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Semantic urban elements: A Design+Science paradigm to augment human-centric cities?

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Abstract

Architecture, engineering, and construction have increasingly integrated automated tools and digital approaches for urban analysis and design. Many of these approaches are tailored towards either urban Design or urban Science, despite both being central to our understanding of cities. The separation between these two core aspects of urban development introduces multidisciplinary challenges when addressing the consequences of urban phenomena. We propose the paradigm of Semantic Urban Elements (SUEs) to combine Science-based and Design-based knowledge about potential solutions to complex urban issues, integrating advances in scientific and design thinking about such solutions using formal, open knowledge representation frameworks. We first present current problems by briefly discussing the relevant state of the art in urban Science and urban Design. Second, we derive the key characteristics that a combined urban Design+Science approach would require. We then posit a definition of SUEs and provide an illustrative example, followed by a contextualization of our proposition and evaluate existing work through the lens of our proposed paradigm. The novel SUEs method is an enabling infrastructure that supports iterative, evidence-informed design exploration and transparent evaluation. In this way, SUEs responds to the digital revolution in urban quantification by integrating Design and Science and provides the necessary framing lens to tackle different challenges in cities in a way that benefit cities, humans, and their future, considering their mutual relationships.

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Introduction

Urban analysis and design have evolved alongside new social, scientific, and cartographic methods to capture the complexities of rapidly growing cities (Habitat 2016; Hein 2017; Seto and Solecki 2015). Cities are widely recognized as complex, interconnected systems characterized by "wicked problems" (Rittel and Webber 1973) and often described as "unknowable" (Marshall 2011), though their complexity is rarely addressed directly (Caldarelli et al., 2023). Urban disciplines have grown increasingly multidisciplinary yet fragmented across socioeconomic, environmental, and design domains (Gleye 2015; Oliveira and Pinho 2010). To meet growing demands for credible, timely, and diverse evidence, researchers advocate leveraging open data, computational power, and Artificial Intelligence (AI) in urban analysis and design (Townsend 2013; Trindade et al., 2017; von Richthofen et al., 2022).

Architecture, Engineering, and Construction (AEC), Urban Design (UD), and City Planning (CP) increasingly integrate data-driven tools. Early computational approaches, such as systems modeling (Forrester 1969; Lowry 1964), mapping (Dangermond and Smith 1988; Robertson 1967), and computer-aided design (Mitchell 1977), laid the groundwork for today's pervasive digital methods to plan cities as-detailed-as-possible. Nevertheless, these often lack human-centered perspectives critical for engaging with urban complexity (Burger et al., 2019; Caldarelli et al., 2023; Quan and Lee 2025; Stead 2021). In urban science, AI facilitates modeling and representation using open data (Engin et al., 2020; Furtado et al., 2024; Luusua and Ylipulli 2020b), while in urban design it supports tasks such as validation and interpreting subjective insights (Helbing et al., 2021; Ibrahim et al., 2020; Luusua and Ylipulli 2020a).

Generative AI (GenAI) is transforming city planning and building design by accelerating concept development and evaluation (Li et al., 2025). However, spatial analysis and design integration remain limited (Batty 2024; Peng et al., 2023; Sanchez et al., 2023). Current AI, including advanced Large Multimodal Models (LMMs), still struggle to provide controllable outputs and reason spatially in informational-rich, complex environments as cities (Choudhury et al., 2024).

Despite urban development relying both on scientific and design approaches, they are rarely integrated. Design, as a speculative and generative practice (Doucet and Cupers 2009), often overlooks insights from urban Science and data analytics. What is needed is a shared framework to learn from and connect both communities of practice. Knowledge Models (KMs) offer this potential through multi-scalar, multi-domain formalization (Pan et al., 2016), supporting incremental, transparent, and generalizable outcomes. Semantics act as integrative "glue" by highlighting interrelations and by enhancing shared understanding, transparency, reproducibility, and interoperability. Semantic Web Technologies (SWT) formally represent built environments and support rich, scalable KMs (Pauwels et al., 2017; von Richthofen et al., 2022). KMs could offer a robust validation layer for critically adopting scientific insights (Marshall et al., 2019).

