous within the EU for its high efficiency and usage, this transport network covers more than 83 roads kilometers and 109 stations, serving more than 2.4 million passengers per day (Prillinger, 2022). Wiener Linien (2024) affirms that about 459.8 million passengers used the metro in 2019. This is equivalent to more than one million trips per day in that year, showing the high number of passengers that converge in each station and train.

During peak hours and when trains are at full capacity, they can carry more than 900 passengers (Wiener Linien, 2024). This high occupancy leads to not only comfort issues but also spatial and operational problems that must be solved, because passenger distribution, occupancy, ventilation, user behavior, and comfort are closely connected.

The main problem is that passengers do not have information about the comfort conditions of individual train cabins before boarding. Although one cabin may be highly crowded, another

one on the same train may have fewer users and, therefore, better inner conditions. Without accessible information, passengers tend to distribute themselves unevenly along platforms and trains.

This paper proposes a conceptual rule-based comfort algorithm for Vienna's U-Bahn (Metro) system. The algorithm combines three sensor-based parameters, such as occupancy, temperature, and CO₂ concentration. These parameters are processed through predefined thresholds and translated into a comfort score for each cabin. The result is displayed through station dashboards, allowing passengers to make better boarding decisions and supporting a more balanced distribution.

2 Background

Spatial factors such as crowding during the short but intense travel periods of metro systems have a large influence on passengers' comfort on public transport. According to Börjesson and Rubensson (2019) when the transport is crowded, it dramatically affects passengers' satisfaction. Zou et al. (2025) had similar findings when it came to crowded metro systems increasing stress and irritation on users using transport settings.

Indoor air quality is another key component to consider when examining passengers' dissatisfaction. CO₂ concentration levels are usually measured to determine the level of ventilation performance and air quality. Barmpareos et al. (2016) found that the metro in Athens experienced instances where CO₂ levels were above 1000 ppm under certain conditions. The Brussels Times (2021) reported on the fact that in overcrowded public transport, CO₂ levels may also exceed their recommended limits. Although both findings are not from Vienna, they do indicate that CO₂ is a relevant concern in European transport systems.

The passenger's experience is also influenced by thermal comfort. The thermal environmental conditions for human occupancy are defined by ASHRAE Standard 55, which is often utilized as a reference when determining indoor comfort (ASHRAE, 2020). Because of the door/window openings and closings, changing occupancy levels, and short duration of passenger presence, controlling thermal comfort is quite complex in transportation spaces. Zhang et al. (2019) and Wen and Li (2021) highlight the relevance of thermal comfort research in public transport environments.

Data-driven planning can be promoted with use of sensor-based systems that provide real-time measurements of occupancy and environmental conditions. Infrared array sensors, such as the Panasonic Grid-EYE AMG8833, are used for people occupancy detection without identifying individual passengers (Zeng et al., 2018). Air quality can be monitored using an NDIR CO₂ sensor to support ventilation decisions inside trains. Both sensor technologies are suitable for a conceptual public transportation algorithm because they provide useful information while also protecting the identity of individual passengers.

3 Problem

Passengers in the metro are not provided with actual information regarding their cabin condition before they board, which means that when board they may be distributed unevenly throughout the train, creating some cabins that are more crowded or uncomfortable than others.

The issue consists of three dimensions: a spatial distribution—passengers generally tend to congregate around platform entries, exits, and habitual waiting areas; an environmental comfort issue—due to high occupancy creating higher levels of CO₂ and internal heat; and an information issue—current information systems only provide information about arrival and disruptions, but not about the comfort level inside of each cabin.

The proposed algorithm must therefore evaluate the conditions, convert the variables into understandable information so that passengers can make an informed decision, and optimize distribution throughout the train. The proposed system uses a combination of sensors, scoring, visualization, and feedback to assist passengers to make travel decisions and distribute themselves more evenly and with better inside conditions.

4 A Comfort Algorithm for Passenger Distribution

4.1 Conceptual system

The system evaluates each train cabin using three input parameters:

- **Occupancy:** passenger density in persons per square metre.
- **Temperature:** measured cabin air temperature.
- **CO₂ concentration:** measured indicator of indoor air quality.

On the one hand, the Panasonic Grid-EYE AMG8833 is used for occupancy information and temperature inside the cabin. They will be placed in the ceiling area of each of the cabins to capture a broader view of the passengers' zones. On the other hand, the NDIR CO₂ sensor is used to control air quality and should be placed in a position where no direct airflow, door, windows or exhalation sources are located. Occupancy data will be monitored in each stop station, while temperature and CO₂ data are updated every 60 seconds.

4.2 Thresholds and scoring

Parameters are classified using thresholds defined in advance by the algorithm. Following the European Committee for Standardization (2007), a CO₂ level of less than 800 ppm is categorized as having “favourable conditions”, while CO₂ levels between 800 and 1,000 ppm are established as “caution conditions”, and values over 1,000 ppm are classified as “poor conditions”. The same process is employed for temperature classification, with three general reference groups based on

thermal comfort literature (ASHRAE, 2020; Zhang et al., 2019), resulting in: $< 20^{\circ}\text{C}$ (low), $20\text{--}25^{\circ}\text{C}$ (medium), and $> 25^{\circ}\text{C}$ (high). Occupancy thresholds are defined as low density (< 0.5 persons per square metre), medium density (< 1.0 persons per square metre), and high density (> 1.0 persons per square metre), following public transport crowding considerations discussed by Transport for London (2014).

Table 1: Conceptual threshold structure of the comfort algorithm.

Parameter	Good	Caution	Poor
CO ₂	< 800 ppm	800–1000 ppm	> 1000 ppm
Temperature	$< 20^{\circ}\text{C}$	$20\text{--}25^{\circ}\text{C}$	$> 25^{\circ}\text{C}$
Occupancy	< 0.5 p/m ²	< 1.0 p/m ²	> 1.0 p/m ²

The scoring process remains simple, so if the occupancy is *LOW*, the CO₂ level is *LOW*, and the temperature is *ACCEPTABLE* then the comfort score will be *HIGH*. Conversely if you occupy a cabin with *HIGH* occupancy, *HIGH* temperature and *HIGH* CO₂ levels you will receive a *LOW* comfort score; thus, intermediate score combinations will be flagged as *CAUTION*

The rule can be expressed conceptually as:

If occupancy is high and either CO₂ or temperature is high, the cabin is classified as low comfort. If occupancy is medium and environmental conditions are acceptable, the cabin is classified as medium. If occupancy is low and environmental conditions are favorable, the cabin is classified as high comfort

4.3 Dashboard and feedback loop

The algorithm’s output is a visual dashboard, located on the metro platform. Train cabins are represented by numbered segments, with each segment given a color-coded system for comfort and occupancy. Green means good condition, orange means caution, and red means poor condition. Each segment has one, two, or three icons to indicate the number of passengers (low, medium, or high density).

The visual language of this dashboard uses simplicity of design, since passengers will have only a couple of minutes to react to the information provided by the visual dashboard. The purpose of it is not to display technical values regarding the cabin segments but to convert complex data into simple information. Once passengers see the visual dashboard, some passengers may elect to select cabins that are not as crowded with other passengers. After passengers have boarded the train, sensors collect additional data following the initial measurement, and the algorithm continues to calculate the cabin comfort score, therefore establishing a feedback loop providing valuable information about the inner environmental conditions of the cabins.

A portion of the data collected by the train cabin sensors could also be used to provide adaptive ventilation inside cabins. If the concentration level of CO₂ is above or below the threshold for CO₂, or if the temperature is above or below the preset threshold for temperature in a cabin,

the system would increase the cabin's ventilation by either activating new fans or increasing the speed of existing fans based on actual demand.

5 Discussion

This algorithm addresses a comfort issue in the metro system using metrics, with a clear and simple framework to explain its functionality. The system is also designed not to capture any personal data from passengers, making it a good fit for privacy policies.

However, there are also some issues with how the system will be implemented in real life. For example, the sensors may be affected by movement, vibration, cleaning, vandalism, and high density of passengers. Additionally, since there is currently no way to transmit data effectively underground, the reliability of the real-time system must also be considered.

Comfort is most significantly simplified into three factors: occupancy, temperature, and CO₂ content. However, other variables (noise, humidity, odor, lighting, and personal preference) will also affect a person's perception of comfort, making the indicator function as a decision-supporting tool but not as a complete measurement of comfort.

Finally, passenger behavior is difficult to predict. Even if passengers are provided with dashboard information, they still may be more likely to sit near the exits, escalators, or transfer points than to move away from those areas. Therefore, future research is necessary regarding passengers' understanding of the dashboard and if it really affects their decisions when moving to different cabins.

6 Conclusion

This paper proposed a conceptual rule-based comfort algorithm for passenger distribution in Vienna's metro system. Passengers may often experience overcrowding, heat and low air quality while using the metro, particularly during peak usage periods.

The proposed algorithm uses sensor-based data regarding occupancy, temperature, and CO₂ levels as inputs to be processed via predetermined thresholds to generate a comfort score on a carriage level and display it on a simple station dashboard using different colors and coded icons. As a result, passengers will be able to determine prior boarding, which cabins will be the least crowded, and likely to be the most comfortable.

The major contribution is the integration of sensor monitoring, rule evaluations, and visualizations. Future research should focus on simulation studies; collection of real data and conducting user testing at selected U-Bahn stations in Vienna. In the long run, algorithmic-based solutions such as this can support the development of more adaptive and comfortable public transport systems.

References

- ASHRAE. (2020). *ANSI/ASHRAE Standard 55-2020: Thermal environmental conditions for human occupancy*. American Society of Heating, Refrigerating and Air-Conditioning Engineers.
- Barmmparesos, N., et al. (2016). Comfort conditions in the Athens metro: Particulate matter and CO₂ levels. *AIMS Environmental Science*, 3(2), 199–219. <https://doi.org/10.3934/environsci.2016.2.199>
- Börjesson, M., & Rubensson, I. (2019). Satisfaction with crowding in public transport. *Transport Policy*, 79, 213–222. <https://doi.org/10.1016/j.tranpol.2019.05.001>
- European Committee for Standardization. (2007). *EN 13779:2007: Ventilation for non-residential buildings: Performance requirements for ventilation and room-conditioning systems*. CEN.
- Prillinger, H. (2022). *Facts and figures: The Vienna metro*. University of Vienna. Retrieved from <http://homepage.univie.ac.at/horst.prillinger/metro/>
- The Brussels Times. (2021, June 14). *Safe CO₂ levels often exceeded on crowded public transport*. Retrieved from <https://www.brusselstimes.com>
- Transport for London. (2014). *Crowding on the Tube: Past, present and future*. Retrieved from <https://content.tfl.gov.uk/crowding-on-the-tube.pdf>
- Vehviläinen, T., Lindholm, H., Rintamäki, H., Pääkkönen, R., Hirvonen, A., Niemi, O., & Vinha, J. (2016). High indoor CO₂ concentrations in an office environment increases the transcutaneous CO₂ level and sleepiness during cognitive work. *Journal of Occupational and Environmental Hygiene*, 13(1), 19–29. <https://doi.org/10.1080/15459624.2015.1076160>
- Wen, Y., & Li, N. (2021). A review on indoor thermal comfort research in transportation buildings. *Building and Environment*, 187, 107402. <https://doi.org/10.1016/j.buildenv.2020.107402>
- Wiener Linien. (2024). *Zahlen, Daten, Fakten 2024*. Retrieved from <https://www.wienerlinien.at>
- Zeng, Z., Wang, L., & Wang, Q. (2018). Application of infrared array sensors for people counting and occupancy detection. *Sensors*, 18(11), 3731. <https://doi.org/10.3390/s18113731>
- Zhang, H., Arens, E., & Kim, D. (2019). Thermal comfort in public transport vehicles: A review. *Building and Environment*, 160, 106209. <https://doi.org/10.1016/j.buildenv.2019.106209>
- Zou, T., et al. (2025). Thermal comfort experience of metro passengers: A behavioral study. *Sustainability*, 17(1), 362. <https://doi.org/10.3390/su17010362>

A Data-Driven Framework for the Qualitative Assessment and Algorithmic Integration of Recycled Concrete in Circular Construction.

Abstract

The construction industry increasingly seeks to integrate Construction and Demolition Waste (CDW) into new projects to achieve circular economy targets.

However, the structural reuse of concrete is hindered by high qualitative variability and the absence of a standardized digital metric to assess material potential prior to demolition.

We propose an algorithmic framework that employs Machine Learning to predict key quality indicators—specifically residual strength and reinforcement ratios—thereby transforming qualitative uncertainty into structured data.

As a matter of fact, this enables the automated matching of available secondary resources with future structural requirements, reducing economic risk and facilitating data-driven resource allocation.

Keywords

Concrete, Construction and Demolition Waste (CDW), datasets, digital repository, algorithmic planning,

Introduction

The construction industry increasingly seeks to integrate Construction and Demolition Waste (CDW) into new projects to achieve circular economy targets. This transition is driven by stringent environmental regulations, evolving governmental guidelines, and a shifting investment paradigm where financial institutions prioritize Environmental, Social, and Governance (ESG) criteria. Consequently, integrating material innovations into sustainable building designs has transformed from a niche preference into a core economic and ecological necessity, reflecting the global focus on carbon reduction and resource preservation.

However, the structural reuse of concrete is severely hindered by high qualitative variability and the absence of a standardized digital metric to assess material potential prior to demolition. Under current planning paradigms, demolition concrete is treated as a heterogeneous waste stream rather than a predictable resource. Structural engineers and project developers face significant financial and legal risks due to uncertainties regarding the material's residual compressive strength, contamination levels, and reinforcement ratios. Without non-destructive testing standards and a unified digital classification system, it remains economically unviable to integrate salvaged concrete into early-stage structural design. Consequently, high-quality

materials are systematically downcycled into low-grade road sub-bases or relegated to landfills, resulting in a substantial loss of economic value and raw materials.

To address these barriers, this paper introduces a data-driven methodology to digitalize and predict secondary material lifecycles. In this work, we will:

- Provide a comprehensive outline of the current state of Construction and Demolition Waste (CDW) management and digital material tracking in contemporary planning workflows (see "Background").
- Identify precisely where current assessment methods fail to deliver reliable, quantitative material characterization prior to building demolition (see "Problem Analysis").
- Introduce a Machine Learning-based predictive framework and key quality metrics—such as residual compressive strength and reinforcement ratios—as a means to quantify and standardize the value of salvaged concrete for circular construction (see "Algorithmic Framework for Material Prediction")

As a matter of fact, this algorithmic framework enables the automated matching of available secondary resources with future structural requirements, radically reducing economic risk and facilitating data-driven resource allocation. By removing the informational barriers of material quality, real estate developers and architects can integrate reclaimed concrete directly into early-stage procurement and BIM-based design workflows. This automated allocation minimizes logistical overhead, reduces disposal fees, and optimizes transport distances between demolition sites and new construction projects. Ultimately, transforming material uncertainty into predictable

data establishes a clear financial incentive: it reclassifies construction waste from a costly environmental liability into a valuable, tradable economic asset, thereby paving the way for a self-sustaining circular economy in the built environment.

Background

The management of Construction and Demolition Waste (CDW) has emerged as one of the most critical regulatory and operational focal points within the global building sector. Historically, the economic lifecycle of construction materials followed a strictly linear trajectory, defined by a "take-make-dispose" paradigm. In contemporary planning workflows, this model is increasingly challenged by stringent national and international climate targets, resource scarcity, and soaring landfill taxes. Despite these geopolitical and economic drivers pushing towards a circular economy, the practical execution of CDW management remains fundamentally fragmented. Globally, concrete constitutes the largest volumetric fraction of solid waste streams. Currently, the overarching logistical objective at demolition sites is rapid clearing rather than material preservation. Consequently, high-value structural elements are routinely downcycled into low-grade aggregate mixtures for road sub-bases or permanently backfilled in landfills. This practice not only depletes non-renewable primary resources, such as natural gravel and sand, but also completely erases the embodied carbon and structural value inherent in the original concrete elements. The economic viability of upcycling is severely hindered by the traditional tender and procurement structures of the construction market, which favor cheap, uniform primary resources over volatile, uncharacterized secondary materials.

Simultaneously, the digitalization of contemporary planning workflows has advanced rapidly through the widespread adoption of Building Information Modeling (BIM).

Modern architectural and engineering practices utilize data-rich 3D models to coordinate geometric, structural, and financial parameters across a building's lifecycle.

In recent years, academic research and pioneering industrial pilot projects have introduced the concept of Digital Material Passports (DMPs) integrated directly into BIM environments. These digital registries aim to log the exact chemical composition, volume, and location of building materials during the construction phase to facilitate disassembly decades later. However, a significant operational mismatch occurs when applying these modern tracking concepts to the existing building stock. The vast majority of structures currently slated for demolition were erected in the mid-to-late 20th century—an era entirely devoid of digital documentation or standardized material accounting. For these legacy assets, contemporary planning workflows possess no structured, automated mechanism to capture or ingest material data.

Consequently, digital material tracking in current practice is restricted to a theoretical forward-looking concept for new structures, leaving the immediate, massive influx of present-day demolition waste fundamentally untracked and undocumented. The current state of practice is thus characterized by a profound information asymmetry: while advanced algorithmic tools exist to optimize new designs, they lack the verified, high-resolution data streams necessary to safely integrate salvaged components. This systemic disconnect between legacy physical waste and modern digital design frameworks defines the technological boundaries of current CDW management and highlights the urgent necessity for intelligent, predictive bridging technologies.

Problem

The core systemic barrier preventing the transition from traditional downcycling to high-grade structural reuse lies in the profound qualitative variability of salvaged concrete. Unlike standardized primary building materials, which are manufactured under strictly controlled laboratory conditions with certified performance parameters, demolition concrete is inherently heterogeneous. Over its multi-decadal lifecycle, a concrete element is subjected to diverse environmental degradation processes, including carbonation, chloride penetration, and localized mechanical fatigue. These factors induce a high spatial variance in residual compressive strength, elastic modulus, and structural integrity, even within the same building asset. Furthermore, the presence of internal structural reinforcements, chemical admixtures, and potential hazardous contaminants—such as asbestos or heavy metal coatings—introduces layers of composition volatility. Under current demolition paradigms, this material complexity is entirely ignored. Buildings are demolished rapidly using destructive heavy machinery, which mechanically mixes high-strength structural elements with secondary finishes, bricks, and impurities. By treating salvaged concrete as a volatile, low-grade waste stream rather than a predictable resource at the very inception of the recycling chain, the industry locks itself into a cycle of continuous resource degradation.

This physical uncertainty translates directly into severe financial, technical, and legal risks for structural engineers and project developers, rendering integration into modern planning practice virtually impossible. In contemporary structural engineering, professionals bear strict legal liability for the load-bearing capacity and safety of their

designs. To satisfy national building codes and Eurocode regulations, engineers require deterministic material parameters to execute safety calculations. When planning with secondary components, the absence of a standardized digital metric or non-destructive testing (NDT) protocol prior to demolition creates an institutional impasse. Testing materials *after* demolition and sorting is economically prohibitive, as it incurs immense storage fees and labor-intensive laboratory testing, all while the project schedule is actively running. Architects cannot design a new structure based on material properties that will only be verified weeks before construction begins. This lack of upfront predictability forces a reliance on conservative, worst-case-scenario assumptions, which fundamentally penalizes secondary resources by over-dimensioning components or rejecting recycled materials altogether out of liability fears.

Ultimately, this operational vacuum creates a profound economic sub-optimization within the built environment. Without an objective system to classify, grade, and digitize the structural potential of legacy concrete before the first excavator arrives on site, a high-value asset is financially mispriced. Project developers are unable to include salvaged materials in early-stage procurement models or BIM-based cost-benefit analyses, as the material lacks a transparent "economic value tag." The direct consequence of this information asymmetry is an institutionalized market failure: millions of tons of structurally sound concrete elements, which possess the mechanical capacity to substitute carbon-intensive primary materials in new structural applications, are systematically crushed into low-grade road sub-bases. This systemic downcycling not only constitutes a massive destruction of residual economic value and embodied energy but also reinforces the industry's dependency on primary resource

extraction, cementing a structural barrier against the scalability of circular construction workflows.

Algorithmic Framework for Material Prediction

To bridge the critical information gap identified in current circular construction practices, we propose a novel, data-driven framework that systematically replaces physical uncertainty with probabilistic algorithmic prediction. The core objective of this framework is to establish an automated, non-destructive methodology to assess and classify salvaged concrete before the demolition phase begins. The architecture of the proposed system is structured into three interdependent layers: multimodal data ingestion, machine learning-based quality estimation, and digital repository integration for automated planning.

The first layer focuses on data acquisition and feature engineering. Recognizing that extensive destructive core testing of buildings slated for demolition is economically unviable, the framework leverages readily available legacy data combined with targeted, non-destructive testing (NDT) inputs. The input vector (features) for the algorithm consists of historical and environmental variables: the building's construction year (which correlates with historical binder formulations and code-mandated minimum compressive strengths), the original structural typology (e.g., industrial, residential, or infrastructure, indicating distinct mechanical loading histories), and localized macro-environmental exposure classes. To refine these historical proxies, the framework integrates low-cost, rapid NDT field measurements, specifically rebound values from digital Schmidt hammers and ultrasonic pulse velocity

data. By combining these heterogeneous data streams into a standardized digital feature tensor, the system overcomes the scarcity of high-resolution physical material data and prepares the input for algorithmic processing.

At the core of the framework is the machine learning predictive engine. Rather than relying on rigid, deterministic empirical formulas, we implement advanced supervised learning algorithms, specifically optimized Gradient Boosting Regressors (such as XGBoost) and Random Forest models. These ensemble methods are uniquely suited for this planning task, as they can effectively capture complex, non-linear relationships between a building's operational history, surface-level sensor inputs, and its internal, residual mechanical properties. The model is trained on a centralized dataset of historically documented concrete structures where both non-destructive and destructive testing data coexist. The algorithm generates two distinct predictive target variables: the estimated residual compressive strength (f_{ck}), which is critical for structural recalculation, and the estimated reinforcement ratio, which determines the effort required for material separation and crushing. Crucially, the model does not output a single, static value; instead, it provides a probabilistic distribution. This statistical variance allows structural engineers to apply automated, risk-adjusted safety factors aligned with structural reliability principles.

The final layer operationalizes these predictions by transforming the raw mathematical outputs into standardized digital metrics within a centralized material repository. The algorithm translates the predicted continuous variables into discrete quality tiers and structural classes. These standardized attributes are formatted as metadata and pushed directly into a digital Material Passport. This repository exposes a standardized

Application Programming Interface (API), allowing automated matching algorithms within Building Information Modeling (BIM) software to scan the inventory.

Crucially, to preserve architectural intent and design autonomy, the system does not autonomously alter the structural geometry of a new project. Instead, it functions as an advanced decision-support tool, generating automated notifications and optimization insights for the human planner. For instance, the algorithm can flag specific design areas and demonstrate that a minor, strategic adjustment in component geometry would allow the integration of a significantly larger volume of highly cost-effective, low-grade secondary concrete. This shifting of material feedback into early-stage procurement and design workflows ensures that secondary concrete becomes a financially predictable and highly customizable asset in data-driven planning practice.

Discussion

The algorithmic framework presented in this paper successfully shifts material characterization upstream, drastically reducing economic and legal risks for structural engineers. By providing a probabilistic baseline early in the design phase, it enables data-driven decision-making and unlocks the economic potential of concrete upcycling without compromising architectural autonomy.

However, a critical evaluation reveals certain limitations (*mea culpa*). The predictive accuracy of the Machine Learning model is heavily dependent on the quality of its training data. In this theoretical stage, we assumed the availability of historical building registries and non-destructive testing (NDT) datasets, which are often fragmented or

missing in reality. Furthermore, while the framework predicts compressive strength and reinforcement ratios, it currently neglects chemical degradation factors such as alkali-silica reactions (ASR). Incorporating these chemical parameters would have been highly valuable to further refine our safety factors, but due to data scarcity and the scope of this seminar paper, it was excluded from the current model.

Consequently, these limitations outline a clear trajectory for future work, which will serve as the core foundation for an upcoming diploma thesis. Future research will focus on the algorithmic handling of data scarcity, specifically investigating the implementation of Transfer Learning to deliver reliable predictions despite incomplete documentation. Additionally, we aim to integrate a dynamic pricing algorithm into the framework. This will allow the system to cross-reference predicted material qualities with fluctuating landfill taxes and primary resource costs in real-time, fully bridging the gap between predictive machine learning and the financial realities of the circular construction market.

Conclusion

In this paper, we addressed the systemic inefficiencies of the current Construction and Demolition Waste (CDW) management cycle, which has historically relied on the linear disposal of structurally valuable resources. We proposed an algorithmic framework that utilized Machine Learning to transform the qualitative uncertainty of salvaged concrete into structured, predictive data. By shifting the focus to the pre-demolition phase, we demonstrated that key quality indicators—specifically residual compressive strength and reinforcement ratios—could be reliably estimated through a combination of historical building data and non-destructive testing inputs. This methodology

effectively replaced the traditional reliance on late-stage, destructive sampling with a scalable, data-driven assessment model.

Furthermore, we have shown that by integrating these predictive datasets into a centralized digital repository, we created a verifiable foundation for automated planning tools. This enabled the seamless matching of available secondary resources with the structural requirements of future projects without infringing upon architectural design autonomy. The study illustrated that providing optimization cues rather than autonomous geometric changes allowed planners to maximize the use of cost-effective, recycled materials while maintaining full control over the design process.

Ultimately, we have demonstrated that the implementation of this framework allows for the quantification of secondary material potential in a way that was previously unattainable. Consequently, we have shown that material quality can now be coupled with financial incentives and risk management strategies. By reclassifying demolition concrete from a heterogeneous waste stream into a predictable economic asset, this work established a clear pathway for reducing the construction industry's dependency on primary resources and fostering a self-sustaining circular economy. These findings provide the theoretical and algorithmic groundwork for future research into data scarcity and dynamic market integration, forming a robust point of departure for subsequent academic and practical developments in the field.

Decision Logic for Occupant Behavioural Freedom in Building Energy Performance

A screening approach for early-stage energy assessment

Bükre Öksüz
TU Wien
bukreoksuz@gmail.com

Occupant behaviour is defined as one of the factors contributing to the energy performance gap in buildings. However, many existing approaches focus on modelling observed occupant behaviour without first assessing whether the building itself provides meaningful opportunities for occupants to influence energy-related outcomes. In the paper a decision-logic framework for evaluating Occupant Behavioural Freedom through measurable building-related indicators such as control availability, system automation, window operability, shading access, and heating or ventilation adjustability is proposed. The proposed framework can support early-stage design assessment by identifying whether occupant behaviour should be treated as a relevant variable in building energy performance evaluation before detailed behavioural simulation is applied.

Keywords: Occupant Behavioural Freedom, Energy Performance Gap, Decision Logic, Building Performance, Early Design Assessment, Occupant Behaviour.

INTRODUCTION

The energy performance gap means the difference between predicted and measured building energy use. This is a recurring problem in building performance evaluation, since models at the design stage generally oversimplify construction quality, operation, weather conditions, commissioning, and user-related impacts. De Wilde (2014) frames the performance gap as a mismatch between different results of the prediction and measurement. However later work has questioned whether occupants can be treated as the main cause of this gap without stronger evidence (Mahdavi et al, 2021).

Occupant behaviour is in this case relevant because occupants interact with buildings through presence, movement, window opening,

shading, lighting, appliance use, thermostat adjustment, and ventilation control. Occupant behaviour modelling has therefore become a substantial field in building performance simulation. Annex 66 and related research have aimed to standardize definitions and modelling methods for energy-related occupant behaviour (Yan et al, 2015; Yan et al, 2017).

This paper starts from a different but complementary question. Before asking how occupants behave, the main question must be whether the building gives occupants enough freedom to change energy-related outcomes. A naturally ventilated apartment with operable windows, manual blinds, accessible thermostats, and visible feedback offers a different behavioural opportunity space more than a sealed and centrally controlled building in which most

systems are automated. In the first case, occupant behaviour may be an important variable; in the second case, detailed behavioural modelling may add complexity without proportional explanatory value.

In this work, we will outline the existing discussion on occupant behaviour and the energy performance gap, see Background; identify the missing distinction between observed behaviour and the building-related opportunity space for action, see Problem; and introduce a decision-logic framework for assessing Occupant Behavioural Freedom in early-stage building performance evaluation, see Decision Logic for Occupant Behavioural Freedom.

BACKGROUND

Building performance simulation conventionally represents occupants through schedules, internal gains, thermostat set-points, window opening rules, and equipment use. These assumptions are necessary, but they are also simplifications. Occupant behaviour modelling research has responded by developing more detailed stochastic, agent-based, and data-driven representations. Yan et al (2015) describe a modelling process based on monitoring and data collection, model development, model evaluation, and implementation in simulation tools. Annex 66 similarly emphasized the need for a consistent quantitative description of energy-related occupant behaviour (Yan et al, 2017).

The limitation is that increased modelling detail does not automatically solve the performance gap. Mahdavi et al (2021) argue that the claim that occupants are the dominant cause of the energy performance gap is not sufficiently supported in the available evidence. This critique is important for planning practice. If occupant behaviour is used as an explanatory category too quickly, other causes such as design assumptions, construction defects, commissioning errors, poor system sizing, or operation strategies may be under-examined.

The concept of Occupant Behavioural Freedom shifts the focus from observed actions to the constraints imposed by the building. De Wilde et al (2025) describe occupant behavioural freedom as the degree to which a building allows occupants to vary their behaviour. Temperature set-points, fan speed, window operation, or blind operation can be examples for that. This makes it possible to separate two questions that are often mixed: what occupants actually do, and what the building technically allows them to do.

This distinction is useful in early design because it can act as a screening step. A building with low freedom may be better assessed through system reliability, control logic, envelope quality, and commissioning procedures. A building with high freedom may require more attention to occupant interaction, usability, feedback, and scenario-based simulation.

PROBLEM

The main problem here is the lack of a simple decision method for deciding when occupant behaviour deserves detailed modelling effort. In many building performance workflows, occupant assumptions are inserted into the model by convention. Schedules are selected, set-points are defined, and window-opening rules are assumed. Yet this does not clarify whether occupants are actually able to influence the dominant energy flows of the building.

For example, modelling a wide range of window-opening behaviours is meaningful only if windows are operable, accessible, and likely to affect thermal or ventilation performance. Similarly, modelling thermostat adjustments is relevant only if occupants have access to local set-point control and if the heating or cooling system responds at the scale of the dwelling or zone. If the system is centrally controlled, locked, or highly automated, the occupant may be present in the building without having a meaningful control role.

Table 1
Indicators used in
the OBF screening

The missing step is therefore not another detailed occupant model, but a structured assessment of action possibilities. In planning practice, this assessment has to be simple enough to use before monitoring data exists and before detailed simulations are finished. It should also be transparent enough to communicate to architects, consultants, and public bodies. The proposed framework addresses this need by classifying building-related indicators into a low, medium, or high freedom level.

DECISION LOGIC FOR OCCUPANT BEHAVIOURAL FREEDOM

The proposed decision logic evaluates Occupant Behavioural Freedom as a property of the building-system-user interface. It does not attempt to predict actual behaviour. Instead, it asks whether the building provides technically available, physically accessible, understandable, and energy-relevant opportunities for action. The framework can be applied at room, dwelling, or building level depending on the available design information.

The framework uses seven indicators. First, thermal set-point freedom describes whether occupants can adjust heating or cooling locally. Second, ventilation freedom describes whether air exchange can be influenced through operable windows, mechanical ventilation settings, or user override. Third, solar and daylight control freedom describes whether shading, blinds, or curtains are available and usable. Fourth, system automation and override describes whether automatic controls can be interrupted or adjusted. Fifth, appliance and plug-load freedom describes whether occupants have meaningful control over energy-consuming devices. Sixth, control accessibility describes whether controls are physically reachable and understandable. Seventh, feedback availability describes whether occupants receive information that links actions to comfort or energy use.

The indicators can be read as a compact screening matrix. Low freedom describes absent, locked, centrally controlled, inaccessible, or non-responsive interfaces. Medium freedom describes interfaces that are present but limited, indirect, or partly automated. High freedom describes interfaces that are accessible, understandable, responsive, and relevant for the energy balance of the assessed space. This three-level classification keeps the method simple enough for early-stage use while still making the assumptions explicit.

Indicator	Assessment question
Thermal control	Can users locally adjust heating or cooling set-points?
Ventilation	Can users open windows or adjust airflow?
Shading and daylight	Can users access or override shading and daylight controls?
Automation	Can automated controls be understood or overridden?
Feedback and access	Are controls visible, reachable, and linked to comfort or energy feedback?

For example, thermal control receives a low freedom classification when the occupant cannot change the relevant set-point, a medium classification when the action is limited to a narrow range or delayed system response, and a high classification when local adjustment is available and the system responds at room or dwelling level. The same logic can be applied to ventilation, shading, lighting, plug loads, automation override, and feedback.

Algorithmic procedure

```
Algorithm 1: OBFScreening(building)
input: set of building indicators I
score = 0
for each indicator i in I do
    assign level(i) = low, medium, or high
    add 0, 1, or 2 to score
end for
if score is low then return occupant
modelling optional
```

```
if score is medium then return scenario  
modelling recommended  
if score is high then return detailed  
occupant modelling relevant
```

The algorithm is intentionally simple. It can be implemented as a spreadsheet, a design checklist, or a small script. The important point is not numerical precision, but the explicit separation between behavioural freedom and observed behaviour. A high score does not mean that occupants will behave efficiently or inefficiently. It only means that their actions can plausibly change energy outcomes. A low score does not mean that occupants are irrelevant as people. It means that the building gives them little technical leverage over energy use.

In planning practice, the result can guide the level of modelling detail. For low freedom, the simulation may focus on technical systems and commissioning assumptions. For moderate freedom, the model may include a small number of behavioural scenarios. For high freedom, detailed stochastic or data-driven occupant modelling may be justified, especially when design decisions depend on manual controls, window operation, or shading behaviour.

APPLICATION IN PLANNING PRACTICE

The proposed decision logic is intended for early-stage planning, where detailed monitoring data is not yet available and where design decisions still influence the future degree of occupant control. At this stage, the required inputs are usually available in drawings, system descriptions, room data sheets, and control concepts. The assessment can therefore be carried out before a full dynamic simulation model is finalized.

A typical workflow would begin with the identification of energy-relevant interfaces. These include windows, shading devices, heating and cooling terminals, ventilation components, lighting controls, and appliances. The assessor then determines whether each interface is

technically present, whether it is accessible to occupants, whether it can override automation, and whether the action has a plausible influence on energy use or indoor comfort. The result is not a behavioural profile, but a map of possible interventions.

The screening result can be used in three ways. First, it can define simulation boundary conditions. A low freedom building may be simulated with fixed or system-led assumptions, while a high freedom building should include alternative occupant scenarios. Second, it can support design decisions. If energy performance depends strongly on occupant action, the design team can improve usability, feedback, and robustness rather than treating behaviour as an external uncertainty. Third, it can support communication with clients and public bodies by showing why occupant behaviour was or was not modelled in detail.

For residential buildings, this is especially relevant because the same energy concept can create different behavioural opportunity spaces. A dwelling with individual heating control, manually operable windows, accessible shading, and visible feedback allows more direct intervention than a dwelling in which heating is centrally controlled, ventilation is fixed, and shading is inaccessible or automated without override. The framework therefore helps to document a design condition that is otherwise often implicit.

DISCUSSION

The main advantage of the proposed framework is methodological economy. Detailed occupant modelling can be valuable, but it also requires assumptions, calibration, and interpretation. A preliminary freedom assessment can prevent the unnecessary use of complex models in buildings where occupants have little control. Conversely, it can highlight cases where the design gives occupants substantial influence and where simple fixed schedules may be misleading.

The framework also supports communication between disciplines. Architects may understand freedom through operability and accessibility; building physicists may understand it through boundary conditions and system responsiveness; facility managers may understand it through automation and override rules. A shared indicator structure can make these perspectives comparable without reducing the discussion to one behavioural stereotype.

There are also limitations. The framework does not measure actual energy consumption, does not predict real occupant choices, and does not replace monitoring. It also depends on the quality of available design information. Some indicators, such as usability and feedback, may be difficult to judge from drawings alone. Further work should therefore test the framework on residential case studies and compare its classification with simulation sensitivity results and measured post-occupancy data.

CONCLUSION

This paper proposed a decision-logic framework for assessing Occupant Behavioural Freedom in building energy performance evaluation. The paper distinguished between observed occupant behaviour and the building-related opportunity space for occupant action. By using measurable indicators such as local control, operability, automation, override, accessibility, and feedback, the proposed framework can identify whether occupant behaviour should be treated as a relevant variable before detailed behavioural simulation is applied.

The contribution is not a new behavioural prediction model, but a screening method for deciding when such models are needed. This is relevant for early-stage planning because it helps align modelling effort with the actual degree of occupant influence allowed by the building. Future work will refine the indicator weights, apply the method to residential case studies, and

test whether OBF classifications correspond to sensitivity ranges in building energy simulation.

REFERENCES

- de Wilde, P. (2014). 'The gap between predicted and measured energy performance of buildings: A framework for investigation', *Automation in Construction*, 41, pp. 40-49. <https://doi.org/10.1016/j.autcon.2014.02.009>
- de Wilde, P., Aly, D., Cho, S., Kim, J.-H., Kim, S. and Park, C.-S. (2025). 'Occupant behavioural freedom in building energy use', *Applied Energy*, 377, Article 124682. <https://doi.org/10.1016/j.apenergy.2024.124682>
- Mahdavi, A., Berger, C., Amin, H., Ampatzis, E., Andersen, R.K., Azar, E., Barthelmes, V.M., Favero, M., Hahn, J., Khovalyg, D., Knudsen, H.N., Luna-Navarro, A., Roetzel, A., Sangogboye, F.C., Schweiker, M., Taheri, M., Teli, D., Touchie, M. and Verbruggen, S. (2021). 'The Role of Occupants in Buildings' Energy Performance Gap: Myth or Reality?', *Sustainability*, 13(6), 3146. <https://doi.org/10.3390/su13063146>
- Yan, D., O'Brien, W., Hong, T., Feng, X., Gunay, H.B., Tahmasebi, F. and Mahdavi, A. (2015). 'Occupant behavior modeling for building performance simulation: Current state and future challenges', *Energy and Buildings*, 107, pp. 264-278. <https://doi.org/10.1016/j.enbuild.2015.08.032>
- Yan, D., Hong, T., Dong, B., Mahdavi, A., D'Oca, S., Gaetani, I. and Feng, X. (2017). 'IEA EBC Annex 66: Definition and simulation of occupant behavior in buildings', *Energy and Buildings*, 156, pp. 258-270. <https://doi.org/10.1016/j.enbuild.2017.09.084>

Algorithmic Support for Post-Disaster Temporary Living Area Planning

Bircan Kömürcü (12432866)

259.669 Algorithmen in der Planungspraxis

June 2026

Abstract

Post-disaster temporary housing areas provide displaced people with shelter, access to basic services and short-term living conditions. However, planning these areas is difficult because initial planning assumptions may not match actual post-disaster needs, as the population size, length of stay, site access conditions and service demand can change after the disaster. Based on the existing studies, this paper proposes an adaptive criteria-based planning approach that uses algorithmic decision support to compare and re-prioritize temporary living area alternatives based on both technical and human-centred criteria. The approach supports faster and clearer planning decisions while helping temporary living areas respond better to the safety, accessibility, comfort and livability needs of displaced people.

Keywords: post-disaster planning; temporary living areas; algorithmic decision support; adaptive planning; human-centred criteria; livability

1. Introduction

Following a disaster, many people may lose access to safe housing, sanitation, health services, infrastructure, and daily services. Post-disaster temporary housing provides displaced people with shelter and basic services while permanent reconstruction is still in progress. Temporary housing can help people regain a sense of stability after displacement. Therefore, temporary housing should not only be considered as emergency shelter, but also as temporary settlements that include housing units, service areas, public spaces, access routes, and basic social needs (Félix et al., 2013; Abulnour, 2014).

However, planning these kinds of areas is highly challenging because many critical decisions need to be made rapidly and under unpredictable conditions. In addition, post-disaster conditions may differ from initial planning assumptions. The number of displaced people, infrastructure capacity, service needs and expected length of use for people may change after the disaster. Therefore, temporary living area alternatives may need to be re-evaluated and reprioritized in light of updated conditions.

Existing studies show that algorithms and decision-support methods can support planning problems such as shelter site selection, location-allocation, layout optimization and design evaluation. However, these approaches often focus on specific aspects of the problem rather than connecting them within an adaptive planning process. Technical criteria such as capacity, accessibility, infrastructure, safety, and proximity to services are necessary, but they should also be supported by human-centred criteria, especially when temporary living areas are used longer than initially planned. Human-centred criteria such as privacy, comfort, cultural suitability, accessibility for vulnerable groups, adaptability, livability and spatial legibility must also be considered. This is because displaced people lose not only their homes after a disaster, but also the familiar physical environment that supports their way of life, daily routines, and social interaction.

Based on this background, this paper presents an adaptive criteria-based planning approach for post-disaster temporary living area planning. The approach focuses on the gap between initial planning assumptions and actual post-disaster needs and evaluates temporary living area alternatives by considering both technical requirements and human-centred needs. This paper aims to:

- outline existing algorithmic approaches for site selection, layout optimisation and design evaluation;
- identify why technical criteria alone need to be supported by human-centred criteria under changing post-disaster conditions;
- introduce a simple adaptive planning approach that combines technical and human-centred criteria to compare and re-prioritize temporary living area alternatives.

Consequently, the proposed approach can help planners identify trade-offs, respond to updated needs and make faster decisions. In this way, temporary living area planning can move beyond rapid placement and become a more adaptive and human-centred process.

2. Background / Related Work

Previous studies show that post-disaster temporary housing is not only a fast shelter solution. It is also a complex planning problem. Temporary living areas need to provide safety, privacy, basic services, and conditions for daily life. However, they are often criticised for being expensive, culturally unsuitable, having limited community participations, and creating environmental problems (Félix et al., 2013; Abulnour, 2014).

Some studies use algorithms and decision-support methods to decide where temporary shelters should be located. Site selection studies compare possible locations by looking at access to hospitals, police stations, fire stations, main roads, and population density (Anjomshoa & Heravi, 2025). Location-allocation studies also ask how shelter capacity can be matched with population demand. Other studies use parametric modelling, multi-objective optimisation, shape evolution, or genetic algorithms to create and compare different temporary housing layouts (Tak & Akay, 2026; Karaoğlu & Alaçam, 2018).

Other studies focus more on human-centred criteria. These studies show that temporary housing is not only about capacity and location, but also about creating a liveable environment for displaced people. Serter and Ayalp (2026) discuss design challenges such as cultural integration, pre-disaster planning, and comfort. Qin et al. (2023) show that thermal comfort is a important issue in temporary residential buildings. Hosseini et al. (2020) show that comfort, safety, and user preferences can be included in design evaluation. Sustainability and reuse is also important, because temporary housing can create waste and may be used longer than expected (Kahvecioğlu & Selçuk, 2025).

Overall, these studies show that technical criteria and human-centred criteria are both important. However, they are often discussed in separate research directions. This forms the starting point for this paper.

3. Problem / Research Gap

The literature shows that algorithms can help with different parts of post-disaster temporary living area planning. Site selection studies help planners find suitable locations. Location-allocation studies help match shelter capacity with population demand. Layout optimisation studies help create and compare different spatial arrangements. Other studies focus on comfort, cultural suitability, user needs, and sustainability. However, these topics are often studied separately.

This creates a gap in temporary living area planning. Technical criteria such as capacity, accessibility, infrastructure, safety, and service proximity are important. They show whether a site or layout can work in an emergency. However, they are not enough to explain whether a temporary living area can support daily life after a disaster. Real post-disaster conditions may also be different from the first planning assumptions. The number of displaced people may be higher than expected. Access routes may be damaged. Infrastructure may be limited. Service areas may become insufficient. In some cases, temporary living areas may also be used longer than expected. In this situation, comfort, privacy, social spaces, spatial legibility and livability become more important.

For this reason, pre-planned site and layout options should be treated as flexible alternatives. As post-disaster needs change, their suitability may need to be reviewed and re-prioritized according to updated conditions. This paper focuses on this gap. It discusses how algorithmic decision support can help planners compare temporary living area alternatives according to both technical and human-centred criteria. In this way, alternatives can be compared not only in terms of efficiency, but also in terms of their ability to support a more adaptable and liveable temporary settlement.

4. Adaptive Criteria-Based Planning Approach

This paper proposes a simple algorithmic workflow for post-disaster temporary living area planning. The approach does not try to create one final design solution. Instead, it compares different site and layout alternatives by using technical and human-centred criteria. The main aim is to help planners review and re-prioritize alternatives when post-disaster conditions change.

The workflow can be explained in five steps.

Step 1: Define input alternatives

The process starts with possible temporary living area alternatives. These alternatives can include candidate sites, layout options, estimated population, access routes, infrastructure conditions and service locations. Each alternative is used as an option in the comparison process.

Step 2: Define evaluation criteria

Each alternative is evaluated through two groups of criteria. Technical criteria include capacity, accessibility, infrastructure, safety and service proximity. Human-centred criteria include privacy, comfort, cultural suitability, accessibility for vulnerable groups, adaptability, livability and spatial legibility.

Step 3: Give priority to criteria

The importance of each criterion can change according to the post-disaster situation. For example, if the displaced population increases, capacity and infrastructure become more important. If access routes are damaged, accessibility and safe routes become more important. If people stay in the settlement longer than expected, comfort, privacy, social spaces and livability become more important.

Step 4: Score and compare alternatives

The decision-support process gives scores to each alternative according to the selected criteria. This helps to compare different strengths and weaknesses. For example, one alternative may have high capacity but low privacy, while another alternative may have better service access but lower capacity.

Step 5: Re-prioritize alternatives

When post-disaster needs change, the criteria priorities can be updated and the alternatives can be ranked again. The output is not one perfect solution but a ranked list of alternatives. This list can show which option should be prioritized, modified, expanded or reconsidered according to the updated situation.

In this way, the proposed approach works as an adaptive decision-support process. It helps planners compare temporary living area alternatives not only by technical efficiency but also by their ability to support safer, more accessible and more livable temporary settlements.

5. Discussion

The proposed approach can support a more flexible planning process for post-disaster temporary living areas. It compares alternatives not only through capacity and fast placement but also through accessibility, safety, comfort, privacy, spatial legibility, and livability. This can help planners see the strengths and weaknesses of different site and layout options, while also supporting temporary living areas that respond better to the daily needs of displaced people.

The approach is useful because post-disaster needs may change over time. For example, the number of displaced people may increase, access routes may be damaged or service areas may become insufficient. In such cases, planners can re-examine alternatives and make decisions as to which one should be given priority, modified or expanded.

However, the approach also has some limitations. It depends on available data, which may be incomplete in the wake of a disaster. It may also be difficult to decide which criteria are more important, as different planners may give different needs a higher priority. Since this paper presents the approach at a conceptual level, future work is needed to develop it into a more detailed digital model.

Future research can test this approach with real spatial data, population scenarios, accessibility maps, infrastructure information, and comfort indicators. The approach may be more useful to emergency planning and the design of temporary settlements.

6. Conclusion

This paper presented an adaptive criteria-based planning approach for post-disaster temporary living area planning. The paper showed that this planning process is difficult because decisions about capacity, accessibility, infrastructure, safety, services, and living quality must be made quickly under uncertain conditions.

Based on the literature, the paper argued that existing studies often address site selection, location-allocation, layout optimisation, comfort, and sustainability separately. Therefore, this paper proposed an approach that connects technical and human-centred criteria in one adaptive decision-support process.

In this approach, algorithms are used to compare alternatives, identify trade-offs, and re-prioritize temporary living area options when post-disaster needs change. In this way, temporary living area planning can become more flexible, systematic and human-centred.

References

- Abulnour, A. H. (2014). The post-disaster temporary dwelling: Fundamentals of provision, design and construction. *HBRC Journal*, 10(1), 10–24. <https://doi.org/10.1016/j.hbrj.2013.06.001>
- Anjomshoa, E., & Heravi, G. (2025). Pre-disaster planning and preparedness for urban seismic resilience: Evaluating critical influential factors for temporary shelter site selection. *Habitat International*, 163, 103478. <https://doi.org/10.1016/j.habitatint.2025.103478>
- Félix, D., Branco, J. M., & Feio, A. (2013). Temporary housing after disasters: A state of the art survey. *Habitat International*.
- Hosseini, S. M. A., Yazdani, R., & de la Fuente, A. (2020). Multi-objective interior design optimization method based on sustainability concepts for post-disaster temporary housing units. *Building and Environment*, 173, 106742. <https://doi.org/10.1016/j.buildenv.2020.106742>
- Kahvecioğlu, B., & Selçuk, S. A. (2025). Review of sustainable temporary housing and reuse strategy for post-disaster architectures: Current trends and strategic gaps. *Journal of Engineering and Applied Science*, 72, 8. <https://doi.org/10.1186/s44147-025-00581-4>
- Karaoğlu, F. C., & Alaçam, S. (2018). Design of a post-disaster temporary living space through the use of shape evolution. In *Proceedings of the 22nd Conference of the Iberoamerican Society of Digital Graphics*.
- Qin, M., Chew, B. T., Yau, Y. H., Yang, Z., Han, X., Li, C., Liu, Y., & Pan, S. (2023). Characteristic analysis and improvement methods of the indoor thermal environment in post-disaster temporary residential buildings: A systematic review. *Building and Environment*, 235, 110198. <https://doi.org/10.1016/j.buildenv.2023.110198>
- Serter, M., & Ayalp, G. G. (2026). Determining design challenges for post-disaster temporary housing units using the DEMATEL method. *Buildings*, 16(1), 33. <https://doi.org/10.3390/buildings16010033>
- Tak, M. D., & Akay, M. (2026). Parametric modelling for temporary housing areas: Integrating multi-source standards with multi-objective optimisation. *Progress in Disaster Science*, 29, 100519. <https://doi.org/10.1016/j.pdisas.2026.100519>

Generative Design System and Evolutionary Optimization for Architectural Layout Planning

Francesca Iaconis

Abstract

In architecture the space layout design phase is particularly important because it defines dimension, shape, construction methods, and costs.

However, the traditional manual process of space layout planning does not give the most suitable result and usually requires a great deal of time and mental effort. Furthermore, the existing computational methods present significant limitations that reduce their effectiveness and applicability in real design scenarios.

This work proposes a Generative design method enhanced with an evolutionary optimization that can be used for space layout planning to improve the process.

In fact, the proposed system can generate a large number of design proposals applicable to complex design problems, continuously refining them through an evolutionary optimization algorithm to identify the best options.

Keywords: Generative design, Layout planning, Parametric, Design stage, Evolutionary optimisation

Introduction

In architecture, the initial design phase is a crucial part of the entire process, because it is in this stage that the foundations of the future building are established. This includes not only the shape and the plan, but also more technical decisions such as construction methods and costs.

This phase is generally time-consuming. For instance, architects typically begin by sketching a large number of drafts to visualize the different possible variations for the building. Furthermore, architects are subjected to an even bigger challenge with the growth of the scale of the building, since at larger scales even more factors come into play and a greater number of variables are influenced by the initial design decisions.

We propose a generative design algorithm capable of generating a wide range of design solutions that can subsequently be explored by the architects themselves, rather than spending considerable time and effort attempting to manually identify the optimal layout.

In this work we will:

- Provide an overview of the design algorithms currently used to address the layout problem (see “Background”)
- Identify the key limitations of these algorithms in solving the problem effectively (see “Problem”)
- Introduce the proposed generative design algorithm as a potential solution (see “Solution”)

We are confident that our approach offers a meaningful contribution to the field, as it significantly reduces the time and effort required during the initial design phase while providing architects with a broader range of viable options to explore.

Background

In architectural education, the initial stage of design has traditionally involved producing a large number of sketches to explore variations of a building's floor plan, manually adjusting whatever appears incorrect or in need of improvement. Over time, this process has become increasingly automated through a variety of computational approaches.

Cellular Automata operates on grids governed by local rules, and their application to architectural design dates back several decades. Herr and Ford explored the use of Cellular Automata as design tools specifically for architectural contexts, addressing density, accessibility, and natural light requirements. More recently, Ng, Chen and Sathikh proposed a procedural model for spatial layout design inspired by game design, where the system accepts user inputs such as geometry, topology and privacy requirements to automatically generate design options.

A further development by the same research group introduced hexagonal cellular automata combined with graph theory: the proposed methodology introduced three algorithms able to show versatility across public spaces and real-world case studies, with a post-processing step that converts hexagonal layouts into rectangular forms to better align with conventional architectural norms.