In this paper, we put forward the idea of an integrated Design+Science paradigm. To be effective, such approaches need to simultaneously consider requirements, goals, and insights of both disciplines. First, we argue that they need to fulfill at least four prerequisites inherited from urban Design and urban Science (Figure 1). Second, we introduce the Semantic Urban Elements (SUEs) method as one example of a Design+Science approach. The core aim of SUEs is to catalyze Design-based and Science-based knowledge to address complex urban issues. We formally introduce Semantic Urban Elements as a dual concept encompassing both a process (the Semantic Urban

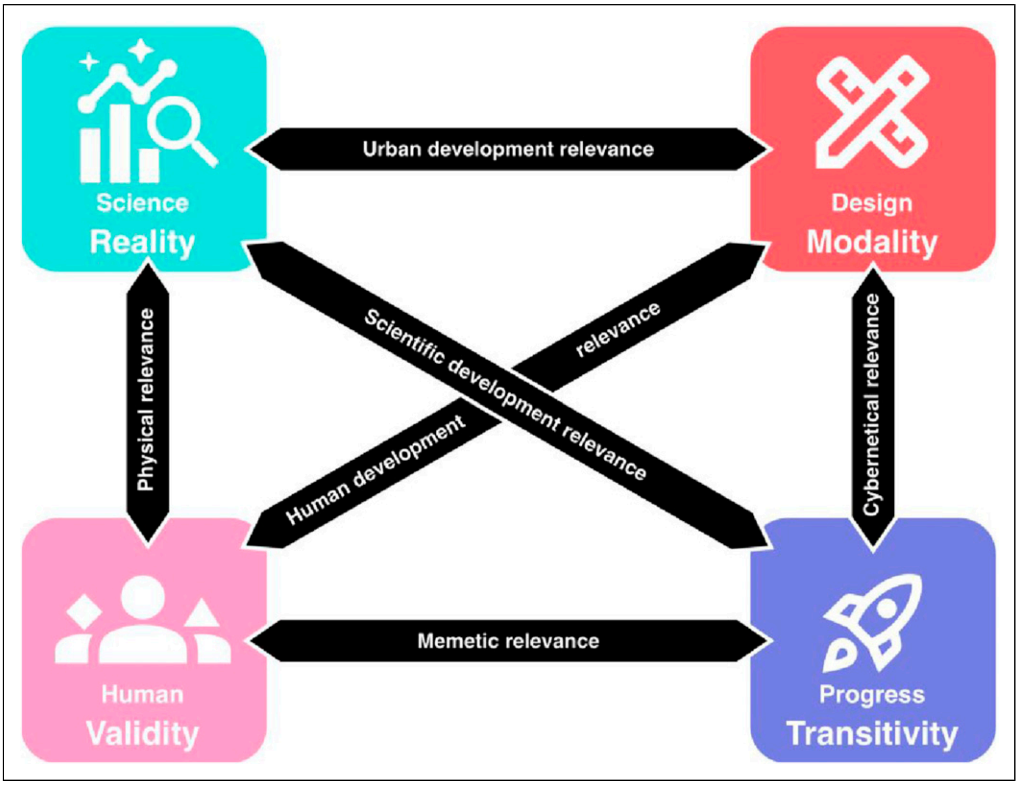

Figure 1. High-level characteristics of an urban Design+Science approach. Design+Science integrates Reality and Modality in urban development, requires Validity for methods verification, and ensures Transitivity to support progress and idea propagation.

Elements (SUEs) method) and its outcome (a Semantic Urban Element (SUE)). Third, to contextualize our proposition, we evaluate existing works through the SUEs lens to exemplify how they could be used. Finally, we conclude this paper by highlighting the opportunities, limitations, and potential impact of our work.

Towards an urban Design+Science paradigm?

This Position Paper argues for an urban Design+Science paradigm that synthesizes scientific and design methodologies to align urban development with tangible built environment outcomes. A synthesis of Design+Science requires one to differentiate the conceptual nature of both parts. Design is commonly defined as a dual nature concept (i.e., an entity referring to both an outcome and the process responsible for that outcome). It simultaneously refers to both goal-addressing artifacts and the processes that create such artifacts (Ralph and Wand 2009); a central goal of Design is hence the achievement of a previously non-existing state of characteristics in a newly created design system. Consequently, Design deals with questions of possibility vs. necessity. Rather than simply describing how thing are, design has the evocative, visionary, and critical aim of changing the way we think about how things work (Doucet and Cupers 2009), that is, speculating about how things could be (Dunne and Raby 2013). Science is also a dual nature concept, but has the discovery of truth as a central goal (Hevner 2021), linking Science to reality. Therefore, urban Design+Science is necessarily a dual nature concept as well, with fundamental requirements related to both Design and Science.