Shape Grammar, introduced by Stiny in 1980, uses primitive shapes and geometric transformation rules (such as rotation, scaling and symmetry) to generate layout variations. A popular application of shape grammars in architecture is the generation of floor plans, where rules encode rotations, splits, scaling and symmetry, and can be extended to structurally conscious rules that assign materials and dimensions to elements.

Researchers have applied Shape Grammar to the study of specific architectural typologies (for instance it was used to explore the generative logic of traditional courtyard dwellings), to define algorithms for the allocation of rooms in floorplans (Wang and Zhang introduced grammar rules to generate graphs depicting adjacency relationships), and more recently to connect it with a more parametric system (for instance Stouffs created a shape grammar plug-in for Grasshopper)

Genetic Algorithms simulate the process of natural evolution and have been widely applied to architectural layout problems since the early 2000s. Genetic algorithms have been found suitable for solving the layout problem because they can provide alternative solutions.

Chen et al. applied Genetic Algorithms to open-plan office layout generation, demonstrating that the approach can assist designers in the early design stage.

Machine Learning models learn from existing floor plan datasets and once trained, can generate new layouts rapidly. Recent advances in Machine Learning for architectural design have led to new developments in automated floor plan generation. Deep learning architectures, including Generative Adversarial Networks (GANs) and diffusion models, have been applied to this domain, shifting from form-driven to performance-driven approaches and significantly reducing time for iterative design modifications in the initial stages.

Problem

The manual search for an optimal layout inevitably brings with it several drawbacks, including the considerable time required, the growing complexity at larger scales, the need to produce a large number of sketches, and the significant mental effort involved.

Despite their respective strengths, also each of these computational approaches presents significant limitations that reduce their effectiveness in real-world architectural design.

Cellular Automata is constrained by their grid-based, rule-governed structure that works for only a few different layout types simultaneously. The hexagonal Cellular Automata approach highlights a further geometric tension; because floor plans are generated from hexagonal cells to facilitate adjacencies, the resulting spaces tend to adopt hexagonal borders and shapes which are not commonly seen in conventional architectural design.

Moreover, Cellular Automata systems are poorly suited for handling complex or irregular building geometries, and their local rule structure makes it difficult to enforce global spatial requirements.

Shape Grammar is limited by its dependence on a predefined, fixed rule set. The geometric configurations are restricted to what the grammar allows, resulting in outcomes that may be theoretically valid but not practically feasible. This ties the system to a single architectural style or typology, severely constraining its flexibility across diverse design problems.

Genetic Algorithms are dependent on the quality of the underlying parametric model and the fitness function used to evaluate solutions. Genetic algorithms are susceptible to the problem of local maxima which can cause the search to stagnate before reaching a globally optimal solution.

A further limitation is the rigidity of the fitness function: when the bounding area is the only measure of success, outcomes of the optimization omit other important aspects of the space. The difficulty of encoding the full complexity of architectural requirements into a single mathematical objective remains an open challenge; algorithms have difficulty understanding all these constraints, a task that only human beings can fully synthesize.

Machine Learning models face a fundamental data problem in the architectural domain. Deep learning models often face challenges due to their dependence on large datasets, which are labour and time-intensive to generate, and floor plan drawings often present challenges such as overlapping elements and similar visual features.

Moreover, Machine Learning models tend to reproduce patterns presented in the training process rather than generating new configurations, constraining creative output. The need for large, annotated datasets not only makes these methods less adaptable, but also significantly increases the time and resources required for model training and re-training in diverse scenarios, limiting scalability especially in contexts where annotated data is scarce.

Other downside is that the output is generally a raster image rather than an editable geometric model, which limits direct integration into professional design workflows.

Solution

The aim of the proposed system is to use computational resources to assist designers by generating a variety of design solutions, which can then be further refined in the successive stages of the design process.

The process includes the following steps:

- Decomposition of the inner area of the building into cells
- Generation of space layout plans by assembling these cells together
- Definition of circulation patterns
- Evaluation of the generated plans according to a set of predefined rules, such as inner area requirements and circulation standards
- Optimization of the generated solutions through an evolutionary algorithm

Layout Creation

The space generation problem is treated as a cells allocation problem. The area inside the building is decomposed into a grid made of cells of equal dimensions. Each room generates a virtual field (as a magnetic field) that is stronger near the centroid and weaker further away from it.

For each cell, the algorithm determines which room has the strongest influence. This process is governed by three rules:

- A room can influence a cell only if the field value exceeds a threshold of 6. This prevents any single room from occupying the entire building.
- A room can influence a cell only if it falls within its active field.
- If multiple rooms compete for the same cell, the room with the strongest field takes priority.

By modifying the formulas and parameters, it is possible to obtain rooms of different shapes and orientations. This allows the designer to indirectly control the shape of the rooms through mathematical parameters.

Space Cell Allocation

Each room generates a field whose shape depends on the dimensions, orientation, and proportions of the room itself.

Different field shapes produce different room geometries: circular fields produce circular rooms, rectangular fields produce rectangular rooms, and octagonal fields produce intermediate geometries.

The main formula is:

$$f = \frac{m_x m_y}{|x'_1 - x_0| + |y'_1 - y_0| + \varepsilon}$$

It measures how much a room influences a point in space.

The field is stronger when the mass of the room is larger, and weaker with increasing distance, similarly to gravity.

In the formula:

- (x_0, y_0) represents the centre of the room.
- (x_1, y_1) the evaluated point
- m_x, m_y are the parameter that control how much the field expands vertically or horizontally

For each cell, the field of every room is calculated, compared, and the strongest one determines the cell assignment.

Circulation system

Once the rooms have been distributed, it is important to understand how occupants move through the building, the space allocated to circulation, and how the different rooms are connected.

After generating the room layout, the main entrance is connected to all rooms in the most efficient way possible using Dijkstra's algorithm, which finds the shortest path between a vertex and all other vertices of a graph.

The layout is first converted into a graph, where each cell of the grid becomes a vertex. Connections and their weights are defined by a set of rules: it is not possible to pass through the interior of a room, but it is possible to traverse empty cells and room boundaries, so that corridors run around the rooms. Three types of cells are defined:

- free cells
- boundary
- interior cells

Each associated with a different path weight:

- free to free, the cheapest
- free to boundary
- boundary to boundary, the most expensive.

In this way, the system favours the use of free cells and avoids complex boundaries.

Since Dijkstra's algorithm connects each room via the minimum path independently, the resulting paths can be very different from one another. To address this, each time a path is used its weight is reduced by 20%, encouraging subsequent rooms to reuse existing paths rather than generating new ones. This method, called Path Generation, reduces the space occupied by corridors, decreases their total length and increases the overall efficiency of the layout.

Evolutionary Optimisation

Creating an efficient layout is a complex process, as it must satisfy multiple requirements simultaneously, such as correct room dimensions, efficient corridors, good connections between rooms, natural light and aesthetics.

Since there is no single correct solution, the most effective approach is one that generates different solutions, evaluates them and progressively improves them.

This is the purpose of the Genetic Algorithm, which creates a set of initial solutions, evaluates them, selects the best ones, combines and refines them.

Selecting the best options is a multi-objective optimisation problem, addressed here using the NSGA-II algorithm, which does not seek a single optimal solution but rather a set of diverse high-quality solutions known as the Pareto front, where it is impossible to improve one aspect without worsening another.

The best solutions are then mixed by combining the genes of solution A and solution B to generate a new one, in a process known as "crossover". Random modifications are also introduced to explore better solutions, and the process is repeated iteratively, with the solutions improving at each generation.

The parameters modified by the algorithm, referred to as genes, include the position of the main entrance, the position of the rooms, mass parameters and room entrances.

This approach is inspired by the mechanisms of genetic mutation and natural evolution, which progressively lead to increasingly optimal outcomes.

Discussion

This work presents a tool capable of generating a variety of optimised layouts, applicable to both conceptual and practical design scenarios.

Compared to existing methods, the proposed system offers several advantages: it is highly flexible, customisable and it is able to address complex design challenges while maintaining control over the outcomes. Furthermore, its compatibility with evolutionary algorithms such as NSGA-II facilitates an effective search for optimal design solutions.

The tool also provides immediate visual feedback through its integration with visualisation software, resulting in a dynamic and interactive design experience. Additionally, the parametric model is scalable and can be applied to projects of varying size and complexity, from individual apartment units to large-scale development projects.

However, the tool is not without limitations. The cell-based grid structure introduces a computational overhead that can make the system slow for large-scale projects, and the higher the grid resolution, the greater the computational cost. The model is also not fully automatic, as it requires the designer to define a set of input parameters.

Furthermore, it does not guarantee the architectural and aesthetic quality that a designer would provide, so the generated layouts can occasionally appear complex, unusual or inconsistent with established architectural principles.

Most importantly, the model cannot substitute the designer, as it lacks architectural culture and aesthetic sensibility, which remain essential qualities that only human expertise can provide.

Conclusion

This work has presented a parametric generative design tool for space layout planning, combining a cell allocation strategy, a circulation system based on Dijkstra's algorithm, and an evolutionary optimisation process driven by the NSGA-II algorithm.

The results suggest that this approach represents a promising direction for the automation of layout planning, particularly for complex design problems where the number of variables makes manual exploration impractical. At the same time, the tool is not intended to replace the designer, but rather to act as a generative assistant that expands the solution space and accelerates the decision-making process, leaving the final architectural judgement to human expertise.

References

Z. Li, S. Li, G. Hinchcliffe, N. Maitless, N. Birbilis, *Automated architectural space layout planning using a physics-inspired generative design framework*

Ng, C. S. X., Chen, C.-H., Sathikh, *A procedural approach based on cellular automata for the generation of spatial layout designs*

Stiny, G., *Introduction to shape and shape grammars*

Herr, C. M., & Ford, R. C., *Cellular automata in architectural design: from generic systems to specific design tools.*

Ng et al., *Hexagonal cellular automata and graph theory for procedural spatial layout generation.*

Haakonsen, S. M., Rønquist, A., & Labonnote, N., *Fifty years of shape grammars: A systematic mapping of its application in engineering and architecture.*

Weber, R. E., Mueller, C., & Reinhart, C., *Automated floorplan generation in architectural design: a review of methods and applications.*

Dalgic, H. O., Bostanci, E., & Guzel, M. S., *Genetic Algorithm Based Floor Planning System.*

Mostafavi, F. et al., *Floor plan generation: The interplay among data, machine, and designer.*

AI such as Chat GPT and Claude AI were used to translate the papers used as references and to correct grammar mistakes in the writing process of the paper.

Covering the Lot: Budget-Constrained Placement of EV Chargers in Parking Lots

Jinsan Ryu_12532894

Algorithmen in der Planungspraxis (259.669)

Abstract

The need to electrify parking bays for electric vehicle charging creates a trade-off between identifying high-demand bays and the cost of trenching and cabling from the electrical panel to each bay. To address this challenge, we formulate the planning decision as a budgeted version of the classic maximum coverage problem on a grid, where the cable cost of each candidate bay equals its aisle distance from the electrical panel. The coverage objective is known to be monotone and submodular (Nemhauser et al., 1978); thus, we apply a partial-enumeration greedy algorithm, which carries a $(1-1/e)$ optimality guarantee. For a sample lot, this approach achieves approximately 90–100% of a certified upper bound on the optimal solution (LP relaxation), and covers up to about twice the chargeable demand of the widely used "nearest-bay" rule for the same cable budget. Additionally, it provides planners with a transparent map of where chargers should be installed first and what level of chargeable demand they can expect for each additional unit of cable budget.

Keywords: EV charging, facility location, maximum coverage, submodular optimisation, greedy algorithm, site planning.

1 Introduction

Electric Mobility's transition from an "ordinary" car park to "infrastructure," presents planners with a practical design question at the individual car park level. Specifically: Given that there will be some parking bays in each car park that will need to be electrified, which ones should these be?

Although the question appears simple enough, it is in fact complicated by two competing factors. In terms of demand (i.e. how many people wish to use the service) — chargers need to go in locations that are accessible to users (entrances or high foot traffic areas). However, as much as possible, they also need to be located in proximity to the electrical panels for the buildings being served — as the cost associated with the installation of a charging station is primarily due to the installation of trenches and cable runs required to connect the charging station back to the electrical panel(s), therefore, installing a charging station far away from the electrical panel(s) is very costly. Planners today do not have a clear method for evaluating both competing considerations within a set budget.

In this work, we will:

- review facility-location theory and the submodular structure the problem rests on;
- formalise charger placement as a budgeted maximum-coverage problem on a grid, with cable cost as the budget, and note why solving it exactly is intractable;
- give a partial-enumeration greedy algorithm with its complexity and a $(1-1/e)$ guarantee, and certify near-optimality with a linear-programming bound;
- and evaluate it on a synthetic lot against a naive baseline and the certified optimum.

This benefits planners and building operators by framing charger siting as a measurable plan — one that comes with a guarantee on how close to optimal it is, shows how much demand each additional unit of cable budget buys, and is fast enough to re-run as demand estimates or budgets change.

2 Background

EV charging in parking lots. The majority of charging takes place in vehicle dwell areas rather than at designated stations (Hardman et al., 2018). The primary expense of converting a parking area is the electrical connections from each point to the panel, not the charger hardware (Nicholas, 2019).

Coverage and submodularity. The maximum-coverage family of problems - maximizing demand served by limiting the number of facilities. This has been traditionally known as the maximal cover location problem. In terms of a coverage objective, coverage is monotone and submodular. For cardinality constraints ("use no more than p facilities") a simple greedy algorithm that repeatedly adds the facility with the largest marginal coverage has a guarantee of $(1 - 1/e) \approx 0.63$ to optimal solutions. If facilities have heterogeneous costs and the constraint is budgetary rather than cardinality-based, the resultant problem is known as the budgeted-maximum-coverage problem; it is solvable via a partial enumeration greedy algorithm which retains the same $(1 - 1/e)$ guarantee. We cast charger placement within a budgeted form - using cable distance to panel as cost. Further, on realistic instances, the results are not merely guaranteed but also show the greedy algorithm is approximately only a few percent off a certified optimum.

3 Problem

We model one parking lot as a grid of cells, each a candidate charger bay. Let $C = \{1, \dots, m\}$ be the cells, $d_j \geq 0$ the charging demand attributed to cell j , and let the building's electrical panel sit at a fixed cell. Two structures define the problem.

Coverage. A charger at bay i serves the demand of every cell within a walking radius r ; write $\text{cov}(i)$ for that set. A set of chosen bays S covers the union of their $\text{cov}(i)$, of total demand $f(S) = \text{sum of } d_j \text{ over the covered cells}$.

Cost. Electrifying bay i requires cabling from the panel along the aisles, so its cost w_i is the aisle (grid) distance from the panel to i , plus a fixed hook-up term.

Given a cable budget B , we want the set of bays that covers the most demand without exceeding the budget:

$$\text{maximise } f(S) \quad \text{subject to } \text{sum of } w(i) \text{ over } S \leq B.$$

The maximum coverage problem with the given maximum budget is an NP-hard optimization problem. However, its objective function is well-structured: f is monotone and submodular; adding a bay to S never decreases the total covered demand $f(S)$ and since once the demand for a cell is met it can no longer be met again, the amount of additional cells that would be covered by a single bay will decrease as we continue to select bays. Submodularity is what makes the greedy approach principled rather than merely plausible, and it underlies the guarantee stated below. A

synthesized example is shown in Fig. 1. In the figure, the demand for service is concentrated into several regions including one region that is distant from the panel and therefore expensive to serve.

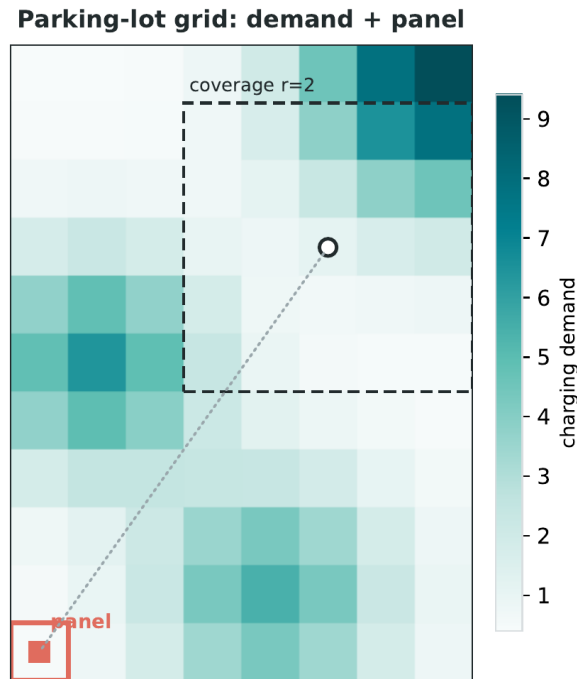


Figure 1. The model. Colour is charging demand; the panel (red) sits in a corner, so a bay's cable cost grows with its aisle distance from it. A charger covers the demand within radius r (dashed square).

4 Covering the Lot

Why the obvious greedy is not enough. The general method for the greedy algorithm follows the same principle as cost-benefit greedy, which adds one additional bay in each iteration that has an acceptable price relative to the maximum possible value. A pure cardinality constraint could give a $(1-1/e)$ bound; however, with a budget constraint, we see that cost-benefit greedy may fail badly. It will spend its total budget on multiple inexpensive bays near the panel and therefore cannot afford to pay for a single high-cost bay that would cover a larger distant group of clusters. In fact, in the given instance this myopic behavior occurs -- at a moderate budget size the cost-benefit greedy method is outperformed even by a completely blind-to-cost greedy method.

Partial-enumeration greedy. A common repair establishes the assurance (Khuller et al., 1999); for each affordable bay use it as a forced first choice, expand by using cost-benefit greedy for all of these choices and keep the best total result (including an empty choice). Using the expensive, high-value bay will allow the algorithm to choose a far away cluster early on in the problem and spend the rest of the money cheaply — which is exactly what the simple rule would miss.

```
Algorithm 1 CoverLot( $C, w, B$ )
  best  $\leftarrow$  Extend({})
  for each bay  $s$  with  $w_s \leq B$ :
    cand  $\leftarrow$  Extend({ $s$ })
    if  $f(\text{cand}) > f(\text{best})$ : best  $\leftarrow$  cand
  return best
```

```

function Extend(S):
    while some unchosen bay i has  $w(S)+w_i \leq B$  and  $gain_i > 0$ :
        add the bay maximising  $gain_i / w_i$  to S
    return S

```

Guarantee and complexity. Because f is monotone submodular, CoverLot returns a set covering at least $(1-1/e) \approx 63\%$ of the optimum's demand (Khuller et al., 1999). Each Extend call costs $O(m^2)$ marginal-gain evaluations and there are $O(m)$ seeds, so the running time is $O(m^3)$ on an m -cell grid — a fraction of a second at the scale of a single lot, and easily re-run as inputs change.

Certifying optimality. Because we do not know what the best possible solution to an NP-hard problem is, we provide a guaranteed upper bound on that value using the linear programming relaxation of our integer model (where the number of bays can be fractional and the number of items covered can be fractional). Therefore, the ratio of the number of items in our solution to the number of items in the optimal linear program is a guaranteed lower bound on how good a solution we have found.

Experiments. On an 8×11 grid (demand and panel as in Figure 1) we sweep the cable budget B and compare CoverLot with the LP upper bound and with a naive “cheapest-bays-first” rule that simply wires the bays nearest the panel until the budget runs out — a realistic default for a cost-driven contractor. We also verified on 60 small instances (solvable exactly by enumeration) that CoverLot matched the exact optimum on every one, far exceeding its worst-case guarantee.

Table 1. Demand covered at each cable budget (total demand ≈ 201).

Budget B	Ours	Cheapest	LP bound	Ours / LP
15	116.5	57.6	128.3	91%
25	174.2	75.9	174.4	100%
40	197.0	104.0	199.8	99%
60	200.7	112.8	200.7	100%
90	200.7	123.2	200.7	100%

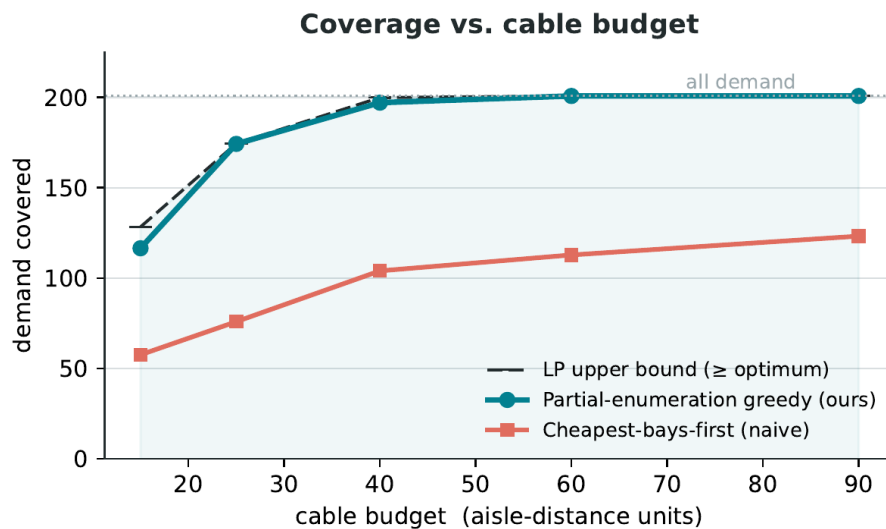


Figure 2. CoverLot (teal) tracks the LP upper bound (dashed) closely at every budget, while the naive nearest-bays rule (red) covers far less. Coverage shows clear diminishing returns.

Same cable budget (B=40), very different coverage

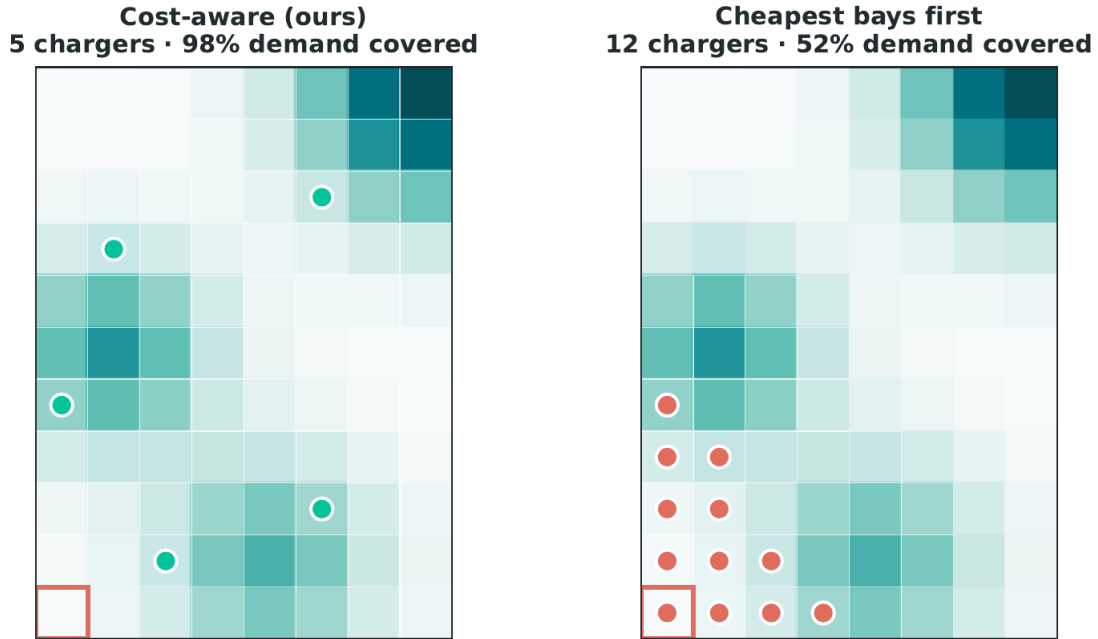


Figure 3. Same cable budget, very different coverage. Left: our cost-aware plan places five chargers to reach every demand zone (98% covered). Right: wiring the cheapest bays first crowds the panel corner and covers only 52%.

In all cases, CoverLot never deviates by much from the LP upper bound (within 9% at most, and 0–1% in most cases) for the given instance; therefore, it is nearly as good as the optimal solution on these instances, as opposed to just possibly the best under extreme conditions. A comparison with cheapest-bay rule indicates that our method has a significantly larger coverage for the same budget - in fact we are covering about twice as much demand (for example, 174 vs. 76 at $B = 25$) because the cheapest-bay method clusters chargers near the panel, where demand is relatively low. The coverage graph provides another illustration of diminishing returns to cost - a modest budget can cover virtually all of the demand; this makes it possible for planners to have a basis for determining when additional cabling costs are no longer justified.

5 Discussion

Limitations. We have assumed that each bay has independent cable costs (whereas adjacent bays are likely to be served from the same trench) -- The actual cost of a set of bays is determined by the length of the cable tree required to connect these bays to the panel rather than simply adding up their individual distances. We assume that demand is static and known for simplicity while we recognize that in real-world scenarios this is an estimate that may vary with time-of-day. Finally, we assume perfect coverage within some fixed radius and do not consider the number of vehicles a charger can service -- although this is often referred to as the capacity or queueing issue, it is orthogonal to where chargers should be placed. A simple cost-blind, demand-only heuristic happened to satisfy similar demand levels in our test case due to the forgiving nature of coverage -- however, this method provides no guarantee of controlling cable expenditure and therefore does not provide the desired control over the planning quantity of interest.

Future work. The shared trench cost turns the problem into connected facility location: in other words, the chosen set becomes a Steiner tree length from the panel, which is itself NP hard but well approximated and would couple placement to the routing of the cable network. Time-varying demand suggests covering a distribution of demand scenarios; adding charger capacity links placement back to the operational question of how the installed chargers are then shared.

6 Conclusion

We modeled the placement of EV charging stations in a parking area as a "budgeted" maximal-coverage problem, where the cost to place a charging station at a candidate bay is equivalent to the length of cable needed to reach the electrical panel from that bay, and the objective was to cover as much of the total charging demand as possible within a given cable budget. Utilizing the fact that the coverage function is submodular, we then used a partial enumeration greedy algorithm to solve this problem, and following Khuller et al. (1999), this approach is guaranteed to find solutions within $(1 - 1/e)$ of the optimal. In comparison to the simple nearest-bay rule where one would simply choose the closest bay to the electrical panel until all available funds were exhausted, on our synthetic lot, we were able to achieve solutions that covered approximately twice as much demand as could be achieved under the same cable budgets.