We posit four fundamental requirements for urban Design+Science, illustrated in Figure 1 along with relevant relationships between these requirements. We put forward that one required characteristic of a Design+Science approach for urban development is a seamless integration of representations of (1) Reality and (2) Modality, relevant to the reality of cities and the modalities of development. Here, Modality refers to representations of possible (counterfactual) urban futures, including design alternatives and interventions generated for exploration so that "what-if" options can be iteratively proposed, compared, and refined before implementation. As Science aims to discover truths about reality, an additional requirement is (3) a seamless integration of methods to verify Validity, namely, to ensure both the relevance of knowledge and solutions in relation to the physical Reality of cities and the relevance of envisioned Modalities for human development. As urban development is anthropogenic, in most cases, Validity refers to a human-centric evaluation of validity. In this context, validity does not imply a single correct form. Rather, it refers to replicable evaluation under stated assumptions, together with the traceability of which evidence and constraints justify an assessment, and robustness under plausible scenario variations. That is, the ability to reproduce why a design alternative (Modality) is considered acceptable, or not, in a given context (Validity), instead of claiming a single convergent "true" form (Hevner 2007; Mastop and Faludi 1997; Rittel and Webber 1973; Schön 1983).

In addition, we argue that taking only Reality, Modality, and Validity as cornerstones of urban Design+Science would have insufficient impact in a rapidly urbanizing world; hence we posit the need to explicitly integrate an additional cornerstone: (4) Transitivity. This refers to the need of Design+Science approaches to have characteristics that allow them to easily "go across" easily in terms of the spread of ideas, solutions, and knowledge. In relation to the three other cornerstones, Transitivity can be viewed from three perspectives: scientific development relevance (in relation to significant knowledge gaps in anthropogenic urban development), memetic relevance to human groups (relating to the development and spread of "fitting" ideas and solutions), and cybernetic relevance (relating to the ability to steer and influence aspects of modal, nonreal representations of real complex systems).

The SUEs method does not seek to improve upon the workflows, processes or methods of either Design or Science. Rather, it aims to incrementally and catalytically improve outcomes and impacts of collaborative efforts in city science and urban development, with a human-centric orientation. Designers and scientists remain free to employ whichever production processes are appropriate to their purpose. What the SUEs method stipulates, and seeks to enable, is a framework for scoping, selecting, formulating, adapting, and propagating the inputs and outputs of those production processes in order to augment outcomes and impacts on urban environments.

Nevertheless, a Design+Science approach will require the introduction of couplings between abductive, "designerly" exploration and scientific specification. By means of illustration, in Semantic Urban Element (SUE) this coupling could be operationalized as an iterative back-forward between problem framing and evidence (Reality), the generation of candidate Urban Element as "whatif" hypotheses (Modality), and their evaluation and refinement (Validity). Such a structure is consistent with design-science research cycles, where relevance (context) and rigor (theory) continuously inform an iterative cycle of building and evaluation (Hevner 2007; Hevner et al., 2004), and aligns with empirical accounts of ways of knowing in design and iterative reflection-in-action in professional practice (Cross 1982; Dorst and Cross 2001; Schön 1983), as well as empirical studies of problem-solution co-evolution in design iteration (Dorst and Cross 2001).

Here, design exploration in complex, multi-objective, constraint-rich urban problems (Rittel and Webber 1973) is typically non-exhaustive (i.e., satisficing) rather than aiming for global optimality (Guo et al., 2024; Simon 1969). Progress is achieved through transparent iteration in an evidence-constrained design space encoded in the Semantic Urban Element (SUE) knowledge representation. Finally, this focus on explicit evidence and repeatable evaluation—a coupling central to modeling & simulation—is also consistent with iterative "what-if" planning support workflows and feedback-loop evaluation traditions in planning and the built environment (Klosterman 1997; Preiser et al., 2015).

Introducing semantic urban elements (SUEs)

We put forward Semantic Urban Elements (SUEs) as a particular type of urban Design+Science approach, introducing a paradigm augmenting human-centric cities, which focuses on operationalising actionable solutions. We start by defining SUE as a method and as an outcome, followed by an illustration of a concrete example. Then, we contextualize why SUEs are needed for Design+Science and how it relates to existing work. Finally, we present the potential of the proposed approach.

Defining semantic urban elements (SUEs). The particular SUE and the SUEs method build on the idea of Urban Elements (UEs) and the Urban Element method (von Richthofen et al. 2018). We rephrased UEs to better align with the general idea of urban Design+Science approaches introduced in this Position Paper. The differentiation between SUEs and UEs—literally, Semantics—is SUEs' formal adherence to a Design+Science paradigm, and the use of SWT for the creation and propagation of SUE KMs.

We define UEs as particular families or types of "urban solutions," which are generally recognizable in terms of the material objects and resulting functions they aim to support (e.g., pocket parks, bus stops, cycling lanes, and smart intersections), used by agents (e.g., people, animals, robots, and smart sensors) and integrated in public spaces. They represent systems or sub-systems of urban systems. An UE is a generalized type (e.g., a pocket park), not one particular instance, that can be characterized using an inherent rule-based logic for variables (e.g., vegetation and benches) and operational mechanisms (e.g., factors determining vegetation density or placement of benches in unshaded areas). As a further boundary condition, the implementation of an UE in a particular context should be within the scope of urban design practices.

We define the SUEs method as a Design+Science approach that could produce Science and Design artifacts about UEs, and incrementally store this artefactual knowledge in a semantic KM. SUEs "as a method" is about the scoping and joint (Design+Science) problem statement rather than an algorithmic or modeling method. We define "a SUE" (as an object) as the union of an Urban Element (UE) and its semantic KM; it is an artifact set resulting from the use of an SUE method. The semantic KM includes the different (inter)relationships and flow of information within the system. The latter is illustrated next with a tangible example. These characteristics highlight the novelties of SUEs as a method and as an object: (i) formal scoping of joint Design+Science problems, (ii) solution-focused, and (iii) transitive requirement.

In this paper, the term Knowledge Model (KM) is used broadly to refer to models of knowledge, and more specifically to those employing formal, machine-readable representations. While the particularities of different knowledge modeling approaches will bear relevance when developing systems to support SUEs-based studies, the term is not intended to signal alignment with any single domain or approach.

Illustrating semantic urban elements (SUEs). Figure 2 shows a concrete example of these aims in an illustration of a smart intersection. Here, the smart intersection is an urban solution supporting pedestrian mobility and transportation, that is, an Urban Element (UE in Figure 2). As an SUE, it embeds knowledge of multimodal factors (e.g., number of cars, waiting time, and noise levels) as