References

- Church, R., & ReVelle, C. (1974). The maximal covering location problem. *Papers in Regional Science*, 32(1), 101–118.
- Hardman, S., Jenn, A., Tal, G., et al. (2018). A review of consumer preferences of and interactions with electric vehicle charging infrastructure. *Transportation Research Part D*, 62, 508–523.
- Khuller, S., Moss, A., & Naor, J. (1999). The budgeted maximum coverage problem. *Information Processing Letters*, 70(1), 39–45.
- Nemhauser, G. L., Wolsey, L. A., & Fisher, M. L. (1978). An analysis of approximations for maximizing submodular set functions—I. *Mathematical Programming*, 14(1), 265–294.
- Nicholas, M. (2019). Estimating electric vehicle charging infrastructure costs across major U.S. metropolitan areas (Working Paper 2019-14). International Council on Clean Transportation.

Algorithmic Optimization of Vaulted Floor Slabs for Structural Performance and CO₂ Reduction

Mohamad Mahdi Kazemi

Abstract

The construction industry significantly contributes to global CO₂ emissions, creating a growing need for structurally efficient and low-carbon building systems. Conventional structural design methods often optimize either structural safety or material reduction separately, limiting the potential for integrated sustainable solutions. This study presents a multi-objective computational optimization workflow for a vaulted floor slab using parametric modeling, finite element analysis, and fitness-function-based optimization to balance structural performance and CO₂ emissions. The proposed approach achieved an optimized shell geometry with reduced environmental impact while satisfying ultimate limit state and vibration performance criteria.

Keywords : Computational Optimization, Parametric Design, Structural Optimization, CO₂ Reduction, Vaulted Floor Slab, Finite Element Analysis, Sustainability, Algorithmic Design

1. Introduction

The building sector is responsible for a considerable portion of global greenhouse gas emissions. While operational energy consumption has been reduced through improved energy standards, embodied carbon associated with construction materials remains a major environmental concern. Structural systems, especially concrete-based systems, contribute significantly to embodied carbon emissions.

Recent advances in computational design and parametric modeling have enabled designers to explore large design spaces and optimize structures according to multiple performance criteria. Multi-objective optimization methods are increasingly used to balance structural efficiency, material consumption, and environmental impact. Vaulted and shell-based structures provide promising opportunities for reducing material usage because they primarily transfer loads through compression rather than bending.

This research investigates a computational workflow for optimizing a vaulted floor slab with the goal of minimizing CO₂-equivalent emissions while maintaining structural safety and stability.

2. Literature Review

The construction industry is responsible for a significant share of global greenhouse gas emissions, with structural systems accounting for a large portion of the embodied carbon of buildings. As operational energy consumption decreases due to improved building efficiency standards, increasing attention has been directed toward reducing embodied carbon through optimized structural design (Mueller et al., 2018). Recent research highlights that material efficiency, low-carbon materials, and component reuse are among the most effective strategies for reducing the environmental impact of building structures.

Parametric and algorithmic design approaches have emerged as powerful tools for exploring large design spaces and

evaluating multiple structural alternatives during the early design stage. Reisinger et al. (2022) developed a parametric optimization framework integrating structural analysis, life-cycle assessment, and decision support, demonstrating how automated workflows can improve resource efficiency and sustainability in industrial buildings. Their work emphasizes the value of linking structural performance assessment with environmental indicators during design development.

Several researchers have focused specifically on minimizing embodied carbon through structural optimization. Jayasinghe et al. (2022) investigated reinforced concrete flat slabs using a parametric design algorithm that varied slab thickness, concrete grade, column spacing, and reinforcement details. Their findings showed that embodied carbon can be significantly reduced through systematic optimization while maintaining structural performance requirements.

Optimization methods have also been applied to larger structural systems. Yepes et al. (2015) proposed a hybrid optimization algorithm for precast prestressed concrete bridges, simultaneously minimizing cost and CO₂ emissions. Their research demonstrated that multi-objective optimization techniques can identify environmentally efficient solutions without compromising structural safety.

Recent studies have increasingly combined sustainability objectives with computational design workflows. Takser (2024) introduced a parametric life-cycle assessment workflow that allows designers to evaluate operational energy demand and CO₂-equivalent emissions directly during the design process. The study demonstrated how parametric tools can support informed decision-making and environmental optimization at early project stages.

Research on low-carbon structural systems has further highlighted the importance of material-efficient geometries. The work of the Block Research Group at ETH Zurich has demonstrated that vaulted and funicular structural forms can significantly reduce material consumption by transferring loads primarily through compression rather than bending. Such geometries provide opportunities for achieving lower embodied carbon while maintaining structural efficiency (Mueller et al., 2018).

Although substantial progress has been made in structural optimization and embodied carbon reduction, relatively few studies have focused on integrating form-finding, finite element analysis, and CO₂-based fitness functions within a single multi-objective optimization workflow for vaulted floor slabs. This research aims to contribute to this area by developing a parametric optimization framework that simultaneously considers structural performance and environmental impact.

3. Methodology

The proposed structural system consists of a vaulted floor slab occupying an 8 m × 8 m × 0.8 m design space. (Figure 1)

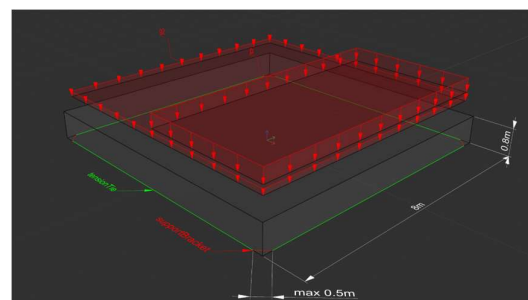


Figure 1: design space and condition

As illustrated in Figure 2 the geometry was generated using a spider-web-inspired topology composed of radial (weft) and concentric (warp) mesh lines to improve force transmission efficiency. Due to the symmetry of the geometry, only one-eighth of the shell was modeled parametrically and

subsequently mirrored to generate the complete slab geometry. This approach significantly reduced computational effort during the optimization process while

maintaining geometric consistency. The parametric workflow and optimization process were implemented using Rhino Grasshopper and Karamba3D

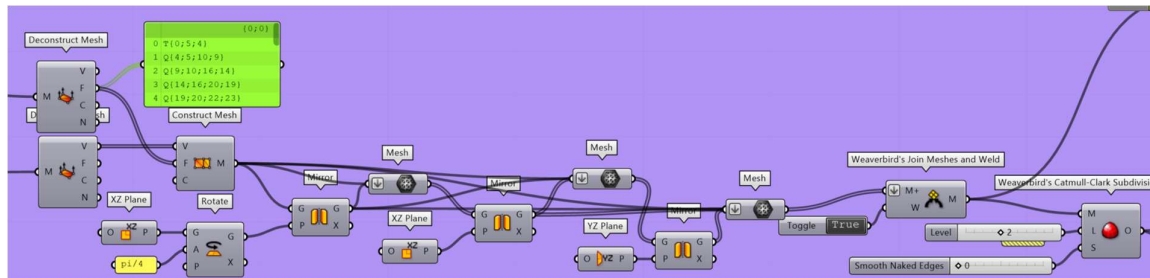
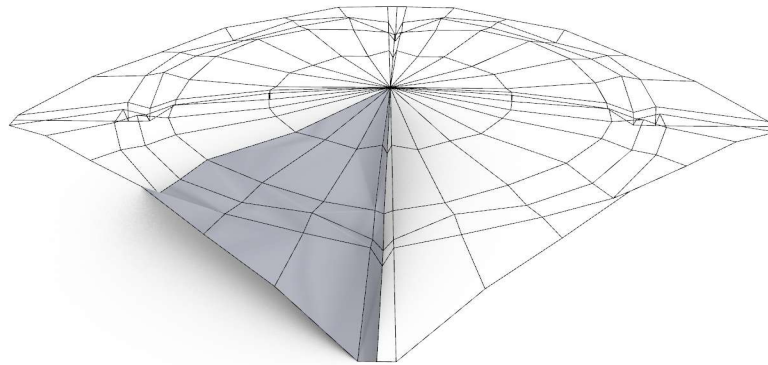


Figure 2: Parametric generation of the shell geometry using one-eighth symmetry modeling

The initial shell geometry was developed through a form-finding and shape-optimization workflow. To avoid stress concentrations at the intersections between mirrored shell segments, the primary mesh was converted into a smoothed SubD

geometry using the Catmull–Clark subdivision method. As illustrated in Figure 3, This smoothing process improved geometric continuity and reduced local stress peaks within the shell surface.

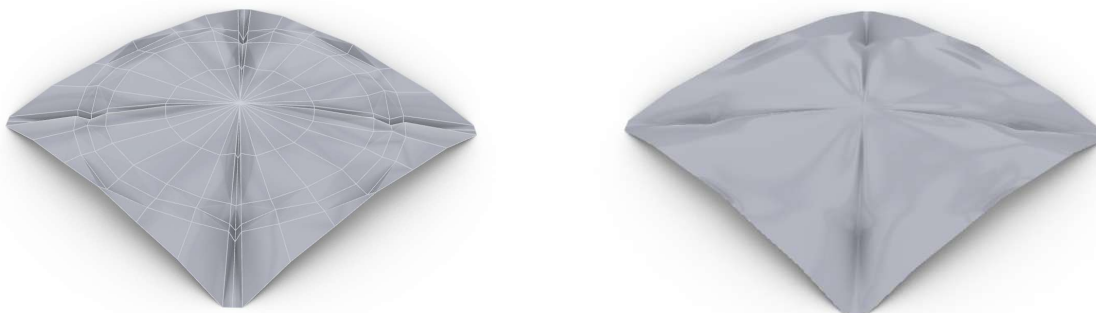


Figure 3: difference between the primary mesh and the smoothed subD

The optimized structural system incorporated several additional structural

elements, including edge beams, diagonal beams, circular reinforcement beams, and

four pre-stressed tension ties. The tension ties were introduced to reduce horizontal

thrust forces because the supports were only allowed to transfer vertical reactions. (Figure 4) The shell and beam system were analyzed using finite element analysis (FEA) under both uniform and asymmetric loading

conditions. The applied load cases consisted of a permanent load of 0.5 kN/m^2 and a variable load of 3.0 kN/m^2 . For the asymmetric load case, the variable load was applied only to one-half of the slab surface in order to evaluate the structural behavior under non-uniform loading conditions.

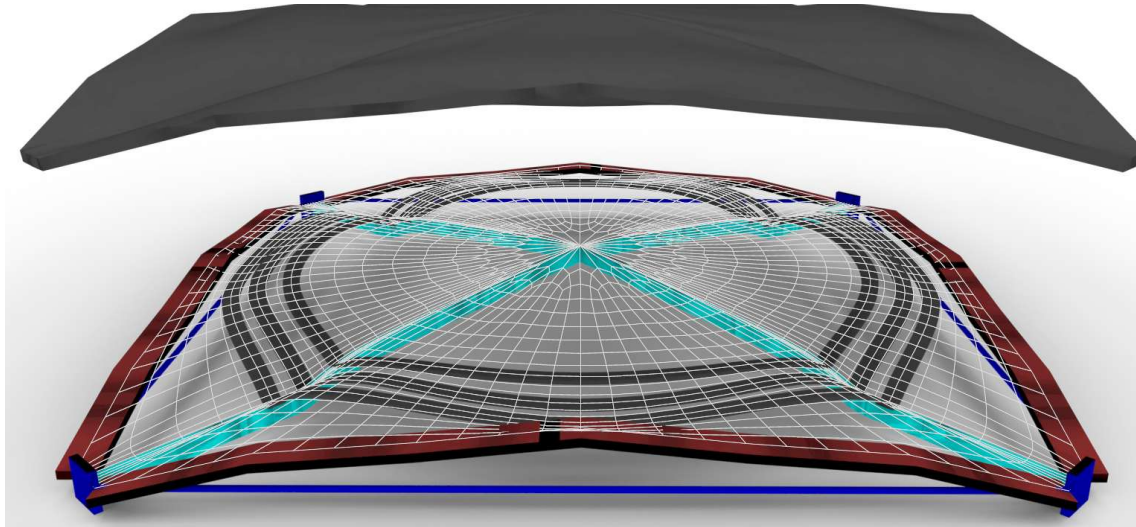


Figure 4: structure layout

To achieve both structural efficiency and environmental sustainability, a multi-objective optimization framework was developed. The optimization variables included shell thickness, beam dimensions, shell control-point elevations, and pretension strain values in the tension ties. In addition, concrete material classes ranging from C20/25 to C40/50 were considered as variable design parameters during the optimization process.

The optimization workflow integrated parametric modeling, finite element analysis (FEA), structural stress evaluation, and environmental impact assessment within a unified computational framework. Structural performance was evaluated under both uniform and asymmetric loading conditions, while environmental performance was assessed based on embodied CO_2 emissions associated with material selection and concrete volume.

A custom fitness function was developed to simultaneously minimize structural stress concentrations and CO_2 -equivalent emissions. Principal tensile and compressive stresses were evaluated at multiple shell layers, and penalty coefficients were introduced whenever allowable stress limits were exceeded. Since concrete is significantly more vulnerable under tensile stresses than compressive stresses, higher weighting coefficients were assigned to tensile stress penalties within the optimization process.

The mathematical formulation and implementation of the fitness function are explained in the following subsection. Figure 5 illustrates the overall optimization workflow and computational process used in this study.

3.1 Multi-Objective Fitness Function

The optimization process aimed to achieve two primary objectives simultaneously:

1. Uniform stress distribution and structural stability
2. Minimum CO₂-equivalent emissions through efficient material usage

If structural stress alone were minimized, the optimization process would naturally favor excessive material usage and thicker concrete sections to reduce stress concentrations. Conversely, if only CO₂ emissions were minimized, the resulting solution would tend toward extremely thin shell geometries with insufficient structural capacity.

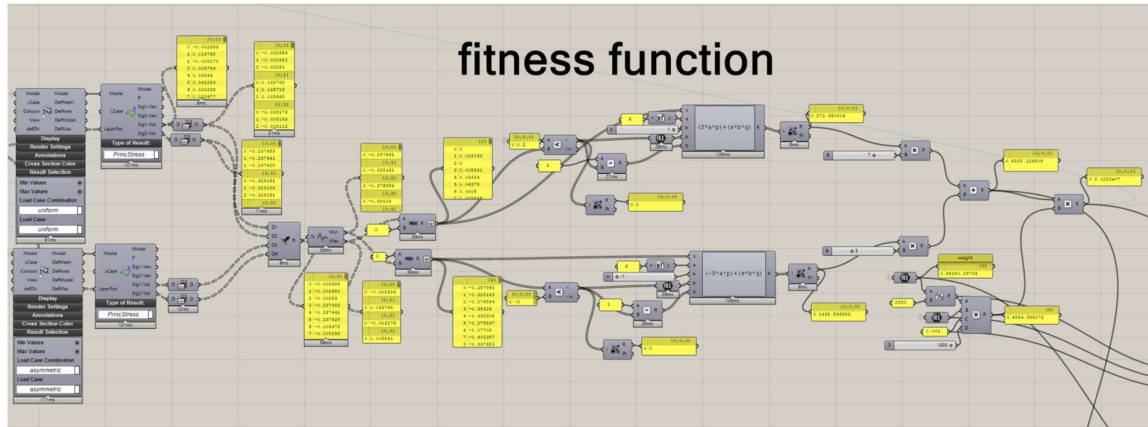


Figure 5: Parametric implementation of the multi-objective fitness function

Therefore, a balanced multi-objective fitness function was developed to prevent these extreme solutions and simultaneously address both structural and environmental performance.

The fitness function combines a structural stability component and an environmental sustainability component:

$$F = \min([S] \times [1000 \times C])$$

Where:

$$S = 7 * \left[\sum_{k=0}^n (P * \max(\sigma_{1i})) \right] + 3 * \left[\sum_{k=0}^n (P * \min(\sigma_{2i})) \right]$$

$$C = V * CO_{2eq}$$

In this formulation, σ_1 represents the first principal stress (tensile stress), while σ_2 represents the second principal stress (compressive stress). The penalty coefficient (P) is activated whenever stress values exceed allowable limits. A large penalty coefficient of 1×10^6 was assigned to overstressed regions in order to strongly

discourage structurally unsafe solutions during the optimization process.

Higher weighting was assigned to tensile stresses because concrete is significantly more vulnerable under tension than compression. Therefore, a weighting coefficient of 7 was assigned to tensile stress terms, while compressive stress terms received a weighting coefficient of 3.

The environmental component of the fitness function was calculated based on the concrete volume (V) and the embodied CO₂-equivalent emissions associated with the selected concrete class. A multiplication factor of 1000 was introduced to increase the influence of environmental impact after structural safety conditions had been satisfied.

This fitness-function formulation enabled the optimization algorithm to identify structurally efficient shell geometries while simultaneously minimizing embodied carbon emissions.

4. Results and Discussion

The optimization process successfully generated a structurally efficient vaulted slab geometry with reduced embodied carbon emissions while satisfying Ultimate Limit State (ULS) requirements. The final optimized structure achieved a CO₂-equivalent emission value of approximately 4854 kg while maintaining acceptable structural performance under both loading scenarios.

The optimized shell geometry featured a variable slab thickness ranging from approximately 8 cm at the center to 13 cm near the slab edges. The final solution also incorporated optimized edge beams,

diagonal beams, and circular reinforcement beams to improve force redistribution and stiffness. The integrated tension-tie system effectively reduced horizontal forces and contributed to the overall stability of the structure.

The optimization results demonstrated a clear relationship between stress reduction and environmental performance. As illustrated in Figure 6, the optimization algorithm progressively reduced the number of overstressed shell nodes while simultaneously minimizing CO₂ emissions. A distinct transition region appeared between infeasible and acceptable solutions due to the stress penalty coefficients included in the fitness function.

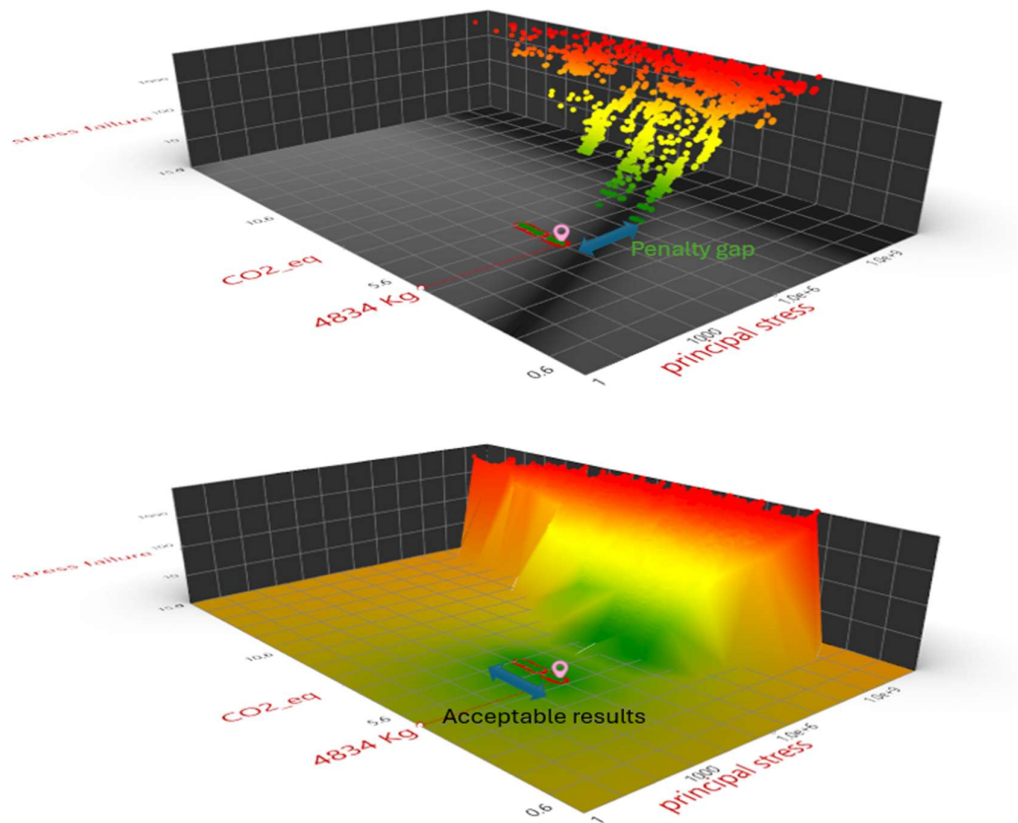


Figure 6: 3D chart of optimization iterations

Under uniform loading conditions, the shell exhibited a maximum tensile utilization of approximately 73.2% and a maximum compressive utilization of approximately 51.9%. Under asymmetric loading, tensile

utilization increased to approximately 88.7%, while compressive utilization remained below critical levels. The stress distributions confirmed that the shell geometry efficiently transferred loads

primarily through compression-dominant force paths.

Figures 7 and 8 demonstrate the structural utilization patterns under uniform and asymmetric loading conditions. The results indicate that stress concentrations were effectively controlled and distributed across the shell surface. The lower shell layer experienced localized tensile stresses primarily along the warp directions, while the upper shell layer remained largely compression-dominated.



Figure 7: Utilization of slab under uniform load

Dynamic performance analysis showed that the optimized slab achieved a natural vibration frequency of approximately 1.71 Hz with a modal mass of 5337 kg. Although the vibration performance was classified as HIVOSS Class E, the results remained acceptable considering that the primary optimization objective focused on reducing embodied carbon rather than maximizing vibration comfort.

Overall, the results demonstrate that algorithmic multi-objective optimization can

effectively balance structural safety, material efficiency, and environmental performance within vaulted floor slab systems. The integration of parametric design and finite element analysis enabled the exploration of numerous design alternatives and facilitated the identification of low-carbon structural solutions.



Figure 8: Utilization of slab under asymmetric load

Additional detailed visualizations of principal stress distributions in the upper and lower shell layers under both uniform and asymmetric loading conditions are provided in Appendix A. Figures 9 to 12 further illustrate the structural behavior and stress-transfer mechanisms within the optimized shell geometry.

5. Conclusion

This study presented an algorithmic multi-objective optimization workflow for the design of low-carbon vaulted floor slabs. By integrating parametric modeling, finite element analysis, and CO₂-based fitness evaluation within a unified computational framework, the research demonstrated how

structural performance and environmental sustainability can be addressed simultaneously during the early design stage.

The optimization process successfully generated structurally efficient shell geometries capable of satisfying Ultimate Limit State requirements under both uniform and asymmetric loading conditions while minimizing embodied carbon emissions. The results showed that the combination of form-finding techniques, stress-based optimization, and environmental assessment can significantly improve material efficiency and reduce the environmental impact of concrete structural systems.

The proposed workflow also demonstrated the advantages of algorithmic and parametric design approaches in exploring large design spaces and evaluating multiple design alternatives efficiently. The integration of structural analysis and sustainability criteria within the same optimization process enabled a balanced decision-making framework that considers both engineering performance and environmental impact.

Although the optimized structure achieved acceptable structural behavior, the vibration performance indicated that further refinement may be required for applications with stricter comfort requirements. In addition, the current study focused primarily on concrete shell systems and did not investigate alternative low-carbon materials or construction methods. The study is also limited to static loading conditions and simplified material assumptions.

Future research could expand this methodology by integrating advanced optimization algorithms, machine learning-assisted form generation, and real-time environmental assessment tools. Further studies may also investigate hybrid structural systems, recycled materials, and

adaptive shell geometries to achieve even lower embodied carbon emissions and improved structural performance.

Overall, this research demonstrates the potential of computational multi-objective optimization as an effective approach for developing sustainable structural systems and supporting environmentally informed architectural and engineering design decisions.

6. References

1. Jayasinghe, A., Orr, J., Ibell, T., & Boshoff, W. (2022). *Minimising embodied carbon in reinforced concrete flat slabs through parametric design*. Structures.
2. Reisinger, J., Kugler, S., Kovacic, I., & Knoll, M. (2022). *Parametric Optimization and Decision Support Model Framework for Life Cycle Cost Analysis and Life Cycle Assessment of Flexible Industrial Building Structures Integrating Production Planning*. Buildings, 12(2), 162.
3. Yepes, V., et al. (2015). *Cost and CO₂ Emission Optimization of Precast Prestressed Concrete Road Bridges*. Automation in Construction.
4. Takser, I. (2024). *Parametric Life Cycle Analysis for the Optimization of Building Construction*. TU Wien.
5. Mueller, C., De Wolf, C., et al. (2018). *Low Carbon Pathways for Structural Design*. IASS Symposium 2018.
6. Hafez, H., et al. (2024). *Parametric Study on the Decarbonization Potential of Reinforced Concrete Buildings*.
7. Block, P., Van Mele, T., Rippmann, M., & Paulson, N. (2017). *Beyond Bending: Reimagining Compression Shells*. Detail Special Edition.