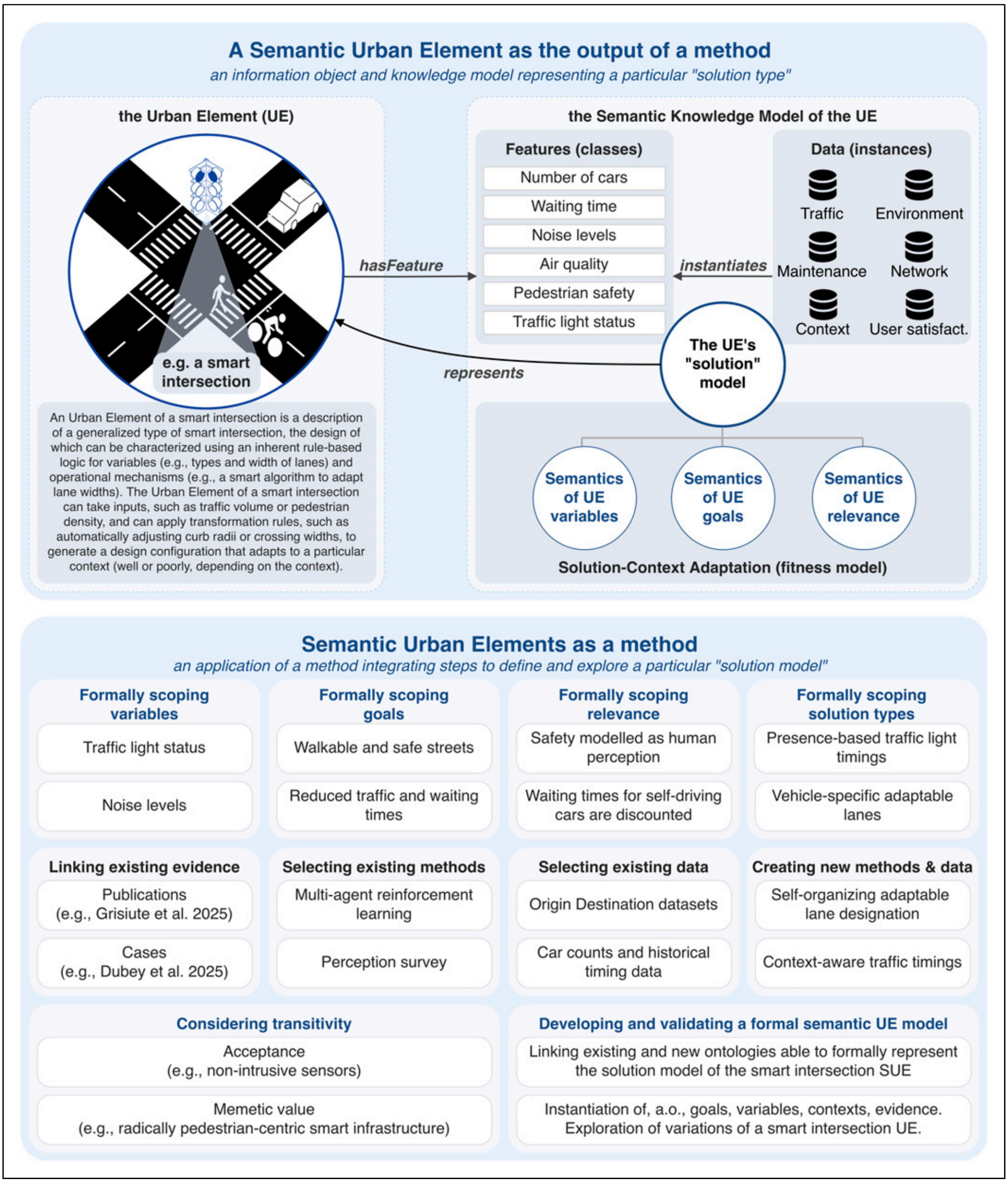

Figure 2. Diagram illustrating the differentiation between SUE as an object (solution type, top) and as a method (solution model, bottom), using a smart intersection as an example urban element (UE). As per the proposed definition, a semantic urban element is a combination of an urban element and its semantic knowledge model (KM). The KM represents the conceptualization and meaning of a modelled UE, capable of handling explorations and evolutions of both design and evidence—in the case of a smart intersection, for example, handling multimodal mobility data streams (Science) alongside movement priorities governed by traffic signals (Design). When considered as a method, applying SUEs involves integrating various steps to define and explore a particular solution model, such as that of a smart intersection. The bottom side of the diagram shows key steps and activities involved in applying the SUEs method, with examples relevant to the smart intersection case. Throughout the figure, the main innovations of SUEs are highlighted in dark blue.

well as the data sources from which these will be instantiated and the relationships and information flow between them. Its representation is portrait by the “solution” model encompassing the semantics of variable, goals, and relevance (Semantic Knowledge Model of the UE in Figure 2). The SUEs method in this instance formalizes the scoping of variables, goals, relevance, and solution sub-types, in a solution-focused manner considering its transitivity (bottom half in Figure 2).

Why semantic urban elements (SUEs) enable Design+Science. The aim of SUEs is threefold: (1) to gain a deeper understanding of a specific type of UE, (2) to improve that UE’s design and implementation, and (3) to manage related knowledge and semantics in a transparent and transitive way. Together, these aims intend to enhance, or correctly assess, the overall functionality and perception of UE solution types across various implementation sites.

Seen as a process, applying the Semantic Urban Elements (SUEs) method implies curating and using a suite of interoperable methods for the representation, evaluation, creation, and knowledge management of SUE artifacts that contribute to Design, Science, or Design+Science. This suite contains methods to find existing and new evidence (e.g., collecting crowd-sourced and on-spot data), methods to predict evidence (e.g., a case-based search engine for retrieving urban space across cities based on user hypotheses of characteristics), and methods to verify hypotheses between specific cases and general conceptual models (e.g., an app sending spot survey requests to human volunteers for on-site validation of AI-generated urban data). It is the composition of this suite of methods that relates to a particular SUE; while the individual methods are agnostic to a particular SUE, and are preferably pre-existing.

The required KM in Design+Science approaches enables SUE methods to develop incrementally, generally, and transparently.

Hence, an SUE requires methods to define, store, and manage knowledge semantically. Systematic implementation would likely require semantic city planning systems (von Richthofen et al., 2022), as it involves incremental knowledge augmentation by interdisciplinary collaborators and requires digital technologies for interoperability at scale. Using semantic web technologies for formal computational representation of meanings, that is, turning the UE into an SUE, increases transparency, reproducibility, and interoperability between Science and Design. Since Science seeks generalizable findings through representative observations while Design pursues case-specific solutions through individual observations, SUE methods should enable bidirectional explorations between general patterns and specific cases. Examples include case-based search engines, empirical data collection for model validation, synthetic datasets, citizen science frameworks, and human perception surveys.

Positioning semantic urban elements (SUEs). The SUEs method is related to approaches in the field of Design Methods that formalize and catalog Design solutions and procedures for implementation into specific contexts, such as most notably Pattern Languages (Alexander 1977). The formal nature of such methods makes them particularly suited for computational approaches—although pattern languages started as an architectural design approach, it had significant impact in computer science, for example, in object-oriented programming (Dawes and Ostwald 2017).

While Alexander’s Pattern Language influenced early computational design, his later work increasingly emphasized morphogenetic, adaptive accounts of design and the generative processes by which living structure unfolds (Alexander 2002). This evolution is consistent with Alexander’s earlier contrast between “self-conscious” and “unselfconscious” processes and the goal of achieving “fit” between form and context (Alexander 1964). Similarly, SUEs, rather than imposing a static classification, aim to provide a formal scoping of joint problems and a semantic infrastructure that makes relevant evidence and constraints explicit and interoperable so that computational workflows could be coupled more directly to context-aware evaluation and iterative refinement.

The original UEs method on which SUEs build was introduced as a pedagogical methodology to facilitate the integration of theoretical concepts, scientific evidence, and applications deriving from urban research into professional urban design practices (von Richthofen et al., 2018), using parametric design methods and specific types of solutions (also called UEs) as facilitators to adapt research results to specific urban design contexts. It was developed specifically for government urban design and planning professionals. One important distinction between the UEs method and Alexandrian pattern languages is that the former does not provide explicit rules and methods to compose such UE into larger functional assemblages across scales (i.e., a language).

The SUEs method shares common ground with computational design methods, especially in representing reality, translating design requirements into machine-readable formats, and enabling automated evaluation that bridges scientific evidence and design outcomes. Computational design methods support urban development by automatically generating, optimizing and recommending design solutions based on predefined variables and models, providing an overview of potential design scenarios and their consequences (Caetano et al., 2020; Cai et al., 2025). However, these methods often rely on geometric simplifications of reality and lack semantic representations, so their approximation of reality is inherently limited (Moosavi 2015). Recent reviews of generative urban design emphasize that many approaches prioritize local geometric optimization while under-specifying problem formulation and contextual integration, leading to inefficient and dysfunctional design solutions (Jiang et al., 2024).

To bridge this gap, SUEs introduce a relation-based, machine-checkable representation of Urban Elements that could be coupled to generative workflows. SUEs combine cross-model semantic integration and machine-checkable constraints. Following Maicher (2007), we use the term semantic handshake to denote an explicit, bottom-up alignment decision that two terms from different vocabularies/ontologies identify the same subject, enabling interoperability across heterogeneous models (Maicher 2007). Building on this integration step, SUEs provide a symbolic constraint layer in which (i) design variables are mapped to ontology classes and (ii) contextual requirements and allowances are represented as explicit relations, enabling rule-based checking and transparent retrieval of boundary conditions.

A concrete example is provided by Singapore's regulatory knowledge graph work, detailed in Subsection "Urban Design Evaluation & Knowledge Representation." In this framework, heterogeneous planning regulations are formalized as explicit allowances and requirements and linked to plots and buildable spaces in a knowledge graph. As summarized there, plot-level boundary conditions such as Gross Floor Area (GFA) estimates at LoD1 are computed from formalized planning rules and instantiated in a dynamic geospatial knowledge graph for querying and reuse (Chadzynski et al., 2023a; Grisiute et al., 2023, 2025).

Moreover, without semantics, individual computational tools typically operate in isolation and lack interoperability, an issue the SUEs method explicitly aims to address.

Within urban science, urban sensing refers to methods and techniques to collect information about built environments and human activities in cities, forming a major pillar of urban analytics (Gao et al., 2023). Geographical Artificial Intelligence (GeoAI) developments enable multiple approaches that tackle urban challenges, using publicly available and human-generated data for smart city solutions. However, these science-first approaches often fall short or overestimate their usability and applications by designers and urban planners (Quintana et al., 2025). Digital twins, defined as (near) real-time representations and replicas of real-world systems, are frequently praised for predictive and management capabilities that would allow one to improve existing and future cities' operations (Abdelrahman et al., 2025; Ketzler et al., 2020). However, they are constrained by interoperability challenges, complex human-system interactions, and limitations of optimization approaches (Caldarelli et al., 2023). Moreover, there is no clear consensus on their definition, and the integration of technical components, such as AI, real-time capabilities, and bi-directional data flows, is yet to mature (Abdelrahman et al., 2025). These limitations reflect the intrinsic complexity of cities that cannot be addressed with Urban Science and the mere cumulation of more data alone (Caldarelli et al., 2023).

As urban planning is a dialogue between actors with often conflicting needs and interests, cities should be considered as out-of-equilibrium systems (Caldarelli et al., 2023). Hence, a complex dynamical systems approach is needed that balances the technological requirements, design and human needs, and complex relationships between (sub)systems.

In such complex dynamic, socio-technical systems, the (inter)relations and interactions between humans, machines, and across different domains with diverse requirements and components open up an interoperability challenge, making formal computational design methods essential. Negroponte (1976) proposed four phases in human-computer collaboration: (i) machines performing exhaustive solution searches beyond human capability, (ii) optimal task division between humans and machines, (iii) integrating human-specific contributions, that is, knowledge, into machines, and (iv) fully automated, task-specific machines. Design Methods such as Pattern Language and UEs fall into the third phase of this development. The SUEs methods build upon and extend the third phase by integrating knowledge into machines and also enabling human participation and validation of the outcomes.