8. Appendix A

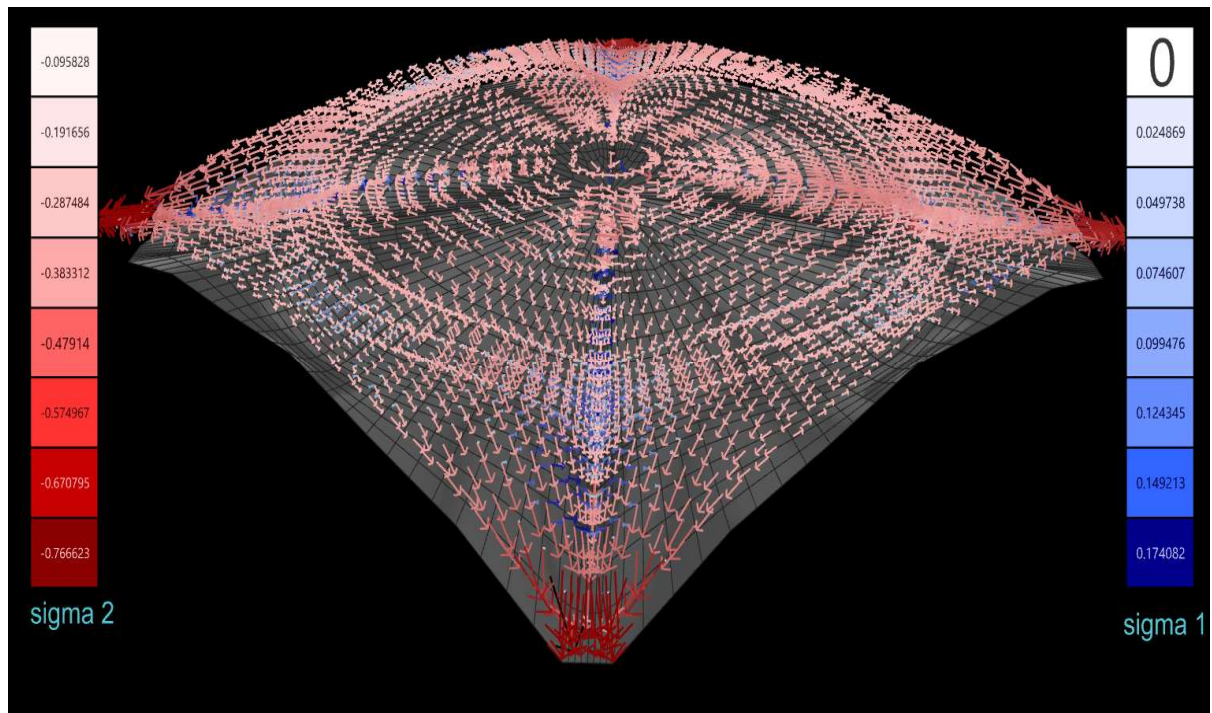


Figure 9: Principal stress of the lower layer of the shell under asymmetric load

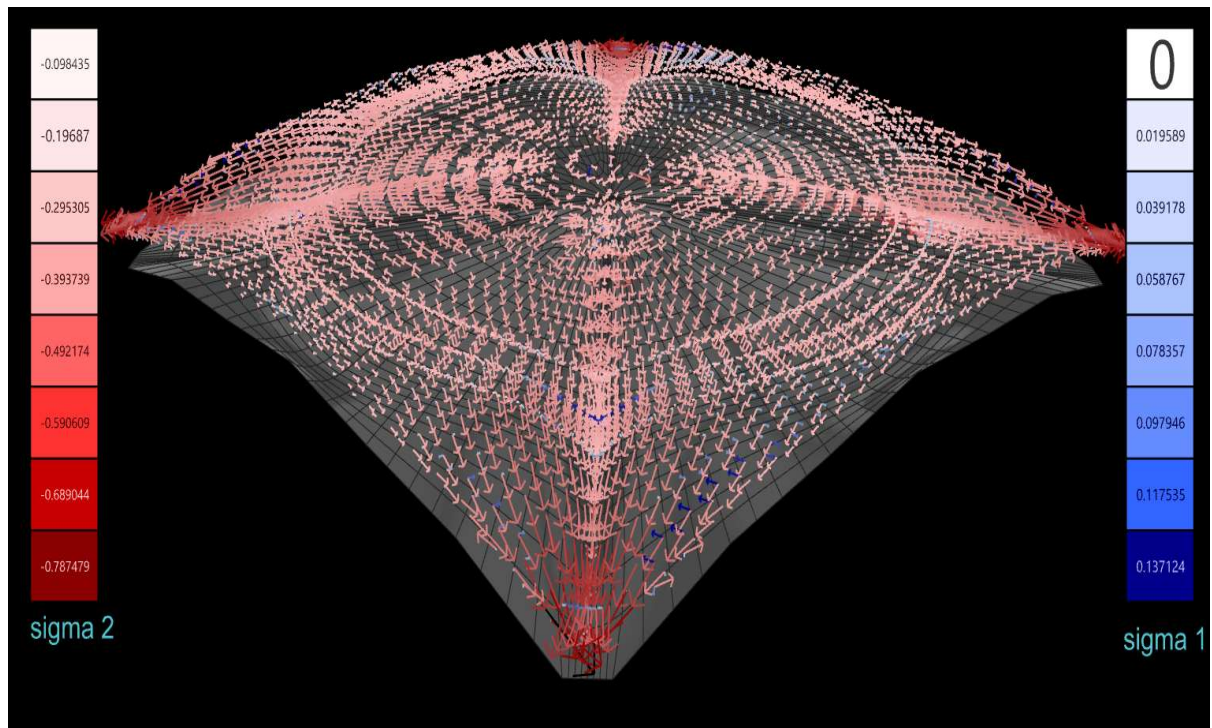


Figure 10: Principal stress of the upper layer of the shell under asymmetric load

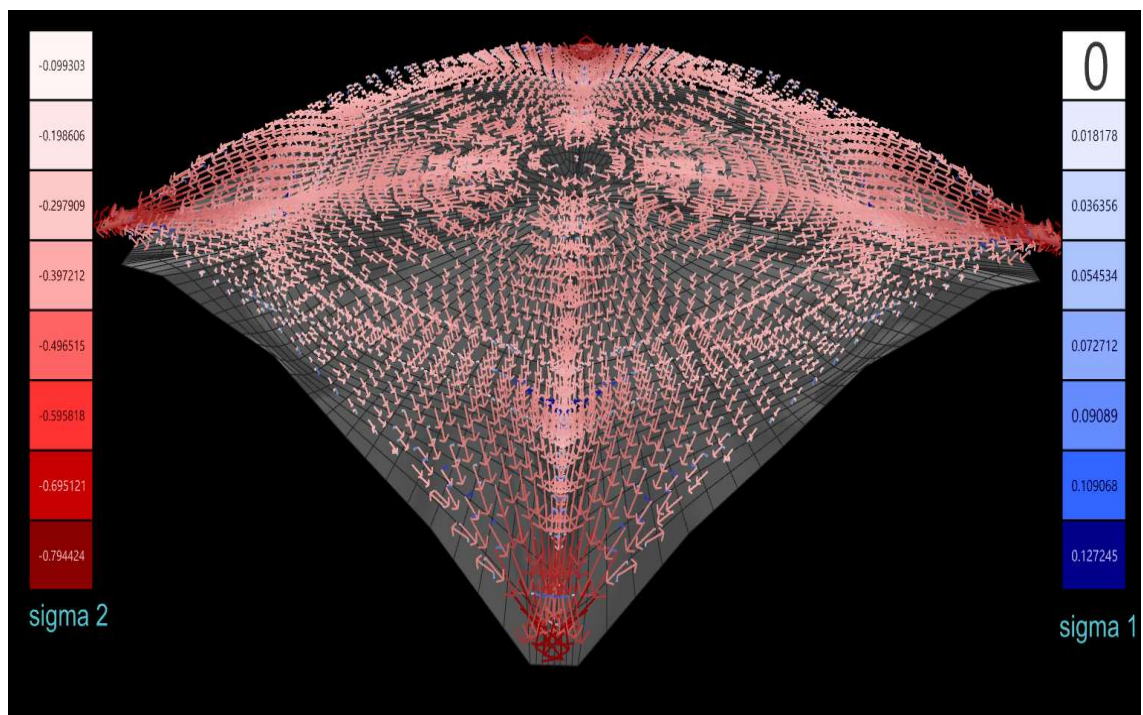


Figure 11: Principal stress of the lower layer of the shell under uniform load

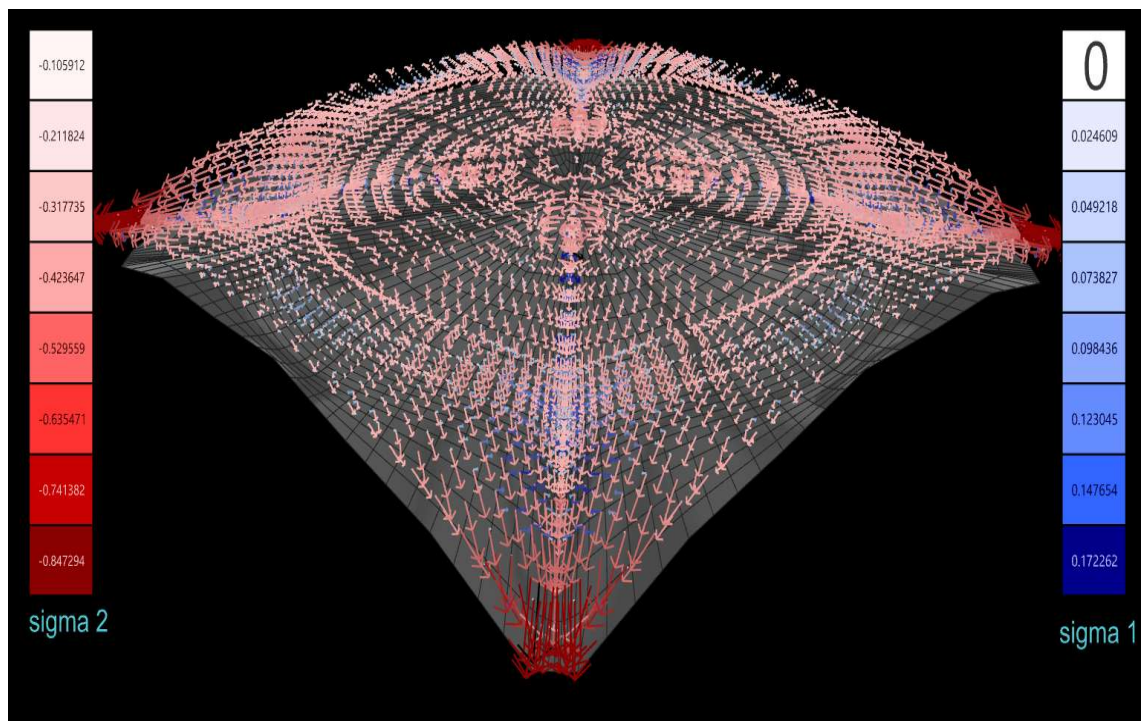


Figure 12: Principal stress of the upper layer of the shell under uniform load

Bridging the Gap: Parametric design model for social housing

Torres Pérez, Esmeralda

259.669 Algorithms in Planning

Abstract

Social housing still represents a challenge within contemporary cities, requiring the integration of economic, social, and spatial factors in high-demand contexts. On the other hand, parametric design has emerged as a tool capable of optimising architectural solutions through the use of computational systems.

However, these methodologies remain greatly disconnected from social housing due to its complexity and limited accessibility. This paper proposes a new social housing design model that includes a hybrid focus that combines simplified parametric design, modular prefabrication and incremental growth.

As a matter of fact, the increasing gap between technological innovation and real housing needs highlights the necessity of developing more accessible and adaptable design approaches. Therefore, the objective is to demonstrate how these tools can adapt for generating more flexible and scalable habitational solutions, recognising at the same time the necessity of integrating social dimensions beyond technical optimisation.

Keywords: Parametric Design, Social Housing, Modular Architecture, Incremental Housing, Computational Design

1. Introduction

Social housing still represents one of the main contemporary challenges for architecture and urbanism. The increasing demand for affordable housing, the limitation of resources and the necessity of adaptation to different climate and cultural contexts have driven the search for new design methods. In this scenario, parametric architecture has been presented as a tool capable of optimizing design processes through the use of algorithms and generative systems (Oxman, 2006; Schumacher, 2009). Furthermore, the use of parametric models in modular and social housing has become more relevant because of their capacity to integrate environmental, normative and social variables within the same computational system (Pibal et al., 2024).

In recent years, computational design and artificial intelligence have greatly transformed the way architecture is perceived and handled, especially in areas related to optimization, sustainability, and adaptable housing. Recent investigations have explored how generative algorithms can address urban and housing problems through systems capable of producing multiple design solutions using automated processes (Cifuentes Q., 2024).

Even though parametric architecture allows the simultaneous management of multiple variables and generates adaptive solutions, its application in social housing raises significant tensions related to accessibility, economic viability, and social relevance. As Galster and Lee point out (2021), affordable social housing requires the interaction of multiple dimensions (economic, spatial, and social) that can't always be solved by technical optimization.

This paper analyses the role of parametric design in contemporary social housing, evaluates its potential and limitations, and proposes a new strategy for a social housing design model that incorporates parametric design, modular prefabrication, and incremental growth to test the potential of these tools to generate more flexible and scalable habitational solutions

2. Methodology

This work is based on a qualitative methodology of bibliographic review and conceptual analysis. From the exploration of the literature on parametric design and social housing (Oxman, 2006; Woodbury, 2010; Galster & Lee, 2021), a gap between the computational potential and its application in realistic contexts was identified.

Based on this analysis, a conceptual proposal is developed consisting of a hybrid system that integrates parametric design, modular prefabrication, and the exploration of a possible future incremental growth. The scope is merely explorative and does not include empirical validation, but a critical reflection on its application.

3. Parametric architecture: definition and principles

Parametric architecture is based on the definition of geometric and environmental variables that allow for the dynamic generation of architectural forms. Schumacher (2009) defines parametricism as an emerging style based on continuous variation and systematic adaptation of architectural elements. Parametric design considers everything from the application of parametric curves to the relationship of general building properties and uses graphical programming and/or analysis software (García R. et al, 2013). It also relies on algorithmic modeling tools such as Grasshopper, integrated into environments like Rhino, which allow establishing relationships between parameters instead of fixed geometries.

Furthermore, parametric design involves a multidisciplinary type of work, including technical and aesthetic considerations, which requires a collective and flexible design generation and consequently, a different approach within the architect and the project, delivering the creative task to a process and work team through various digital systems employed (García R. et al., 2013). In consequence, the approach of parametric design changes the perspective of architecture from the ambiguity of open-endedness to a digital design process focused on the diversity of spatial configurations that reflect a complex array of spatial and programmatic performance criteria central to the design, and that can certainly be applied to the planning process of residential architecture in urban contexts (Madkour Y. et al, 2009).

4. Parametric design for social housing

Social housing represents a particular challenge for architecture due to the need to balance economic constraints, high demand, land limitations, and user diversity. The incorporation of parametric architecture into social housing responds to the necessity of addressing complex problems through tools capable of managing multiple variables (economic, spatial, and social) that directly influence housing design (Galster, G. & Lee, K. O., 2021).

Even though the use of parametric architecture is more common for large-scale projects, its application for social housing, in combination with modular and prefabricated systems, is becoming more important. According to Tak and Akay (2026), recently, the work of computational design has also delved into humanitarian topics and contexts at different scales. At the unit scale, studies have addressed shelter design through parametric optimisation and digital fabrication methods.

Parametric design systems allow the creation of multiple housing configurations from a series of limited rules. This approach relates to the idea of “design space explorer”, where design is understood as a space of possibilities rather than a single form (Woodbury, 2010).

5. Solution proposal: parametric hybrid system for social housing

This work proposes a hybrid system that integrates methodologies of parametric design with modular prefabrication strategies and incremental growth. The objective is to reduce the gap between the capacities of computational design and the real restrictions of social housing.

Instead of using parametric design as a complex process more oriented towards formal generation, its use as a simplified system based on rules is introduced, capable of organising spatial relations, optimising configurations, and allowing variability within an accessible constructive limit.

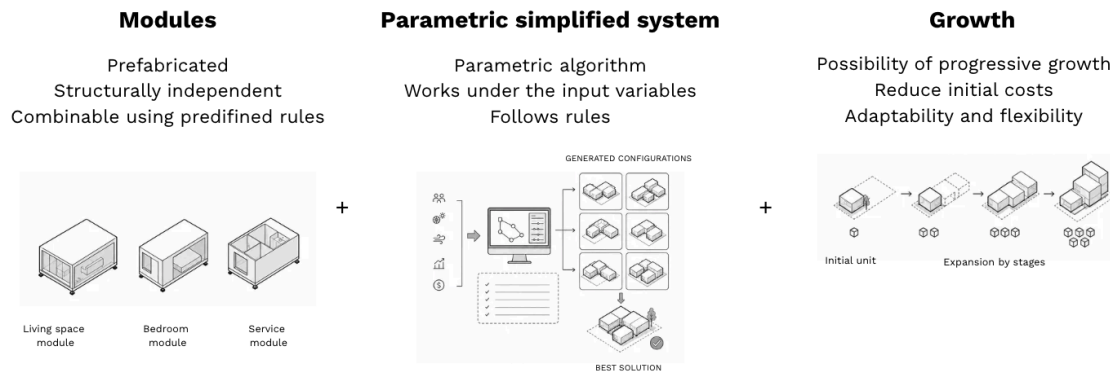


Figure 1. Conceptual diagram for the system.

5.1 System components

The system is structured into three main components:

a. Modules definition

The system is based on a limited group of prefabricated modules: living spaces, bedrooms, and service areas. These are designed to be structurally independent, easily transported, and combinable using predefined rules for reducing the constructive complexity and facilitating possible scalability.

b. Parametric rules system

A simplified parametric logic establishes the relation between modules by operating through clear, predetermined rules related to spatial relationships (e.g., kitchen adjacent to living area), environmental conditions (orientation, ventilation), and user requirements (household size, future expansion). In this way, the algorithm functions as an accessible tool to generate multiple living configurations.

c. Incremental growth strategy

The system incorporates the possibility of progressive growth of the dwelling. A basic initial unit is proposed that can expand over time, allowing the reduction of initial costs, familiar changes and adaptations, and maintaining structural coherence.

5.2 Design process

The workflow is composed of three stages:

1. Definition of initial parameters: basic parameters are defined, such as the number of occupants, site conditions, and budget constraints.

2. Generation of configurations using the parametric system: the parametric system generates multiple layout options based on predefined rules.
3. Selection and adaptation of the most suitable solution: a final configuration is selected and adjusted according to specific user or site needs.

5.2 Expected advantages and limitations

This process allows for increasing the adaptability of the design and avoiding complexity. It is also expected that the prefabrication integration contributes to the cost reductions as well as greater typological flexibility. Furthermore, the accessibility of design is accomplished by a simplified parametric logic that does not require advanced technical expertise.

However, despite the system's potential, it also presents limitations. In the first place, the reliance on the initial design of modules, followed by the need for coordination between design and construction processes, and the possible constraints in highly irregular urban contexts. Moreover, questions regarding the practical implementation also arise due to the fact that the translation of this conceptual framework into real-world contexts depends on economic feasibility, technical accessibility, and social acceptance.

6. Discussion

The proposed hybrid system shows a possible way to reintegrate parametric design with the conditions of social housing. By simplifying the logic for the algorithm and integrating it into modular and incremental strategies, it is expected to achieve a more accessible computational design.

Nevertheless, some challenges remain. In the first place, even though it is presented as a simplified parametric system, its implementation requires a certain minimum level of technical knowledge and great coordination between design and construction, which may not be available in low-resource contexts. Secondly, even though the system incorporates flexibility, it does not completely solve the difficulty of translating social and cultural factors into parametric rules. Social housing is determined by complex dynamics that can't be completely reduced to quantifiable variables (Galster & Lee, 2021).

In addition, there is a risk that these types of proposals will remain in the theoretical or experimental realm, without achieving large-scale implementation. As warned by Salingaros (2013), the architectural focus centered on technological innovation can easily be disconnected from the real necessities of the users. Therefore, the proposed system must be

understood not as a definitive solution, but as a framework that highlights both the possibilities and limitations of parametric design in this context.

7. Conclusion

This work has explored the relation between parametric design and social housing, identifying the gap that exists in the technological potential in relation to its real application. Even though parametric tools offer advantages in terms of optimization and adaptability, their implementation in social housing remains limited.

As a response, a hybrid system was proposed that combines parametric logics with modular prefabrication and incremental growth. This focus demonstrates that the value of parametric design relies not only on the formal complexity but also on its capacity to organise and adapt housing solutions.

Nevertheless, no computer system by itself can solve the social dimensions of housing. The success of these strategies depends on their integration with local knowledge, participatory processes, and public policy. Finally, the future of social housing will depend not only on technological innovation but also on the capacity to align design tools with human living realities.

8. References

1. Galster, G., & Lee, K. O. (2021). Housing affordability: A framing, synthesis of research and policy, and future directions. *International Journal of Urban Sciences*, 25(1), 7–58. <https://doi.org/10.1080/12265934.2020.1713864>
2. García Alvarado, R., & Lyon, A. (2013). Diseño paramétrico en arquitectura: Método, técnicas y aplicaciones. *ARQ (Santiago)*, (83). <https://doi.org/10.14409/ar.v1i3.938>
3. Grobman, Y. J., & Neuman, E. (2011). Programmatic formation: Practical applications of parametric design. In *Proceedings of the International Conference on Education and Research in Computer Aided Architectural Design in Europe (eCAADe)*.
4. Kolarevic, B. (2003). *Architecture in the digital age: Design and manufacturing*. Spon Press.
5. Oxman, R. (2006). Theory and design in the first digital age. *Design Studies*, 27(3), 229–265. <https://doi.org/10.1016/j.destud.2005.11.002>
6. Ramalhete, I., & Amado, M. (2011). Parametric elements to modular social housing. In *Housing – A Critical Perspective Conference*, Liverpool, United Kingdom.
7. Salingeros, N. A. (2013). *Anti-architecture and deconstruction* (3rd ed.). Umbau-Verlag.
8. Schumacher, P. (2009). Parametricism: A new global style for architecture and urban design. *Architectural Design*, 79(4), 14–23.
9. Turner, J. F. C. (1976). *Housing by people: Towards autonomy in building environments*. Pantheon Books.
10. Woodbury, R. (2010). *Elements of parametric design*. Routledge.



TECHNISCHE
UNIVERSITÄT
WIEN

Algorithmic Compliance Checking in BIM: A Rule-Based Approach for Austrian Building Regulations

259.669 Algorithms in Planning

Submitted at:

Vienna University of Technology

Department of Building Science and Environment

by

Rineta Sinani

12447744

Wien, Datum

03.06.2026

Table of Contents

Abstract.....	3
1.Introduction.....	3
2. Background.....	4
3. Problem.....	5
4. Rule-Based BIM Compliance Checking	6
5.Discussion.....	8
6. Conclusion.....	8
References.....	9

Abstract

Building Information Modeling (BIM) is increasingly used in architectural design, interdisciplinary coordination, and digital building permit workflows. However, compliance checking against Austrian building regulations, including OIB guidelines, accessibility requirements, fire safety provisions, and municipal planning rules, is still largely performed manually, making the process time-consuming, interpretation-dependent, and prone to error. This paper proposes a rule-based BIM compliance checking workflow that translates measurable regulatory requirements into machine-readable rules and evaluates them against IFC-based BIM models. Consequently, automated compliance checking can improve efficiency, consistency, and transparency within planning and approval processes while supporting earlier detection of regulatory violations.

Keywords: BIM, Rule-Based Algorithms, Compliance Checking, Building Regulations, OIB, IFC

1. Introduction

Building Information Modeling (BIM) has become a central digital method in architectural and engineering practice. In contrast to conventional two-dimensional drawing workflows, BIM models contain geometric information as well as semantic information about building elements, materials, spaces, quantities, and technical properties. This makes BIM relevant not only for visualization and coordination, but also for model-based analysis, quality control, and approval procedures. In Austria, where building design must respond to technical regulations, municipal requirements, and approval processes, BIM has the potential to become more than a modelling tool: it can become a structured information base for checking planning decisions.

However, the regulatory review of building projects is still often based on manual interpretation of drawings, schedules, documents, and model information. Architects and authorities must verify whether a design complies with requirements such as minimum dimensions, accessibility, fire safety, escape routes, energy-related information, and site-specific development rules. Research on automated code compliance checking has repeatedly described this manual process as labor-intensive and vulnerable to inconsistency or error (Eastman et al., 2009; Dimyadi & Amor, 2013). The difficulty is not only the number of regulations, but also the fact that many rules are written in natural language and must be translated into computable logic before they can be checked automatically.

This paper therefore addresses the following question: How can rule-based algorithms support BIM-based compliance checking in Austrian planning practice?

In this work, we:

- review the current state of BIM-based automated compliance checking and OpenBIM standards (see Background);
- identify the limitations of manual regulatory verification and the challenges of translating regulations into computable logic (see Problem);
- propose a rule-based BIM compliance checking workflow for Austrian building regulations based on IFC models and machine-readable rules (see Rule-Based BIM Compliance Checking).

By doing so, the paper demonstrates how measurable regulatory requirements can be evaluated more efficiently and consistently while maintaining human oversight for qualitative design decisions.

We believe that automated compliance checking can support architects, engineers and public authorities by improving consistency and reducing the effort required for repetitive regulatory review.

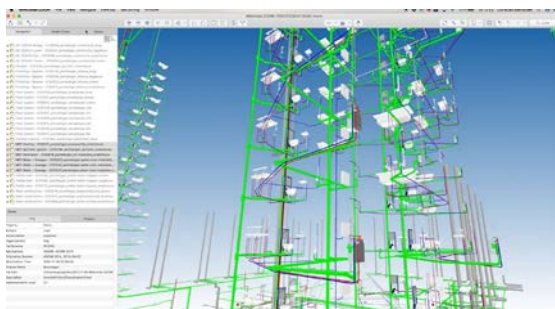
2. Background

Automated compliance checking is not a new research topic. Eastman et al. (2009) reviewed major industrial rule-checking initiatives and described rule checking as a process in which building designs are assessed against predefined criteria using digital building models. Dimyadi and Amor (2013) later summarized decades of research on automated and semi-automated compliance checking, demonstrating that the concept is well established in both academia and industry. However, practical implementation remains challenging due to the complexity of regulations and the need to translate natural-language requirements into computable rules.

A key prerequisite for automated checking is the availability of reliable and structured building data. Industry Foundation Classes (IFC) provide an open and vendor-neutral standard for exchanging BIM information across software platforms (buildingSMART International, 2024a). In addition, the Information Delivery Specification (IDS) enables the definition of machine-readable information requirements, allowing compliance checks to verify not only geometry but also the completeness and quality of model information (buildingSMART International, 2024b).

The complexity of regulatory requirements remains one of the main obstacles to implementation. Eastman et al. (2009) identified rule interpretation, model preparation, rule execution, and reporting as the main stages of automated checking, while Solihin and Eastman (2015) emphasized that different types of rules require different checking approaches and levels of automation.

In Austria, automated compliance checking has gained increasing relevance through OpenBIM initiatives and digital building permit processes. The BRISE-Vienna project demonstrated the use of IFC-based submissions and semi-automated compliance verification within the building



approval process (City of Vienna, n.d.; Urban et al., 2024). These developments indicate that rule-based compliance checking is gradually moving from research into practical applications, while still requiring human oversight for qualitative and interpretation-dependent decisions.

Figure 1. Example of a BIM model displayed in a model-checking environment. The platform enables the inspection of IFC-based building information and supports rule-based compliance verification.

3. Problem

Building regulation compliance is essential, yet the verification process in practice still relies heavily on manual review. Before a project can be submitted or approved, architects must verify compliance with numerous requirements related to geometry, accessibility, fire safety, energy performance, parking provisions, and municipal planning regulations.

This manual process creates several challenges. It is time-consuming because each requirement must be identified, interpreted, and compared with the design. It is also error-prone, as complex projects contain large numbers of elements and relationships that must be checked consistently. Furthermore, different stakeholders may interpret the same regulation differently, leading to inconsistent results. Solihin and Eastman (2015) note that automated rule checking is challenged by both the complexity of regulations and the broad range of conditions to which they apply.

In Austria, the situation is further complicated because compliance requirements originate from multiple sources, including OIB guidelines, municipal regulations, and project-specific conditions. While some requirements are quantitative and measurable, such as widths, heights, areas, distances, and slopes, others remain qualitative and require professional judgement. This distinction defines the realistic limits of automation.

Therefore, the gap addressed in this paper is not the absence of BIM itself, but the lack of a systematic connection between BIM model information and computable regulatory logic. If measurable regulations can be translated into machine-readable rules, repetitive compliance checks can be performed earlier, faster, and more consistently within the planning process.

4. Rule-Based BIM Compliance Checking

Rule-based BIM compliance checking is an algorithmic approach in which regulatory



requirements are represented as explicit conditions and then evaluated against model data. The basic logic can be expressed as IF-THEN rules. For example: IF a corridor width is below the required value, THEN the corridor is marked as non-compliant. This simple structure can be extended to more complex rules that combine several conditions, such as room type, building use, number of occupants, floor level, or fire compartment.

The proposed checking workflow consists of five steps: model preparation, data extraction, rule formalization, rule execution, and report generation. The BIM model first needs to contain the necessary geometric and semantic information. Then the relevant data is extracted, often through IFC or another structured exchange format. Next, the regulation is translated into formal logic. The rule engine then compares the model data with the requirements and produces a report that identifies compliant and non-compliant elements.

Figure 2. Simplified workflow of rule-based BIM compliance checking.

Step	Input / action	Output
1. Model preparation	BIM model is structured and exported, for example as IFC.	Checkable model data
2. Data extraction	Relevant spaces, elements, dimensions and properties are identified.	Required parameters
3. Rule formalization	Regulations are translated into IF-THEN or logical conditions.	Machine-readable rules
4. Rule execution	The rule engine compares model data with requirements.	Pass / fail results
5. Report generation	Violations are listed and linked to model objects.	Compliance report

Table 1. Simplified workflow for rule-based BIM compliance checking.

To illustrate the practical implementation of rule-based checking, selected Austrian building requirements can be translated into machine-readable conditions.

Requirement	Machine-readable rule
Minimum corridor width 1.20 m	IF CorridorWidth < 1.20 THEN Non-Compliant
Minimum door width 0.90 m	IF DoorWidth < 0.90 THEN Non-Compliant
Minimum room height 2.50 m	IF RoomHeight < 2.50 THEN Non-Compliant
Accessible route slope $\leq 6\%$	IF RouteSlope > 6% THEN Non-Compliant

Table 2. Examples of simplified compliance rules.

These examples demonstrate how regulations written in natural language can be formalized as explicit logical conditions. The rule engine evaluates the corresponding BIM properties and generates compliance reports for designers and authorities.

This workflow follows the general direction described by Eastman et al. (2009), who organized rule-checking systems into functional stages, and by Preidel and Borrmann (2015), who explored visual language approaches for making code checking more understandable to users. The need for rule classification is also important. Solihin and Eastman (2015) explain that rules vary in complexity: some rules are simple property checks, while others require spatial reasoning, derived geometry, or relationships between multiple building elements. This distinction matters for Austrian regulations because not all rules can be automated with the same level of effort.

For the Austrian context, a realistic implementation would begin with rules that are quantitative and clearly measurable. Examples include required widths of circulation spaces, minimum door dimensions, room areas, clear heights, slopes, accessible routes, or certain energy-related model properties. More complex requirements, such as fire strategy or contextual urban design, could be supported by automated pre-checks but would still require expert review.

The output of such a system should not only be a binary yes or no. A useful checking report should identify the relevant object, the rule that was violated, the measured value, the required value, and the location of the issue in the model. This makes the result understandable for architects, reviewers, and authorities. It also supports design iteration because non-compliance can be detected earlier, before formal submission.

5. Conclusion

5. Discussion

The main benefit of rule-based BIM compliance checking is efficiency. Repetitive checks that would otherwise require manual review can be performed automatically during design development, helping designers identify issues earlier and allowing authorities to focus on more complex regulatory questions. The BRISE-Vienna project demonstrates that BIM-based permit processes and automated checking approaches are already being explored in Austrian planning practice (City of Vienna, n.d.; Urban et al., 2024).

Another important benefit is transparency. By linking failed rules directly to model elements, compliance reports become easier to understand and communicate among architects, engineers, clients, and authorities.

However, automated checking also has limitations. The reliability of results depends on the quality and completeness of BIM data, and many regulations contain ambiguous or qualitative requirements that are difficult to translate into formal rules. Furthermore, not all planning decisions can be reduced to algorithmic logic, and professional judgement remains necessary for design quality and contextual considerations (Urban et al., 2024).

Therefore, the most realistic role of rule-based compliance checking is decision support rather than full automation. While measurable requirements can be verified automatically, architects and authorities remain responsible for interpretation and final decision-making. Future work could investigate the integration of IDS, BCF issue management, and AI-supported interpretation of regulatory texts.

6. Conclusion

This paper proposed a rule-based BIM compliance checking workflow for Austrian building regulation processes. Through a review of existing research, OpenBIM standards, and Austrian initiatives, it was shown that BIM models, IFC-based data exchange, and machine-readable rules can support the automated verification of measurable regulatory requirements. The proposed workflow demonstrated how repetitive compliance checks can be performed more efficiently, consistently, and transparently than traditional manual review procedures. While qualitative design decisions still require human judgement, rule-based checking represents an important step toward the digitalization of planning and building permit processes. Future developments may further expand automation through the integration of IDS, AI-assisted rule interpretation, and digital permitting platforms.

References

buildingSMART International. (2024a). *Industry Foundation Classes (IFC)*. <https://www.buildingsmart.org/standards/bsi-standards/industry-foundation-classes/>

buildingSMART International. (2024b). *Information Delivery Specification (IDS)*. <https://www.buildingsmart.org/standards/bsi-standards/information-delivery-specification-ids/>

City of Vienna. (n.d.). *BRISE Vienna: Planning and living together*. Digitales Wien. <https://digitales.wien.gv.at/en/projekt/brise-vienna/>

Dimyadi, J., & Amor, R. (2013). Automated building code compliance checking: Where is it at? In *Proceedings of the CIB World Building Congress 2013*.

Eastman, C., Lee, J.-M., Jeong, Y.-S., & Lee, J.-K. (2009). Automatic rule-based checking of building designs. *Automation in Construction, 18*(8), 1011–1033. <https://doi.org/10.1016/j.autcon.2009.07.002>

Österreichisches Institut für Bautechnik. (2023). *OIB-Richtlinien 2023*. <https://www.oib.or.at/kernaufgaben/oib-richtlinien1/richtlinien/oib-richtlinien-2023/>

Preidel, C., & Borrmann, A. (2015). Automated code compliance checking based on a visual language and Building Information Modeling. In *Proceedings of the 32nd International Symposium on Automation and Robotics in Construction (ISARC)*.

Solihin, W., & Eastman, C. (2015). Classification of rules for automated BIM rule checking development. *Automation in Construction, 53*, 69–82. <https://doi.org/10.1016/j.autcon.2015.03.003>

Urban, H., Fischer, S., & Schranz, C. (2024). Adapting to an OpenBIM building permit process: A case study using the example of the City of Vienna. *Buildings, 14*(4), 1135. <https://doi.org/10.3390/buildings14041135>

Translating Urban Air Quality Data into Planning Knowledge: Algorithmic Approaches in Urban Planning

Ermira Sejdiu

Technische Universität Wien, Vienna, Austria

E12535713@student.tuwien.ac.at

Urban areas worldwide are generating environmental data at an unprecedented scale, yet transforming this raw information into actionable planning knowledge remains a persistent challenge. This paper discusses how algorithmic and data-driven approaches may help bridge the gap between complex urban air quality datasets and the spatial decisions that shape the built environment. By reviewing spatial analysis methods, sensor network architectures, machine learning-based forecasting models, and interactive visualisation frameworks, the paper explores how computational tools can support the interpretation and communication of pollutant measurements in planning-relevant terms. A conceptual framework of five key performance indicators (KPIs) per major air quality dimension - concentration levels, spatial dispersion, temporal variability, population exposure, and regulatory compliance is proposed as a means to structure this translation. The literature reviewed suggests that integrating such algorithmic approaches into municipal planning workflows may contribute to more informed, evidence-based decision-making toward healthier and more sustainable urban environments.

Keywords: Urban Air Quality, Algorithmic Planning, Spatial Analysis, Environmental KPIs, Data-Driven Urban Planning, GIS, Sensor Networks, Machine Learning.

INTRODUCTION

Urban air quality has emerged as one of the most pressing public health and environmental governance challenges of our era. The World Health Organization (WHO, 2021) estimates that approximately 99 percent of the world's population breathes air that exceeds safe guideline limits, contributing to around seven million premature deaths annually. Cities as the sites where industrial activity, transportation, and dense human habitation converge are the primary theatres of this crisis. Yet for all the urgency of the problem, urban planners have historically struggled to integrate air quality data into the spatial, regulatory, and infrastructural decisions that define the built environment (Vardoulakis et al., 2011).

The last decade has witnessed a dramatic expansion of environmental monitoring capacity. Low-cost sensor networks, satellite-derived datasets, and open-data platforms have made air quality measurements far more granular and temporally dense than traditional monitoring stations could provide (Kumar et al., 2015). However, data abundance does not automatically produce planning knowledge. Raw pollutant readings concentrations of PM_{2.5}, NO₂, O₃, and CO, measured in micrograms per cubic metre across thousands of spatial and temporal points are not self-explanatory. Without interpretive frameworks, computational methods, and accessible visual interfaces, this data tends to remain at the margins of planning practice (Batty, 2013).

This paper discusses how algorithmic approaches can serve as a connective layer between environmental data and planning action. Drawing on a review of existing literature and methods, this paper explores:

- The current state of urban air quality monitoring and its relationship to planning processes (see Background)
- The points at which the translation from raw data to actionable planning knowledge tends to break down (see Problem)
- A conceptual framework of algorithmic tools and five KPIs per air quality dimension as a means to structure environmental performance within planning workflows (see Algorithmic Approaches to Urban Air Quality Planning)

Algorithmic methods of the kind reviewed here may offer meaningful support to municipal authorities, urban designers, and public health bodies seeking to integrate air quality considerations into spatial planning, and to link environmental performance to financial instruments, zoning decisions, and infrastructure investments.

BACKGROUND

The relationship between urban form, air pollution, and public health has been studied since the industrial revolution, but the systematic integration of air quality monitoring into planning practice is comparatively recent. Early regulatory frameworks, such as the United States Clean Air Act of 1970 and the European Union's Ambient Air Quality Directives, established pollutant thresholds and mandated monitoring, but these were conceived primarily as compliance instruments rather than planning tools (Fenger, 1999). The spatial and temporal resolution of regulatory monitoring networks – typically one fixed station per several square kilometres – was fundamentally ill-suited to the fine-grained decisions that urban planning requires.

The Emergence of Urban Environmental Data Platforms

From the mid-2000s onwards, the proliferation of geographic information systems (GIS), remote sensing technologies, and citizen science initiatives began to reshape what was technically possible in urban environmental monitoring. GIS platforms allowed planners to overlay pollutant concentration data with land use maps, population density grids, and transport network models, enabling a first generation of spatially-informed air quality analyses (Briggs et al., 1997). Simultaneously, satellite instruments such as NASA's MODIS and ESA's Sentinel-5P provided regional aerosol optical depth and trace gas column measurements at progressively finer resolutions, creating a new class of spatial environmental datasets available to planning agencies (Veefkind et al., 2012).

The emergence of low-cost electrochemical and optical sensors from the early 2010s marked a further inflection point. Devices costing hundreds rather than tens of thousands of euros could now measure PM_{2.5}, NO₂, and O₃ with sufficient accuracy for planning-relevant purposes when properly calibrated and deployed in networks (Kumar et al., 2015). Cities including London, Amsterdam, and Vienna began deploying these sensor networks alongside

open-data initiatives, creating publicly accessible, near-real-time air quality datasets at the neighbourhood scale (EEA, 2020).

Algorithmic Methods in Urban Planning

Algorithmic and computational methods have long been embedded in urban planning, from the traffic simulation models of the 1960s to the parametric urban design tools of the early 2000s (Batty, 2013). What has changed in recent years is both the scale and the sophistication of these methods. Machine learning approaches particularly gradient-boosted tree models and deep neural networks have shown strong performance in air quality forecasting tasks, with studies reporting 24-hour ahead PM_{2.5} prediction accuracies of $R^2 > 0.85$ when trained on combined sensor, meteorological, and traffic data (Chen et al., 2021). Spatial interpolation algorithms, including kriging and inverse distance weighting, allow point measurements to be extended into continuous spatial surfaces that planners can read as maps (Oliver & Webster, 1990).

City-scale digital twins computational representations of urban systems that integrate real-time data streams from multiple sources represent an emerging frontier in this space. Nochta et al. (2021) discuss how such platforms, being developed in cities including Cambridge, Helsinki, and Singapore, may enable planners to test the environmental consequences of urban design alternatives in a comparative and iterative manner. Vienna's Smart City initiative reflects a similar ambition at the municipal level.

PROBLEM

Despite the expanding availability of urban air quality data and the growing sophistication of computational analytical tools, a significant gap persists between what environmental monitoring systems produce and what planning processes can absorb. Austria provides an illustrative example: the country has adopted extensive EU air quality directives and operates a national monitoring network administered by the Umweltbundesamt (Environment Agency Austria), yet there is no standardised mechanism by which planners at the municipal or district level can account for how much fulfilment of air quality norms has contributed to sustainable development outcomes in a quantitative fashion (Umweltbundesamt, 2022).

The literature points to several interconnected dimensions of this gap:

First, a semantic gap. Air quality datasets are produced by environmental scientists and engineers whose vocabulary, data formats, and analytical conventions are not natively shared by planners, architects, or urban designers. A PM_{2.5} concentration of 18 $\mu\text{g}/\text{m}^3$ is immediately meaningful to an atmospheric chemist, but conveys little to a land use planner deciding on the placement of a residential zone (Vardoulakis et al., 2011).

Second, a temporal mismatch. Planning decisions operate on timescales of years to decades, while air quality data is produced at hourly or sub-hourly resolution. Synthesising a continuous, high-frequency environmental signal into a durable spatial indicator requires non-trivial aggregation work that most planning agencies currently lack the tools and capacity to perform (Batty, 2013).

Third, institutional fragmentation. Responsibility for air quality monitoring, urban planning, transport policy, and public health sits across different agencies with different mandates and data standards. The absence of shared computational platforms and interoperable data infrastructures means that air quality information rarely flows effectively into planning workflows even when the underlying data exists (EEA, 2020).

Taken together, the literature suggests that cities currently lack the tools to account for air quality improvement as a measurable outcome of planning intervention, and to couple environmental performance to the financial instruments development levies, green bonds, performance-based zoning that could incentivise private actors to contribute to healthier urban environments.

ALGORITHMIC APPROACHES TO URBAN AIR QUALITY PLANNING

This paper proposes a conceptual framework that organises algorithmic approaches to urban air quality planning into three functional layers: data acquisition and harmonisation, spatial and temporal analysis, and planning knowledge translation. Across all three layers, five Key Performance Indicators (KPIs) per air quality dimension are introduced as a means to structure the monitoring of progress in a structured and comparable manner. Figure 1 presents the framework as a conceptual diagram.

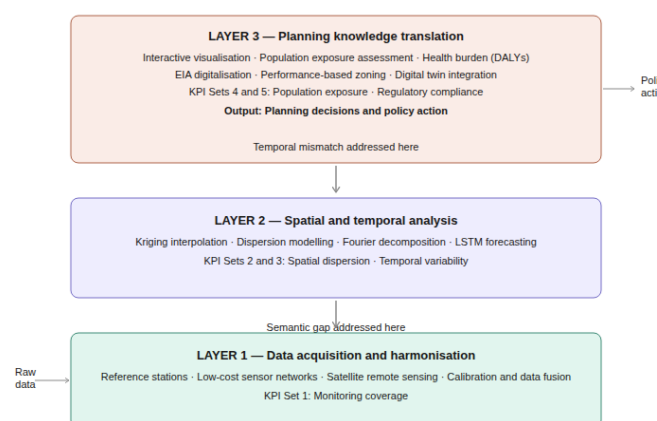


Figure 1. Three-layer algorithmic framework for translating urban air quality data into planning knowledge.

Layer 1: Data Acquisition and Harmonisation

The literature suggests that robust, multi-source data pipelines form the foundation of any algorithmic planning approach to air quality. Contemporary best practice, as reviewed by Kumar et al. (2015) and Veefkind et al. (2012), combines three sensor typologies: regulatory-grade reference stations (high accuracy, sparse spatial coverage), low-cost sensor networks (moderate accuracy, dense spatial coverage), and satellite-derived remote sensing products (moderate accuracy, complete spatial coverage, limited temporal resolution for individual sites). Harmonising these sources involves calibration algorithms typically cross-referencing low-cost sensor readings against co-located reference stations and applying machine learning

correction models and data fusion techniques that produce a unified, spatially continuous dataset.

KPI Set 1- Monitoring Coverage: (1) percentage of urban area within 500 m of an active sensor node; (2) temporal data completeness rate (% of expected readings received); (3) inter-sensor agreement index (mean absolute deviation between low-cost and reference sensors); (4) calibration currency (mean days since last sensor calibration); (5) open data publication rate (% of data published to public platforms within 24 hours).

Layer 2: Spatial and Temporal Analysis

Once a harmonised dataset is available, spatial and temporal analytical algorithms can translate point or pixel measurements into the continuous, interpretable surfaces and time series that planning decisions require. Kriging-based spatial interpolation is a well-established method for generating air quality maps from sparse monitoring networks, with ordinary and universal kriging variants accommodating spatial trends driven by traffic, topography, and land use (Oliver & Webster, 1990). Dispersion models — particularly Gaussian plume models and their computational fluid dynamics extensions — can simulate how emissions propagate through the urban atmosphere, enabling scenario analysis of proposed planning interventions such as traffic calming schemes or industrial rezoning (Vardoulakis et al., 2011).

Temporal analysis focuses on decomposing air quality signals into their constituent drivers: diurnal cycles linked to traffic and human activity, seasonal cycles driven by heating and meteorological regimes, and episodic events caused by atmospheric inversions or long-range pollution transport. Long short-term memory (LSTM) neural networks trained on multi-year historical datasets may provide planners with the temporal context to distinguish short-term pollution episodes from chronic exposure conditions (Chen et al., 2021).

KPI Set 2 - Spatial Dispersion: (1) mean population-weighted PM_{2.5} concentration across the planning area; (2) coefficient of spatial variation (ratio of standard deviation to mean concentration); (3) area exceeding WHO AQG limits as a percentage of total urban area; (4) hotspot persistence index (percentage of hotspots persisting across all four seasons); (5) gradient index (concentration difference between highest- and lowest-exposure census tracts).

KPI Set 3 - Temporal Variability: (1) annual mean concentration against WHO annual guideline value; (2) number of days per year exceeding WHO 24-hour guideline value; (3) peak-to-mean ratio (ratio of 99th percentile to annual mean hourly concentration); (4) trend slope ($\mu\text{g}/\text{m}^3$ per year, from linear regression over five-year rolling window); (5) seasonal amplitude (difference between summer and winter mean concentrations).

Layer 3: Planning Knowledge Translation

The third layer concerns the translation of analytical outputs into decision-relevant knowledge. Research in environmental communication suggests that interactive, spatially-referenced visual representations can support non-expert comprehension of air quality conditions and their health implications (Roth, 2013). Platforms such as the European Environment Agency's Air Quality Index and Vienna's Luftgüte online portal represent current practice, though their integration with planning information systems remains limited.

Population exposure assessment calculating the integrated dose of pollutants received by residents weighted by time spent in different microenvironments is discussed in the literature as a critical analytical bridge between spatial air quality data and public health planning. The Global Burden of Disease methodology, when operationalised at urban scales, may provide a framework for converting ambient concentration maps into health burden estimates expressed in disability-adjusted life years (DALYs) per 100,000 population, a metric directly comparable across different interventions and policy domains (Cohen et al., 2017).

KPI Set 4 - Population Exposure: (1) percentage of residential population exposed above WHO annual PM_{2.5} guideline (15 µg/m³); (2) DALYs attributable to PM_{2.5} per 100,000 residents; (3) exposure inequality index (ratio of mean exposure in highest- vs. lowest-income population quartile); (4) sensitive-use building exceedance rate (% of schools and healthcare facilities in areas exceeding guideline values); (5) estimated exposure reduction for residents within 200 m of green infrastructure corridors.

KPI Set 5 - Regulatory Compliance: (1) exceedance frequency for EU Ambient Air Quality Directive limits (days per year above PM_{2.5} daily limit of 25 µg/m³); (2) NO₂ annual mean against directive limit (40 µg/m³); (3) ozone exceedance index (sum of exceedances above 120 µg/m³ 8-hour mean across all station-days per year); (4) compliance trend (year-on-year change in number of exceedance days); (5) action plan implementation rate (% of air quality management plan measures implemented on schedule).

KPI dimension	Indicators (representative)	Layer
KPI Set 1 Monitoring coverage	% urban area within 500 m of sensor node Temporal data completeness rate Inter-sensor agreement index Calibration currency (mean days)	Layer 1
KPI Set 2 Spatial dispersion	Mean population-weighted PM _{2.5} concentration Coefficient of spatial variation Area exceeding WHO AQG limits (%) Hotspot persistence index	Layer 2
KPI Set 3 Temporal variability	Annual mean vs WHO annual guideline value Days/year exceeding WHO 24-hr guideline Peak-to-mean ratio (99th percentile) Trend slope (5-year rolling window)	Layer 2
KPI Set 4 Population exposure	% population above WHO PM _{2.5} guideline (15 µg/m ³) DALYs attributable to PM _{2.5} per 100,000 residents Exposure inequality index (income quartile ratio) Sensitive-use building exceedance rate	Layer 3
KPI Set 5 Regulatory compliance	EU Directive exceedance days (PM _{2.5} , 25 µg/m ³) NO ₂ annual mean vs directive limit (40 µg/m ³) Ozone exceedance index Action plan implementation rate	Layer 3

All KPIs are proposed as conceptual measures; empirical validation is identified as a direction for future research

Figure 2. Overview of the proposed KPI framework across five dimensions and three framework layers.

Integration into Planning Workflows

The literature reviewed suggests that the practical value of the framework depends on embedding all three layers and their associated KPIs in the planning tools and institutional processes that govern urban development. Three integration pathways appear particularly promising. First, environmental impact assessment (EIA) digitalisation: replacing static, narrative-based air quality sections in EIA documents with model-connected assessments that can recalculate projected impacts as project parameters change. Second, performance-based zoning: embedding air quality KPI thresholds into zoning regulations, so that development permissions in pollution hotspots are conditional on demonstrable mitigation. Third, digital

twin integration: coupling air quality simulation engines with city-scale digital twin platforms, which may allow planners to explore the air quality implications of alternative urban design scenarios in a comparative and iterative manner (Nochta et al., 2021).

DISCUSSION

The conceptual framework discussed in this paper addresses a gap that the reviewed literature consistently identifies: the absence of structured, algorithmic pathways from environmental monitoring data to planning knowledge. Several limitations and open questions remain, however, and should be acknowledged.

The accuracy of low-cost sensor networks particularly under conditions of high humidity, temperature extremes, or sensor ageing introduces uncertainties that would propagate through every subsequent analytical layer (Kumar et al., 2015). Calibration protocols are evolving rapidly, yet planning agencies would need to develop literacy around measurement uncertainty before they can responsibly use sensor-derived data in regulatory or investment decisions.

The five KPI sets proposed here are intended as a starting framework rather than a universal standard. Different cities have different priority pollutants, monitoring network architectures, and policy contexts. Future work could usefully explore participatory KPI development processes that involve communities particularly those in disadvantaged neighbourhoods that the literature identifies as bearing disproportionate pollution burdens in defining what constitutes meaningful environmental progress (Cohen et al., 2017). Empirical testing of the proposed framework against a specific case study city, with Vienna presenting an obvious candidate, is identified as a priority for future research.

The institutional dimension of the problem may be the most difficult to address through algorithmic means alone. The literature suggests that dedicated inter-departmental coordination structures such as Vienna's collaboration between the Umweltschutzabteilung (MA22) and the Urban Development and Planning Department (MA18) are often the decisive factor in whether data-driven environmental approaches are absorbed into planning decisions, rather than the technological sophistication of the tools themselves.

CONCLUSION

This paper discussed a conceptual framework of algorithmic approaches for translating urban air quality data into planning knowledge, organised around three functional layers and five KPI sets covering monitoring coverage, spatial dispersion, temporal variability, population exposure, and regulatory compliance. The reviewed literature suggests that such a framework may support cities in measuring air quality progress in planning-relevant terms and in coupling environmental performance to financial incentives, zoning instruments, and infrastructure investment decisions. The integration of spatial analysis, machine learning forecasting, population exposure assessment, and interactive visualisation offers a coherent conceptual pipeline from sensor readings to policy-relevant knowledge. The fundamental challenge is no longer primarily technical, many relevant algorithms and data platforms exist but institutional and communicative: ensuring that planners, developers, and communities can engage with these tools in ways that are both meaningful and equitable.