The SUEs methods will naturally rely on interoperable KMs of various types: representational KMs (datasets, built environment models, simulation models) to represent the environment; projective KMs (rules for built-form generation) to represent adaptation options; evaluative KMs (performance and goal models) to represent fit; and synthesis KMs to enrich and link across KMs (Validity/relevance verification models, cross-domain retrieval models, incremental learning models, and top-level ontologies ensuring long-term interoperability).

As SUEs rely on such formal KMs and the symbolic AI technologies that support them, implementations of the method will necessarily rely on hybrid AI technologies. Symbolic AI, a cornerstone of hybrid AI, relies on formal knowledge representation. This involves a shared vocabulary with necessary concepts and their relationships using the Resource Description Framework (RDF), formally defined ontologies and developed Knowledge Graphs (KGs) for a wide range of applications using the Web Ontology Language (OWL), and the ability to query and retrieve data across distributed systems and databases using, for example, the SPARQL Protocol and RDF Query Language (von Richthofen et al., 2022).

We argue that, for a strongly human-centric field like Urban Design, automated and generated outcomes need to be explainable and transparent. While there is a low barrier for creating automated evaluation workflows using GenAI, for example, LMMs, these models often exhibit limitations, such as “hallucinations” facts or failing to capture complex domain-specific logic. Especially in fields that rely on the creation of modal states (i.e., newly imagined futures) and the regulation of human environments, AI methods require KMs and intelligence that goes beyond what already exists, in a way that captures human goals and regulations.

For example, an exploration of GPT-4’s ability to audit urban design quality demonstrated that using more formalized knowledge in prompts makes automated screenings more consistent and repeatable (Cai et al., 2025). However, GPT-4 failed to correctly answer questions about Singapore’s land use planning regulations (Ching and Chua 2023); questions a KG-based search engine (Grisiute et al., 2025) can answer. Moreover, human-labeled data can support the development of more interpretable, reliable, and verifiable LMMs (Quintana et al., 2025; Sun et al., 2024). Further research is needed to fully understand the extent to which hybrid AI approaches can be effectively implemented (Yang et al., 2024).

Even though the digital revolution fuels an increasing “automation of society,” there is a necessity to support all members of society to co-create their urban neighborhoods and their entangled futures (Helbing et al., 2021). Accordingly, bottom-up modeling approaches can enhance urban analysis and collaborative design methods by bridging general scientific findings and specific individual observations to inform the design of human-centered UE. Spatial, legal, environmental, social, and cultural constraints could be easily considered across the space of design possibilities, also in a participatory way.

The SUEs method integrates bottom-up modeling approaches to emphasize human-centricity from three perspectives: human perception, preference, and participation. First, it looks at anonymized individual experiences and aggregates them considering context-aware factors such as the distribution of people's location or demographic statistics. Second, it develops a systematic workflow to integrate evidence into design strategies, improving urban design interventions by considering preferences based on user archetypes and their abilities. Third, SUEs enhance participation as it includes a richer, more diverse, and nuanced description of urban life (e.g., citizens can share their subjective experience, such as postwalk satisfaction or enjoyment in given locations), which is closer and more relevant to people's preferences and priorities, and might, therefore, be beneficial to consider. Together with the three perspectives, SUEs advance the development of human-centric cities that are more inclusive, adaptive, and reflective of the needs and experiences of their diverse people.

Future cities with semantic urban elements (SUEs). We currently have an opportunity to unlock the full potential of urban planning in the digital age, thus progressing towards a fourth phase of digitization and human-computer collaboration (Negroponte 1976). SUEs has the potential to create new tools for urban analysis, design, and scenario modelling. Analyzing, designing, and operating the dynamic cities of the future require generating and harnessing big open urban data; inferring urban analytics and design knowledge; and responsively adapting these spaces, buildings, and infrastructures based on computational social scientific insights.

In future adaptive cities, the complex interactions between urban features and inhabitants will be operationally significant, rather than purely conceptual. The SUEs method introduces a new paradigm of digitally representing the physical environment as functional connections between people, urban elements, and among these SUEs themselves. This digital representation should enable a seamless collaboration between people and their physical environment that transforms cities from static structures into dynamic and responsive "ecosystems." This approach can help to extend our understanding of cities, particularly of the essential relationships that bind or "glues" urban elements and their users together. SUEs offer a critical strategy to enable this integrated urban cooperation, potentially improving residents' quality of life by reshaping the ways how cities are understood, represented, and function.