REFERENCES

- Batty, M. (2013). *The New Science of Cities*. MIT Press, Cambridge, MA.
- Briggs, D.J., Collins, S., Elliott, P., Fischer, P., Kingham, S., Lebre, E., Pryl, K., Van Reeuwijk, H., Smallbone, K., & Van der Veen, A. (1997). 'Mapping urban air pollution using GIS: A regression-based approach', *International Journal of Geographical Information Science*, 11(7), 699–718. Available at: <https://doi.org/10.1080/136588197242158>.
- Chen, G., Li, S., Knibbs, L.D., Hamm, N.A.S., Cao, W., Li, T., Guo, J., Ren, H., Abramson, M.J., & Guo, Y. (2021). 'A machine learning method to estimate PM_{2.5} concentrations across China with remote sensing, meteorological and land use information', *Science of The Total Environment*, 780, 146151. Available at: <https://doi.org/10.1016/j.scitotenv.2021.146151>.
- Cohen, A.J., Brauer, M., Burnett, R., Anderson, H.R., Frostad, J., Estep, K., Balakrishnan, K., Brunekreef, B., Dandona, L., Dandona, R., Feigin, V., Freedman, G., Hubbell, B., Jobling, A., Kan, H., Knibbs, L., Liu, Y., Martin, R., Morawska, L., ... Forouzanfar, M.H. (2017). 'Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: An analysis of data from the Global Burden of Diseases Study 2015', *The Lancet*, 389(10082), 1907–1918. Available at: [https://doi.org/10.1016/S0140-6736\(17\)30505-6](https://doi.org/10.1016/S0140-6736(17)30505-6).
- European Environment Agency (EEA). (2020). *Air Quality in Europe: 2020 Report*. EEA Report No 09/2020. Copenhagen: EEA. Available at: <https://www.eea.europa.eu/publications/air-quality-in-europe-2020-report>.
- Fenger, J. (1999). 'Urban air quality', *Atmospheric Environment*, 33(29), 4877–4900. Available at: [https://doi.org/10.1016/S1352-2310\(99\)00290-3](https://doi.org/10.1016/S1352-2310(99)00290-3).
- Kumar, P., Morawska, L., Martani, C., Biskos, G., Neophytou, M., Di Sabatino, S., Bell, M., Norford, L., & Britter, R. (2015). 'The rise of low-cost sensing for managing air pollution in cities', *Environment International*, 75, 199–205. Available at: <https://doi.org/10.1016/j.envint.2014.11.019>.
- Nochta, T., Wan, L., Schooling, J.M., & Parlikad, A.K. (2021). 'A socio-technical perspective on urban analytics: the case of city-scale digital twins', *Journal of Urban Technology*, 28(1–2), 263–287. Available at: <https://doi.org/10.1080/10630732.2020.1798177>.
- Oliver, M.A., & Webster, R. (1990). 'Kriging: A method of interpolation for geographical information systems', *International Journal of Geographical Information Systems*, 4(3), 313–332. Available at: <https://doi.org/10.1080/02693799008941549>.
- Roth, R.E. (2013). 'Interactive maps: What we know and what we need to know', *Journal of Spatial Information Science*, 6, 59–115. Available at: <https://doi.org/10.5311/JOSIS.2013.6.105>.
- Umweltbundesamt Austria. (2022). *Luftgüte in Österreich: Jahresbericht 2021*. Wien: Umweltbundesamt GmbH. Available at: <https://www.umweltbundesamt.at/luftguete>.

- Vardoulakis, S., Fisher, B.E.A., Pericleous, K., & Gonzalez-Flesca, N. (2011). 'Modelling air quality in street canyons: A review', *Atmospheric Environment*, 37(2), 155–182. Available at: [https://doi.org/10.1016/S1352-2310\(02\)00857-9](https://doi.org/10.1016/S1352-2310(02)00857-9).
- Veefkind, J.P., Aben, I., McMullan, K., Förster, H., De Vries, J., Otter, G., Claas, J., Eskes, H.J., De Haan, J.F., Kleipool, Q., Van Weele, M., Hasekamp, O., Hoogeveen, R., Landgraf, J., Snel, R., Tol, P., Ingmann, P., Voors, R., Kruizinga, B., ... Levelt, P.F. (2012). 'TROPOMI on the ESA Sentinel-5 Precursor: A GMES mission for global observations of the atmospheric composition for climate, air quality and ozone layer applications', *Remote Sensing of Environment*, 120, 70–83. Available at: <https://doi.org/10.1016/j.rse.2011.09.027>.
- World Health Organization (WHO). (2021). WHO Global Air Quality Guidelines: Particulate Matter (PM_{2.5} and PM₁₀), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide. Geneva: World Health Organization. Available at: <https://www.who.int/publications/i/item/9789240034228>.

Introducing KPIs for Sustainable Development Goals

Utku Arslan

02.06.2026

Table of Contents

1. Abstract
2. Introduction
3. Background
 - 3.1 Sustainable Development Goals
 - 3.2 Existing Assessment Approaches
 - 3.3 Key Performance Indicators
4. Problem Statement
 - 4.1 Lack of Quantitative Measurement
 - 4.2 Challenges in SDG Assessment
5. Introducing KPIs for SDGs
 - 5.1 KPI Development Methodology
 - 5.2 KPI Selection Criteria
 - 5.3 Proposed KPI Framework
 - 5.4 Implementation and Monitoring Mechanism
 - 5.5 Incentive and Penalty Framework
 - 5.6 Example Application: Austria
6. Discussion
 - 6.1 Benefits
 - 6.2 Limitations
 - 6.3 Future Work
7. Conclusion
8. References

List of Tables

- Table 1: Proposed KPIs for SDG 3 – Good Health and Well-Being
- Table 2: Proposed KPIs for SDG 11 – Sustainable Cities and Communities
- Table 3: Proposed KPIs for SDG 13 – Climate Action

Abstract

For approximately 20 years, the United Nations Sustainable Development Goals (SDGs) have served as a worldwide guideline for sustainable development. However, there are no standardized metrics exists to quantitatively assess the degree to which these goals are being fulfilled. Despite this, governments demonstrate the reliability of these goals and announce their progress. This paper proposes five Key Performance Indicators (KPIs) for each SDG, creating a standardized measurement framework for evaluation. Consequently, SDG fulfilment can now be evaluated in quantitative terms and linked to mechanisms such as financial incentives or policy accountability.

Keywords: SDG, KPI, sustainability assessment, quantitative measurement, performance indicators

Introduction

The United Nations Sustainable Development Goals (SDGs) have served as a framework for the United Nations to address problems such as global problems such as poverty, climate change, and inequality 20 years ago (Arora & Mishra, 2019). In 2015, the 17 Sustainable Development Goals were accepted by the scope of the 2030 Sustainable Development Agenda, and these goals constitute a universal call to action for organizations and individuals (World Health Organization, 2015). Until this year, many countries have officially integrated the SDGs into their national policies and development strategies.

However, despite this widespread political commitment, a fundamental deficiency remains: There is no standardized metric for the measurement of how the goals are successfully applied. In the scope of the Austria example, it has integrated the SDGs and publishes progress reports regularly (Wretschitsch et al., 2024). However, the impact of the reports on the Sustainable Development Goals and how each reported measure quantitatively contributes to sustainable development remains unclear.

This problem is not unique to Austria; other countries which integrated the SDGs into their political decisions also have no metric evidence.

This study, it aims to fill this gap with the following contributions:

- It provides an overview of the current state of SDG implementations and existing evaluation approaches.
- It highlights the shortcomings of current approaches in providing quantitative measurement.
- It proposes a KPI-based framework for measuring SDG performance.

This study believes this approach will help public institutions, municipalities, and organizations track and communicate their progress toward the SDGs in a transparent and comparable manner.

3. Background

3.1 Sustainable Development Goals

The Sustainable Development Goals were adopted by 193 member states of the United Nations in 2015 (Eberle et al., 2022). These goals are a continuation of the Millennium Development Goals implemented between 2000 and 2015, but have a more comprehensive and complex structure. In total, they have 17 goals and 169 sub-goals, and this framework includes topics such as poverty reduction, quality education, clean energy, climate action, and sustainable cities (Stafford-Smith et al., 2017). SDGs are defined as targets to be achieved and fully applied until 2030, and countries are obliged to develop their own national action plans for this period (Colglazier, 2015).

3.2 Existing Assessment Approaches

The UN has identified 232 global indicators to monitor the progress towards the SDGs for all countries (MacFeely, 2020). These indicators theoretically allow us to measure progress; however, serious problems in practice were observed. Many countries do not have the capacity to collect reliable data on these indicators. In addition, indicators are interpreted differently from country to country, so international comparisons are difficult to make (Dickens, et al., 2019). At the EU level, Eurostat publishes annual SDG monitoring reports for member states. However, these reports are also based on qualitative assessments and cannot show whether the targets have been met quantitatively (Lafortune et al., 2020). How is progress towards the sustainable development goals measured? Comparing four approaches for the EU. *Sustainability*, 12(18), 7675.).

3.3 Key Performance Indicators

Key Performance Indicators (KPIs) are numerical values used to measure an organization's success in achieving a specific goal (Momete & Momete, 2021). KPIs have been used in the private sector for a while and have become popular and common in urban planning in recent years (Angelakoglou et al., 2019). A good KPI needs to be measurable, time-bound, and directly linked to the goal. Although some studies have been conducted on the use of KPIs in the field of sustainability, in general, these studies focus on a single sector or a single objective and cannot successfully provide an integrated framework encompassing all SDGs.

4. Problem Statement

4.1 Lack of Quantitative Measurement

SDGs are defined as worldwide and comprehensive goals. This has made the universal acceptance of the goals, but has also made concrete measurement more difficult. For example, SDG 11 aims to make cities inclusive, safe, and sustainable (Klopp & Petretta, 2017). However, there is no common method for calculating what percentage of a city has achieved this goal. Countries typically share input-focused information in their progress reports, such as the number of completed projects or the number of laws enacted (Giles-Corti et al., 2020). This input-focused information can vary by the country's infrastructure and current situation. The same amount of low implementation might be satisfied and not satisfied, according to the country. This information does not show how well the target has been met.

4.2 Challenges in SDG Assessment

In addition to the lack of measurement, there are other problems with the current evaluation process. Firstly, comparisons between countries are not possible because each country interprets the SDGs according to its own national priorities. Secondly, several required data for some SDGs are not collected regularly or shared transparently (Saner & Nguyen, 2020). Third, existing reporting systems are not based on any accountability mechanism. This means that

even if a country declares its commitment to the SDGs, this declaration does not have any sanction or financial consequences (Pizziet al.,2022). This situation contributes to the SDGs having a symbolic character in practice.

5. Introducing KPIs for SDGs

5.1 KPI Development Methodology

The KPIs proposed in this study were selected from among indicators that can numerically reflect the core objective of each SDG. However, expert participation is essential for this selection process. Each SDG belongs to different disciplines. Public health experts should be involved in health goals, urban planners and architects for urban goals, and environmental scientists for climate goals (Giles-Corti et al., 2016). Therefore, it is recommended that the final set of KPIs be determined by a multidisciplinary expert group containing academics, NGOs, and representatives from relevant sectors.

5.2 KPI Selection Criteria

For a KPI to be used within this framework, it must meet the following criteria:

- It must be measurable and based on reliable data sources
- It must be comparable to the 2015 baseline year
- It must be consistently applicable across countries
- It must be directly linked to the relevant SDG target
- It must be resistant to manipulation

5.3 Proposed KPI Framework

The following KPIs are proposed for three selected SDGs, representing environmental, social, and urban development domains respectively.

SDG 3 – Good Health and Well-Being

KPI	What it measures	How it is calculated
KPI 3.1	Primary healthcare access	Number of general practitioners per 10,000 people
KPI 3.2	Infant mortality rate change	Deaths per 1,000 live births, percentage change since 2015
KPI 3.3	Mental health service access	Number of psychologists and psychiatrists per 100,000 people
KPI 3.4	Physical activity rate	Percentage of adults meeting 150 minutes of activity per week
KPI 3.5	Air pollution related mortality	Deaths per 100,000 people attributed to air pollution

Table 1: Proposed KPIs for SDG 3 – Good Health and Well-Being

SDG 11 – Sustainable Cities and Communities

KPI	What it measures	How it is calculated
KPI 11.1	Green space access	Green area in m ² per capita
KPI 11.2	Public transport usage	Percentage of daily trips made by public transport
KPI 11.3	Energy efficient building stock	Percentage of buildings with energy class A or B
KPI 11.4	Housing affordability	Ratio of average rent to average income
KPI 11.5	Walkable street coverage	Percentage of urban streets with dedicated pedestrian infrastructure

Table 2: Proposed KPIs for SDG 11 – Sustainable Cities and Communities

SDG 13 – Climate Action

KPI	What it measures	How it is calculated
KPI 13.1	Per capita carbon emissions	Tonnes of CO ₂ per person, percentage change since 2015
KPI 13.2	Renewable energy share	Percentage of renewable energy in total energy consumption
KPI 13.3	Extreme weather event frequency	Annual change in number of floods, storms and droughts
KPI 13.4	Climate education coverage	Climate-related hours in national school curriculum
KPI 13.5	Green public investment	Percentage of public budget allocated to climate measures

Table 3: Proposed KPIs for SDG 13 – Climate Action

Scoring for all KPIs is based on a 0–100 normalized scale. The baseline year is 2015, corresponding to the adoption of SDGs. Positive change toward the target increases the score, while deviation from the target reduces it. The average of five KPI scores represents the overall SDG score for a given country.

5.4 Implementation and Monitoring Mechanism

To ensure the reliability of the KPI measurement process, an independent methodology is needed. This study proposes that the measurements be carried out by area-based commissions established within the United Nations. Each commission would consist of experts from the relevant SDG area. For example, urban planners and architects for SDG 11, and climate

scientists for SDG 13 (Davis et al., 2025). The commissions would conduct annual measurements, share the results publicly, and request a development plan from the relevant government in case of deviations from the target.

5.5 Incentive and Penalty Framework

The methodology remains dysfunctional without linking KPI results to concrete mechanisms that can affect government decisions. Therefore, a two-layered structure is proposed. Countries that fall below the threshold and fail to implement the improvement plan face sanctions such as international funding restrictions. However, if the reason for unsatisfactory performance is identified as a lack of resources, grants, and technical support will be provided instead of sanctions. The commission will decide which mechanism should be applied by considering the country's possibilities.

5.6 Example Application: Austria

When Austria is assessed under SDG 11, a mixed picture emerges. It is above the European average in terms of per capita green space and public transport use (Salvo et al., 2021). However, housing accessibility and the rate of energy-efficient buildings are insufficient (Umoh et al., 2024). The Commission evaluates this picture to calculate the overall SDG 11 score and requests improvement plans in the weak areas. Since Austria is an advanced economy, a sanctions mechanism, rather than support, is applied in this scenario.

6. Discussion

6.1 Benefits

The framework proposed in this study offers several important contributions to the SDG assessment. First and most important, the goals can be expressed quantitatively for the first time. This allows governments and organizations to objectively view their own performance. Furthermore, a standardized measurement framework enables comparisons between countries. Thus, concrete data can be used to show which country is progressing or lagging in which area. Finally, a scoring system linked to enforcement and support mechanisms transforms the SDGs from mere political rhetoric into an accountable structure.

6.2 Limitations

This study has some limitations. Data collection capacity for the proposed KPIs varies significantly from country to country. Reliable data may not be available for some KPIs in developing countries. Furthermore, assigning equal weight to each KPI may lead to misleading results in some cases. For example, a country may perform very well in four KPIs but underperform in the most critical indicator, yet the overall score may not adequately reflect this.

6.3 Future Work

This study should be considered a starting point. The development of KPI sets for the remaining 14 SDGs is necessary in the future and 3 SDGs suggestion should be examined by experts and improved. Furthermore, instead of assigning fixed weights to each KPI, a system that weights them according to context could be designed. How the commission structure will be established and on what legal basis it will be based a separate area of research. Finally, piloting the proposed framework in a few countries and comparing the results would be valuable in testing the system's reliability.

7. Conclusion

This study proposes five Key Performance Indicators (KPIs) for each SDG (Sustainable Development Goal) to enable quantitative assessment of the United Nations Sustainable Development Goals. It demonstrates that the current system is inadequate for quantitative measurement and makes comparisons between countries difficult. Through the proposed KPI framework and independent commission structure, it is shown that SDG achievement can now be measured in quantitative terms and linked to financial incentives and enforcement mechanisms. This study is expected to contribute to governments, municipalities, and international organizations monitoring SDG progress in a transparent and comparable manner.

7. References

- Angelakoglou, K., Nikolopoulos, N., Giourka, P., Svensson, I. L., Tsarchopoulos, P., Tryferidis, A., & Tzovaras, D. (2019). A methodological framework for the selection of key performance indicators to assess smart city solutions. *Smart Cities*, 2(2), 269–306.
- Arora, N. K., & Mishra, I. (2019). United Nations Sustainable Development Goals 2030 and environmental sustainability: race against time. *Environmental Sustainability*, 2(4), 339–342.
- Colglazier, W. (2015). Sustainable development agenda: 2030. *Science*, 349(6252), 1048–1050.
- Dickens, C., Smakhtin, V., McCartney, M., O'Brien, G., & Dahir, L. (2019). Defining and quantifying national-level targets, indicators and benchmarks for management of natural resources to achieve the sustainable development goals. *Sustainability*, 11(2), 462.
- Eberle, U., Wenzig, J., & Mumm, N. (2022). Assessing the contribution of products to the United Nations' Sustainable Development Goals: A methodological proposal. *The International Journal of Life Cycle Assessment*, 27(7), 959–977.
- Giles-Corti, B., Lowe, M., & Arundel, J. (2020). Achieving the SDGs: Evaluating indicators to be used to benchmark and monitor progress towards creating healthy and sustainable cities. *Health Policy*, 124(6), 581–590.
- Giles-Corti, B., Vernez-Moudon, A., Reis, R., Turrell, G., Dannenberg, A. L., Badland, H., & Owen, N. (2016). City planning and population health: a global challenge. *The Lancet*, 388(10062), 2912–2924.
- Klopp, J. M., & Petretta, D. L. (2017). The urban sustainable development goal: Indicators, complexity and the politics of measuring cities. *Cities*, 63, 92–97.

- Lafortune, G., Fuller, G., Schmidt-Traub, G., & Kroll, C. (2020). How is progress towards the sustainable development goals measured? Comparing four approaches for the EU. *Sustainability*, 12(18), 7675.
- MacFeely, S. (2020). Measuring the sustainable development goal indicators: an unprecedented statistical challenge. *Journal of Official Statistics*, 36(2), 361–378.
- Momete, D. C., & Momete, M. M. (2021). Map and track the performance in education for sustainable development across the European Union. *Sustainability*, 13(23), 13185.
- Pizzi, S., Del Baldo, M., Caputo, F., & Venturelli, A. (2022). Voluntary disclosure of Sustainable Development Goals in mandatory non-financial reports: The moderating role of cultural dimension. *Journal of International Financial Management & Accounting*, 33(1), 83–106.
- Salvo, D., Garcia, L., Reis, R. S., Stankov, I., Goel, R., Schipperijn, J., & Pratt, M. (2021). Physical activity promotion and the United Nations sustainable development goals: building synergies to maximize impact. *Journal of Physical Activity and Health*, 18(10), 1163–1180.
- Saner, R., Yiu, L., & Nguyen, M. (2020). Monitoring the SDGs: Digital and social technologies to ensure citizen participation, inclusiveness and transparency. *Development Policy Review*, 38(4), 483–500.
- Salvo, D., Garcia, L., Reis, R. S., Stankov, I., Goel, R., Schipperijn, J., & Pratt, M. (2021). Physical activity promotion and the United Nations sustainable development goals: building synergies to maximize impact. *Journal of Physical Activity and Health*, 18(10), 1163–1180.
- Stafford-Smith, M., Griggs, D., Gaffney, O., Ullah, F., Reyers, B., Kanie, N., & O'Connell, D. (2017). Integration: the key to implementing the Sustainable Development Goals. *Sustainability Science*, 12(6), 911–919.
- Umoh, A. A., Ohenhen, P. E., Chidolue, O., Ngozichukwu, B., Fafure, A. F., & Ibekwe, K. I. (2024). Incorporating energy efficiency in urban planning: A review of policies and best practices. *Engineering Science & Technology Journal*, 5(1), 83.
- World Health Organization. (2015). Health in 2015: from MDGs, millennium development goals to SDGs, sustainable development goals.
- Wretschitsch, E., Spittler, N., & Kirchner, M. (2024). Modelling national pathways to achieving the SDGs in Austria: Insights from a system simulation approach with focus on inequality, economic growth and climate mitigation. Available at SSRN 5038315.

Forecasting Building Futures: An Algorithm for Measuring Transformation Diversity

Enkeljetë Ademi
Technical University of Vienna
e12535714@student.tuwien.ac.at

Abstract

Cities contain thousands of existing buildings assessed almost exclusively on their current condition. No instrument exists to measure how many and which future functions a given building could support. We introduce the Transformation Diversity Index (TDI), an algorithm that computes a compatibility score for each of eight candidate functions by applying a function-specific, reference-grounded weight matrix to six measurable building parameters. The eight functions cover the dominant urban conversion typologies in European cities; weights are justified by building standards rather than arbitrary assignment; and parameter rubrics are defined to ensure consistent assessment. The result is a ranked profile of viable future uses and a normalized diversity score. An illustrative example demonstrates the algorithm's output format. Acknowledged limitations include the absence of empirical weight calibration and the exclusion of economic viability.

Keywords: adaptive transformation, transformation diversity index, building assessment algorithm, future use compatibility, circular built environment

1. Introduction

European cities hold a vast stock of ageing buildings that no longer meet contemporary spatial, climatic, or programmatic demands. Around 75% of EU buildings predate modern energy standards (European Commission, 2020), and demographic shifts, post-pandemic use patterns, and climate targets are simultaneously rendering much of this stock functionally obsolete. The conventional planning response has been binary: renovate for the existing use, or demolish and replace. This framing skips the prior and more important question: what could this building become?

A post-war office block may be unsuitable for continued office use but ideal for residential conversion. A disused industrial shed may be incompatible with healthcare but well-suited to co-working. The capacity of a building to support a diversity of future functions is a distinct and measurable property — but it has never been systematically measured. In this work, we will:

- Review existing transformation assessment tools and identify their limitations (see “Background”)
- Define the methodological gap current tools leave open (see “Problem”)
- Introduce the TDI algorithm with function selection rationale, weight justification, parameter rubrics, and pseudocode (see “Forecasting Building Futures”)

The TDI reframes building assessment from condition diagnosis to futures forecasting, providing planners and developers with a reproducible basis for transformation decision-making.

2. Background

Langston's Adaptive Reuse Potential (ARP) model (2008) is the most widely cited quantitative instrument in the field, combining physical, functional, economic, and social obsolescence factors into a percentage score. The AdaptSTAR model (Conejos, Langston & Teng, 2015) extended this logic to new-building design. Circular economy research has produced component-level Reuse Viability Indices (Sivers & Fivet, 2025) and whole-building circularity KPI sets (Khadim et al., 2023; Mani et al., 2026). Brand's long-life, loose-fit, low-energy framework (1994) established why spatial indeterminacy is a precondition for long-term adaptability.

All of these tools share a common limitation: they return a single aggregate score. They answer “how good is this building?” rather than “good for what?” A building may score poorly on a general adaptability index yet be highly suited to a specific use type. No existing instrument returns a function-differentiated compatibility profile. This is the gap the TDI is designed to fill.

3. Problem

Planners and developers currently have no standard way to answer the question: which uses could this building support, and how well? Without such an instrument, transformation potential remains locked in expensive, non-comparable, bespoke expert assessments. A municipality cannot screen a district's building stock for residential conversion candidates. A green bond issuer cannot set quantifiable eligibility thresholds. A developer cannot rank a portfolio by functional versatility. The ARP model does not fill this gap because it measures obsolescence, not transformation capacity — related but distinct concepts. The TDI is designed to fill this specific gap.

4. Forecasting Building Futures: An Algorithm for Measuring Transformation Diversity

The TDI algorithm takes six measurable building parameters as input and returns a compatibility score for each of eight candidate functions, a ranked viability profile, and a normalized diversity score. Given the same survey data, any two assessors using the defined rubrics will obtain the same output.

4.1 The eight candidate functions

The eight functions: Housing, Student housing, Hotel, Office, School, Healthcare, Co-working, Mixed use, were selected to cover the dominant urban conversion typologies documented in European planning practice and adaptive reuse literature, spanning the full range of spatial and technical demands from low-complexity (co-working) to high-complexity (healthcare). Retail, cultural facilities, laboratories, and sports facilities are acknowledged omissions: retail and cultural uses overlap substantially with the included types in their spatial requirements; laboratory and sports facilities require highly specialized parameters beyond the scope of the six general inputs. Extending the function set is identified as future work.

4.2 Input parameters and rubrics

Four parameters are continuous measurements; two require rubric-based scoring to ensure inter-assessor consistency. Floor height (m) is normalized linearly between 2.4 m (S=0) and 4.5 m (S=1). Grid span (m) is normalized between 3.0 m (S=0) and 12.0 m (S=1). Façade adaptability is the ratio of mechanically fixed elements to total façade area, with a -0.20 penalty for heritage-listed buildings. Accessibility is scored as the proportion of EN 17210 universal access criteria met. Structural type is mapped to a fixed score to eliminate assessor discretion (Table 1). Core adaptability is scored using the five-band rubric in Table 2, which specifies observable criteria to ensure consistent assessment.

Structural type	S(Structure)	Rationale
Load-bearing masonry (cross-wall)	0.20	Wall removal requires structural replacement; reconfiguration costly and complex.
Load-bearing masonry (perimeter)	0.50	Perimeter walls fixed; internal layout open. Moderate reconfiguration feasible.
Reinforced concrete frame	0.75	Internal walls non-structural; wide reconfiguration range within column grid.
Steel frame	0.90	Maximum span-to-depth ratio; lightest structural footprint; maximum freedom.
Hybrid (RC frame + masonry core)	0.60	Frame permits floor-plate changes; core zone constrained.

Table 1. Structural type to score mapping

Score	Band	Observable criteria (any two sufficient)
0.0–0.2	Closed	Fully embedded wet services; no accessible risers; service routes through structural elements.
0.3–0.4	Rigid	Accessible risers present but fully occupied; duct routes fixed by slab penetrations.
0.5–0.6	Partial	At least one accessible shaft with spare capacity; dry riser present; electrical boards expandable.
0.7–0.8	Flexible	Dedicated service zone separate from structural grid; multiple accessible shafts; raised floor or exposed ceiling.
0.9–1.0	Open	Full structure/service separation; all risers accessible and documented; BIM or as-built record available.

Table 2. Core adaptability rubric — five bands with observable criteria.

4.3 Weight matrix

Each function is assigned a weight vector across the six parameters. The weighting scheme is conceptually informed by adaptive reuse literature and building performance requirements identified in previous studies (Brand, 1994; Langston et al., 2008; Conejos et al., 2015).

Function	Fl.H.	Grid	Core	Façade	Access.	Struct.	Dominant weight — rationale
Housing	0.25	0.20	0.15	0.15	0.15	0.10	Fl.H.: min. 2.5 m habitable room height (ÖNORM B 1600)
Student housing	0.20	0.20	0.15	0.15	0.20	0.10	Access.: EN 17210 mandates universal access in student facilities
Hotel	0.30	0.15	0.20	0.20	0.10	0.05	Fl.H.: hotel brand standards require ≥ 3.0 m clear
Office	0.35	0.30	0.15	0.10	0.05	0.05	Office: clear floor heights above 2.7 m and open-plan spans above 6 m are common requirements in contemporary office design.
School	0.25	0.20	0.15	0.10	0.20	0.10	Access.: OIB RL 3 strict egress and circulation requirements
Healthcare	0.30	0.15	0.25	0.10	0.15	0.05	Core: clinical infrastructure is primary conversion cost driver (WHO)
Co-working	0.25	0.35	0.15	0.10	0.10	0.05	Grid: column-free floor plates defining requirement (CBRE Flex 2023)
Mixed use	0.20	0.25	0.20	0.15	0.10	0.10	Grid + Core: stacked program demand both spatial and service flex

Table 3. Weight matrix W [function $\times$ parameter] with dominant weight rationale.

4.4 Viability threshold and pseudocode

A function is viable if $CS(f) \geq \tau = 0.50$. This midpoint threshold represents a building meeting approximately half of the weighted requirements for a given function — sufficient for transformation with targeted interventions. The threshold is configurable; the algorithm always returns the full ranked profile regardless of τ .

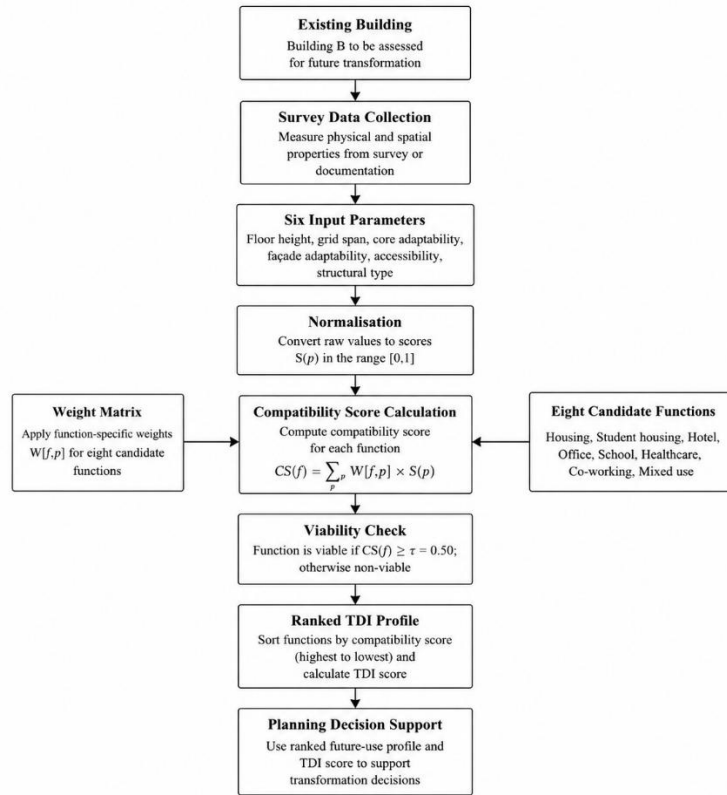


Figure 1. Workflow of the Transformation Diversity Index (TDI) algorithm

4.5 Illustrative example

Table 4 shows a hypothetical TDI output for an illustrative RC frame building (floor height 3.6 m, grid span 7.2 m, core adaptability 0.55, façade adaptability 0.62, accessibility 0.71, structural type RC frame = 0.75). These values are hypothetical and are intended solely to demonstrate the algorithm’s output format; they do not represent a surveyed building.

Function	CS	Limiting parameter	Viable?
Office	0.84		Yes
Co-working	0.79		Yes
Hotel	0.71		Yes
Mixed use	0.67		Yes
Housing	0.63		Yes
Student housing	0.58	Accessibility (0.40)	Yes
School	0.49	Floor height (0.35)	No
Healthcare	0.38	Core adapt. (0.20)	No

Figure 2. Illustrative TDI output — hypothetical RC frame building.

The profile immediately communicates that this building type has strong office and co-working compatibility, moderate residential viability, and structural or service barriers to school and healthcare use. The limiting parameters for non-viable functions (floor height for school, core adaptability for healthcare) directly indicate which physical interventions would be required to unlock those uses.

5. Discussion

The TDI's primary contribution is a differentiated profile rather than a single score, enabling planners to identify not just whether a building is transformable, but which uses it can support and why. The function-specific weight matrix, grounded in building standards, ensures that the assessment reflects actual technical demands rather than a generic adaptability criterion.

The most significant limitation is the absence of empirical validation. The weights are conceptually informed by adaptive reuse literature and building performance requirements and have not yet been empirically calibrated. Whether they correctly predict transformation feasibility across diverse typologies and national contexts remains to be tested. A retrospective study correlating pre-transformation parameter values with project outcomes targeting 80 projects across Austria, Germany, and the Netherlands is the planned next step. The illustrative example in Section 4.5 demonstrates output format only and does not constitute empirical validation.

A second limitation is that the TDI measures physical compatibility, not economic viability or market demand. A building may score high for office conversion in a market where office demand is saturated. The TDI is a technical screening tool designed to sit before feasibility studies and financial modelling, identifying which buildings and uses are worth investigating not replacing that analysis. Integration with economic appraisal frameworks is identified as future work.

The current version covers eight functions and six parameters. Both sets can be extended. Retail, cultural facilities, and sports uses are the most immediate candidates for inclusion; automated parameter extraction from building registries or point-cloud surveys would enable portfolio-scale application without individual site visits.

6. Conclusion

No standard instrument currently exists for measuring which future uses a building can support. We introduced the Transformation Diversity Index (TDI), an algorithm that computes function-specific compatibility scores for eight candidate uses by applying a reference-grounded weight matrix to six measurable building parameters. Weights are justified by building standards specific to each use; parameter rubrics are defined for consistent assessment; the viability threshold is explained as a configurable screening criterion. The algorithm returns a ranked profile of viable future functions and a diversity score, making transformation diversity a reproducible, comparable, and actionable property of the built environment for the first time.

References

- Brand, S. (1994). *How buildings learn: What happens after they're built*. Viking Press.
- CBRE. (2023). *CBRE Flex Index 2023: The State of Flexible Office Space*. Los Angeles: CBRE Group.
- European Commission. (2020). *A renovation wave for Europe – Greening our buildings, creating jobs, improving lives* (COM(2020) 662 final). European Commission.
- Sivers, M., & Fivet, C. (2025). *Unlocking the circular economy: The Reuse Viability Index for predicting building component reusability*. *Journal of Physics: Conference Series*, 3140(16), 162015.
<https://doi.org/10.1088/1742-6596/3140/16/162015>
- Mani, S., Karunasena, G., Perera, S., Oyedele, L. O., Ruparathna, R., & Murtaza, M. B. (2026). *What to assess in circular buildings: Key performance indicators for circular transformation*. *Smart and Sustainable Built Environment*. <https://doi.org/10.1108/SASBE-11-2025-0708>
- European Committee for Standardization. (2021). *EN 17210: Accessibility and usability of the built environment*. CEN.
- Khadim, N., Agliata, R., Thaheem, M. J., & Mollo, L. (2023). Whole building circularity indicator: A circular economy assessment framework for promoting circularity and sustainability in buildings and construction. *Building and Environment*, 241, 110498. <https://doi.org/10.1016/j.buildenv.2023.110498>
- Langston, C., Wong, F. K. W., Hui, E. C. M., & Shen, L.-Y. (2008). Strategic assessment of building adaptive reuse opportunities in Hong Kong. *Building and Environment*, 43(10), 1709–1718.
<https://doi.org/10.1016/j.buildenv.2007.10.017>
- Conejos, S., Langston, C., & Teng, J. (2015). Designing for future building adaptive reuse using AdaptSTAR. *Facilities*, 33(9/10), 584–602. <https://doi.org/10.1108/F-06-2013-0049>
- World Health Organization. (2022). *Guidance on health facility design*. World Health Organization.

Beyond Geometric Efficiency: Integrating Social Constraints into Multi-Objective Zoning Algorithms

259.669 Algorithms in Planning

Aikhomu Evans Onokevbagbe

Abstract

Conventional data structures (Grids and Arrays) were used to create computational zoning tools which were designed to optimize space only for mechanical efficiency and in turn actively reinforced socio-economic differences by mathematically equating all urban points. Additionally, the evaluation of generative design software revealed serious deficiencies in the real-life implementation of the legally required limits of biological activity, such as not meeting the legally required biologically active area in the city of Włocławek. Instead of fixing this algorithmic blind spot by changing the algorithm, this paper proposed that one should change the algorithmic data structure, which is introduced here as Spatial Attributed Graphs (SAG), and socialize the data structure. Finally, the research showed that Human in the loop Framework was the only approach to ensure democratic accountability and not automating historical bias.

Keywords: Generative Design Spatial Attributed Graphs, Multi-Objective Optimization, Social Equity, Human-in-the-Loop

Introduction

Computational systems have become an integral part of urban design. In the past, planning was largely based on human interpretation, qualitative community involvement, and a gradual adjustment of policies (Li & Dang, 2025). In today's world, algorithmic planning is focused on "data-driven" and automatic spatial configuration. They're fantastic for dealing with complicated spatial problems and are incredibly fast for their purposes, but the underlying principles behind their operation are all purely of a mathematical optimization and mechanical efficiency nature. This leaves a huge disconnect between the algorithmic spatial results and the socio-spatial actuality of the city.

To fill this void, I use technical definitions of this discipline as they are precisely defined. As Wurzer and Lorenz (2022) explain, an algorithm is "a set of instructions a computer will follow to do a calculation. All algorithmic processes have to be semantically valid, i.e., must be self-consistent and must be explicitly decidable in a finite time. In most important of all, the algorithms work with particular data structures that store and process the geometric information of a city.

A Generative Design (GD) system, which determines land use solely based on mechanical efficiency, is "opaque." They are at risk of reinforcing historical stereotypes, failing to hold people to account and reducing democratic participation. An agnostic or color blind algorithmic solution doesn't help to solve any of these social issues.

This paper examines the potential for the planning profession to facilitate the link between 'geometric optimization' and 'social sustainability'. My research is structured in the following way:

- Defining the Baseline: I explain the mechanism of existing data structures and geometric optimization models.
- The Gap: I describe the shortcomings of deterministic models in considering qualitative aspects of human welfare and statutory zoning laws, based on recent empirical case studies.
- Integrating Social Variables: I state my case for the use of more sophisticated data structures like the Spatial Attributed Graphs proposed by Wang (2023) that will require social equity
- Recognizing Constraints: I agree that there are technical problems of capturing social values numerically and the need for human control.

From a blind geometric optimization to socially conscious data structures directly improves the benefit of municipal planners and the society they serve. Human-centric measurements will be incorporated into the algorithmic benchmark and allow cities to leverage the computational power without compromising their ethical and statutory responsibilities. This way, the development of the city is done for the people and not for the developers to make as much money as they can.

The Architecture of Mechanical Efficiency

In order to evaluate the current computational zoning tools, we need to understand how they function. An algorithm is a set of steps a computer has to follow to perform a calculation. A data structure is the basis of every algorithmic process. This architecture helps shape the physical place of a city by way of abstraction, storage, and manipulation.

Today, the most popular data-structures available for spatial design are Arrays, Grids and Graphs. The simple sequence of coordinates or building parameters is stored in an Array. A Grid is a two-dimensional array with values for each cell, such as elevation or zoning type. A Graph is used to represent a network and it is the simplest graph type to use when calculating street layouts, using nodes and connections (called edges). Tensors are also employed in modern machine learning techniques. A Tensor is a multi-dimensional array that describes the distribution of Points of Interest over an urban grid and is the foundation for deep generative learning.

These structures are the basis for current algorithmic planning in order to optimize spatial variables. There are rule-based generation and performance-based selection methods in Generative Design platforms such as Autodesk Forma and Archistar. They play with arrays of dimensional variables (e.g., building height, width, and building setbacks) and investigate an extensive design space. The algorithm just follows its steps in a procedural manner until it produces a mathematically optimal result, determined entirely by hard geometric constraints.

The main issue is that these calculations are purely mechanical. For example, the Voronoi subdivision algorithm. It uses a Grid data structure to assign cells to the closest input point, only according to the physical distance. This results in a mathematically ideal arrangement of space for best coverability.

However, the algorithm operates on each individual cell based on its co-ordinates. It isn't aware of the demographics or social reality of its newly subdivided land.

Generative massing tools measure success in terms of quantitative values such as total floor area and construction cost. The ideal building massing based on economic return and land area does not necessarily lead to a physically comfortable and fair urban space. In today's day and age, machine learning models move away from rules to learning patterns from past data, making this more complex. These models are able to process huge volumes of urban data to get geometric relationships but systematically fail to consider unquantifiable social contexts. This mechanical base provides the building blocks and seeds for significant ethical and practical flaws in planning practice.

Algorithmic blindness and statutory failure.

Existing zoning algorithms are mathematically efficient and socially blind. They can maximize dimensions, such as physical distance or floor area without knowing how important those dimensions are socially. Generative systems heavily depend on past data, which means that past data embed systemic inequalities in the data structures that underlie generative systems. In fact, when a machine learning model is fed with past investment information from the municipality, and it starts to learn how to predict investments, it reflects the characteristics of richer neighborhoods naturally, since they have greater capital flow. This automated process speeds up practices that are similar to historical redlining, which is a practice of excluding vulnerable communities but which are active rather than passive. The algorithm isn't malicious. It only perpetuates buyer in a mechanical way.

This automation is also dangerously harming the profession of planning. There is a need for professional judgment in urban planning which takes into account the competing interests of the community. Delegating these decision-making tasks to "black box" machine learning systems are losing this deliberative practice. Their underlying mechanism is still a mystery to the scientists who built them. Planners cannot give the exact math that went into suggesting a zoning mix that leads to fast gentrification when a computational tool outputs such an answer. This opacity empowers inaction and undermines democratic accountability. If stakeholders are not able to see the logic behind a zoning change, there is no public participation.

Planners are also confronted with an important epistemological difficulty, the "validation paradox". Generative models: propose new spatial layouts for which there is no historical ground truth. Empirically testing these AI-generated policies on current populations is too dangerous, since the impact on housing access and economic stability would be too much.

In addition to these theoretical shortcomings, generative tools are not always able to meet basic statutory requirements. As an empirical proof, we can take into account the case study of Włocławek. Experiments were conducted to determine the effectiveness of Autodesk Forma and the One Click LCA generative design plugins in creating compliant layouts in accordance with a Local Spatial Development Plan from 2004 in Poland. A 50% biologically active area was a concession of the statutory law for certain residential plots.

This requirement was not met at all by the generative algorithms. They were optimised so as to maximise the geometric volume and positioned buildings straight on the plot boundary and covered virtually the whole site. The programs considered the critical environmental laws and negative space as unproductive geometric resources rather than limits. Planners were required to manually correct the layouts generated to regain the required amount of green space.

The shortfall is that conventional geometric optimization doesn't work in the social and environmental world. This needs to change by significantly reshaping the way that algorithms are reading urban space.

Evaluation Metric	2004 Statutory Plan (Legal Mandate)	Generative Output (Autodesk Forma)	Compliance Status
Optimization Goal	Qualitative Community Welfare	Maximum Geometric Volume / Yield	Misaligned
Spatial Strategy	Contextual Integration	Placement on Absolute Plot Boundaries	Misaligned
Biologically Active Area	Minimum 50% Required	Near 0% (Negative Space Eliminated)	Failed

Table 1. Discrepancies between statutory environmental mandates and the algorithmic outputs of generative design platforms in the Włocławek case study.

Integrating Social Metrics into Spatial Graphs

The planning industry needs to rethink how to measure success in algorithms, as it has compromised with both ethical and practical issues. We can no longer continue to do the easy things like calculate "building volume" and "physical distance" with simple Grids or Arrays. An algorithm is a run-down of steps a computer has to follow to perform a calculation. To enable a system to compute fair zoning, we need to be able to act at the lowest level of the data structure. Such trade-offs between the geometric efficiency and human-centric metrics of such tools can only be achieved via multi-objective optimization, which planners need to push.

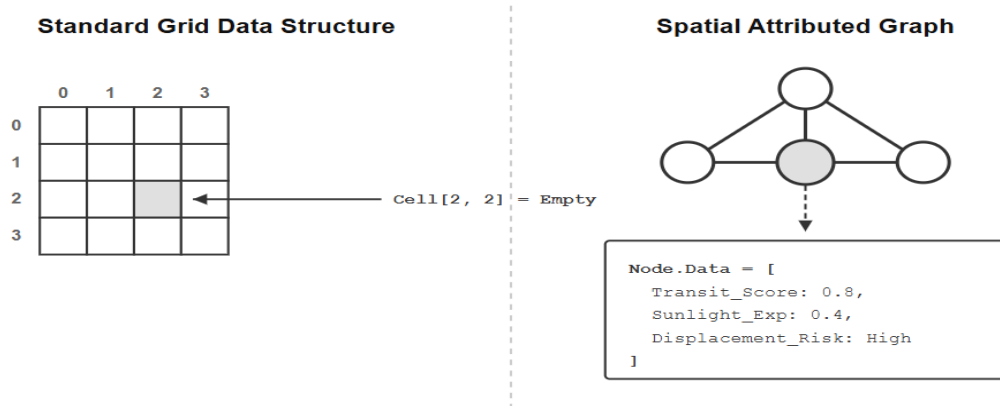


Figure 1. A conceptual comparison between standard geometric grids, which treat space uniformly, and Spatial Attributed Graphs, which encode specific socio-economic metrics directly into the underlying data structure.

Replacing blind data structures with representations that have actual socio-economic weight is the first step. This traditional approach sees space as socially homogeneous. I propose to move toward higher order representations such as Spatial Attributed Graph. Here, each node is an actual area, and each edge is a link from one to another. Not only are physical dimensions stored at each node, but also, importantly, other dimensions. Consists of an Array of particular socio-economic attributes. A hard definition of 'transit accessibility', of 'localized green-space deficits', of 'sunlight exposure', and of 'demographic displacement risk' are examples of concepts that can be encoded instead of the vague 'equity'. The computer uses this Graph to develop a zoning plan, but this expanded data structure is a necessary prerequisite that provides the real-world variables that can be explicitly programmed into a multi-objective algorithm to be evaluated.

The same reasoning can be used for deep learning models. Typical (standard) generative models include a Tensor that maps points of interest (POI) based on the coordinates (latitude, longitude). Additional channels for community-defined equity scores are needed to supplement these Tensors. This is a problem that Li and Dang (2025) point out that such data cannot be obtained from real estate prices measured in the past alone, as these prices are naturally biased toward higher-income neighborhoods. What we need to do is convert the qualitative comments from the community into computable Tensor weights. This makes it difficult for massive neural networks to minimize the networks' error rates while being aware of social distribution, as it is embedded in the data structure.

The ultimate goal does not depend on the data structure, but rather, a change of the data structure enables the multi-objective algorithm to incorporate the variables required to impose social equity as a mathematical constraint. There is a need to reject models focusing on a single objective such as maximizing the financial return or the geometric density. Vital values are in conflict in real urban planning. We need to be able to maximise the density of affordable housing and ensure all the biologically active areas which are basic to all present software are adhered to. These conflicts are translated into a multi-objective algorithm, which determines a Pareto frontier: a set of solutions where if one value is raised, one value has to be lowered. High mechanical efficiency, but non-meeting the social equity "baseline" criterion, is automatically rejected (by coding social equity as one of the fitness criteria).

The upgrade to our data structures provides computational tools with the ability to process social constraints. Nevertheless, it is very hard to quantify human values and there is yet no mathematical model that can run safely without strict human control.

Discussion: The Human-in-the-Loop Imperative

By upgrading our data structures, computational tools can now deal with social constraints. However, this is only one way to deal with it and it has its boundaries. It is very hard to quantify human values. It is not possible to accurately approximate a community's historical association with a neighborhood with an integer in a Tensor. Make no mistake, if we pretend to have solved all ethical problems in math with multiple objectives, we still end up with another kind of “color blind” automation.

Another challenge that planners must address is the validation paradox. Generative algorithms suggest completely new zonings. These layouts generated by AI cannot be safely tested on living populations due to the risk of harm to housing access and economic stability. No one can truly tell if a socially weighted algorithm is effective at preventing displacement until the buildings are built. Disease will be too far advanced by then.

This paradox is the very reason that an algorithm shouldn't work in isolation. Despite using a multi-objective tool to balance housing density and equity on a Spatial Attributed Graph, the resulting results should still be supervised by human actors, in order to ensure compliance with the hard laws, such as the law on the biologically active area in Włocławek. There is no way to test these models in the real world and nothing is more unethical than full automation.

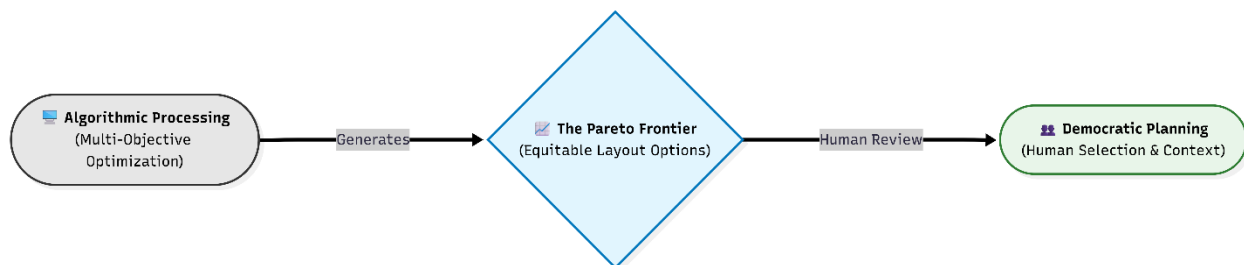


Figure 2. The proposed Human-in-the-Loop framework. The algorithm's role is restricted to generating compliant options along a Pareto frontier, while the final spatial decision remains explicitly human (Li & Dang, 2025).

We need to have a strong human-in-the-loop framework in the planning profession. The role of the algorithm is not to make the final decision on the policy. It's just supposed to provide a set of fair choices in the Pareto frontier. On the part of the planner, this is a task to be accomplished on the basis of qualitative information surrounding a context, professional judgment, and genuine democratic participation.

The architecture and planning industry isn't in need of faster algorithms for optimizing concrete volume. Tools which make social equity a hard constraint are needed. Advanced data structures and putting human planners firmly in control of planning by incorporating human-centric metrics will finally move us past the mere mechanical efficiency. Computation can be used to create a city that meets geometric, legal and social requirements.

References

- Arup. (2024). *Issue 01: AI for future cities - Urban planning and design*. Arup Foresight. <https://www.arup.com/globalassets/downloads/insights/a/ai-for-future-cities-urban-planning-and-design/ai-for-future-cities-urban-planning-and-design-v1.pdf>
- Bittencout, João Carlos & Flores, Thommas & Jesus, Thiago & Costa, Daniel. (2026). On the role of AI in building generative urban intelligence. *Artificial Intelligence Review*. 59. 10.1007/s10462-025-11469-3. <https://doi.org/10.1007/s10462-025-11469-3>.
- Borkowski, A. S., Pawlikowski, F., Ptaszek, A., Raczowska, P., Winiarska, W., & Wyrzykowska, N. (2026). Generative Design in Urban Planning with Regard to Local Zoning Regulations: A BIM Case Study. *Urban Science*, 10(5), 267. <https://doi.org/10.3390/urbansci10050267>
- Mirzaei, Bahare & Adibhesami, Mohammad Anvar. (2025). Human-in-the-loop, multi-objective generative retrofit of Studio 5 at Razi University: a participatory, performance-driven upgrade for a hot–dry climate. *Engineering, Construction and Architectural Management*. 1-33. 10.1108/ECAM-07-2025-1148. <https://doi.org/10.1108/ECAM-07-2025-1148>.
- Nagy, D., Villaggi, D., & Benjamin, D. (2017). Generative urban design: Integrating financial and energy goals for automated neighborhood layout. *Autodesk Research*. <https://damassets.autodesk.net/content/dam/autodesk/www/autodesk-research/Publications/pdf/Generative-Urban-Design-2018.pdf>
- Netser, Y., & Burshtein, M. (n.d.). *Ethics in computational design: Infusing equity into AI and generative design for building design processes* [Conference presentation]. Autodesk University. <https://www.autodesk.com/autodesk-university/>
- Sanchez, T. W., Lim, T., & Miotto, C. (2024). *Planning with artificial intelligence* (PAS Report 604). American Planning Association. https://planning-org-uploaded-media.s3.amazonaws.com/publication/download_pdf/PAS-Report-604.pdf
- Sun, Kailai & Liang, Yuebing & He, Mingyi & Zheng, Yunhan & Prakash, Alok & Wang, Shenhao & Zhao, Jinhua & Pentland, Alex. (2026). Envisioning global urban development with satellite imagery and generative AI. 10.48550/arXiv.2603.26831. <https://doi.org/10.48550/arXiv.2603.26831>.
- Tim Heinrich Son, Zack Weedon, Tan Yigitcanlar, Thomas Sanchez, Juan M. Corchado, Rashid Mehmood, Algorithmic urban planning for smart and sustainable development: Systematic review of the literature, *Sustainable Cities and Society*, Volume 94, 2023,104562, ISSN 2210-6707, <https://doi.org/10.1016/j.scs.2023.104562>.
- Wang, D., Fu, Y., Liu, K., Li, H., & Xiong, H. (2023). Automated urban planning for reimagining city configuration via adversarial learning. *IEEE Transactions on Knowledge and Data Engineering*, 35(5), 4859–4870. <https://doi.org/10.1109/TKDE.2022.3154800>
- Wurzer, G., & Lorenz, W. E. (2022). *Algorithms in planning* [Course materials]. Institute of Architectural Sciences, Department of Digital Architecture and Planning, TU Wien.

Authors

A

Ademi, Enkeljetë	131
Arslan, Utku	121

C

Chencheva, Veronica	17
---------------------	----

I

Iaconis, Francesca	73
--------------------	----

K

Kazemi, Mohamad mahdi	85
Kömürcü, Bircan	67
Korff, Elisabeth	5

O

Öksüz, Bükre	61
Onokevbagbe, Aikhomu Evans	137

P

Pando, Diego	43
Pykhacheva, Mariia	25

R

Ryu, Jinsan	79
-------------	----

S

Sejdiu, Ermira	111
Sinani, Rineta	101
Stalzer, Anna	49

T

Torres Perez, Esmeralda	95
-------------------------	----

Y

Yılmaz, Aslı	37
--------------	----