SUEs in existing works from three domains

The idea of a Design+Science paradigm, and SUEs as one particular implementation of this idea, formalizes concepts and practices related to city Science and Urban Design and outlines methodological requirements and solution scopes. We believe that this standardization of requirements and characteristics of elements within the built and urban environment has the potential to facilitate the exchange and cross-pollination of ideas and applications.

While the composing elements are already common in city science and urban design practice, fully or in part, a more integrative paradigm underpinned by relevant human-centric goals and potential solutions still requires attention. Hence, in this section we can illustrate the SUEs idea using existing work that, while not necessarily the result of explicit applications of a Design+Science approach or the SUEs method, nevertheless demonstrates key qualities that sets SUEs apart.

We present examples from three domains: urban analytics, design evaluation & knowledge representation, and computational social science. These domains represent the backgrounds of the authors and their particular rendition of the posited SUEs method. Naturally, this particular set of domains and their methods and practices is able to satisfy the core requirements of a Design+-Science approach. However, other sets of domains could also meet these requirements; we therefore encourage readers to consider how their own domains could be seen through the SUEs lens.

Urban analytics. Urban analytics enable bottom-up modeling by applying data-driven methods to map general patterns onto specific cases, especially as urban data increasingly come from users rather than just from sensors; for example, pedestrians, drivers, and cyclists; rather than just sensors.

A key example is the surge in human-generated data sources, such as billions of Street View Imagery (SVI), both from proprietary (e.g., Google Street View and Baidu Maps) and crowd-sourcing platforms (e.g., Mapillary or KartaView). Street-level imagery closely reflects people's individual experiences and, when aggregated, informs decision-making (Lee and Park 2023), closely aligning with the SUE method. These images can be semantically enriched by linking them with geo-spatial data like points of interest or building attributes, aiding architectural evaluation (Liang et al. 2024) and data completion (Lei et al. 2024). Their interoperability under a KM is essential for advancing GeoAI and enabling global, longitudinal analyses of behavior and perception (Quintana et al. 2025).

Urban design evaluation and knowledge representation. Compared to scientific fields, there is a dearth of explicit, formal knowledge of design practices. Design practices traditionally rely on significant amounts of tacit knowledge, among others due to the multiplicity of domains and systems that are catered for, the reliance on decision-making, the modeling of modal built environments and their dispositions, and the variety of implementation contexts. Hence, "good" design solutions are driven more by the absence of misfit than the presence of fit (Alexander 1964). Nevertheless, formal models representing and evaluating urban design knowledge exist and demonstrate how explicit knowledge representations could help to automate and scale design and planning in more transparent, human-centric ways.

While land use planning regulations are necessarily public, related regulatory processes typically rely on tacit and common knowledge. A land use regulation ontology for Singapore demonstrated how Knowledge Models, specifically Semantic Web Technology based on ontologies and Knowledge Graphs, enhance accessibility and usability of land use regulation data, supporting site selection and exploration tasks in urban planning processes (Silvennoinen et al., 2023) when embedded in a KG of the city (Chadzynski et al., 2021). Adding additional regulatory and built-form ontologies enabled an automated semantic policy model determining all allowable gross floor areas per plot (Grisiute et al., 2023). This mechanism operationalizes the constraint-checking part of the SUEs workflow by translating regulatory knowledge into explicit, machine-checkable requirements and allowances. This enables query-based compliance checking and decision support, reducing reliance on tacit manual cross-referencing, while acknowledging the non-trivial digitization of multimodal regulations (Grisiute et al., 2025). In its final form, it can generate a fine-grained 3D land use map for Singapore using these ontologies, with each option and value linked to a particular regulatory document and decision workflow; a search engine enables the retrieval of all plots allowing queried development mixes and densities (Grisiute et al., 2025), thereby enabling the quantification of regulatory effects on energy system performance at the plot scale (Kang et al., 2026).

Formal models of human regulatory systems not only unlock the ability to perform quantitative analyses on human knowledge that has been largely implicit and tacit, they also enable machines to reason in ways that are compatible with human knowledge systems, and to automate at scale. For example, exploratory results for Singapore's land use regulations illustrate how a machine can apply reasoning to a KG to derive planning categorization structures (Chadzynski et al., 2023b). Such formal knowledge models can also support the development of agentic AI solutions for urban design and planning, for example, to dynamically handle key representation and visualization processes that require large-scale data conversions and model updates in digital twins (Chadzynski et al. 2022, 2023a).

Computational social science. Participatory city-making faces the challenge of reconciling diverging needs, interests, and values while generating actionable, inclusive, and feasible urban plans. Addressing risks such as manipulative legitimacy misappropriation requires tools that are both accessible to non-experts and capable of capturing complex urban interrelations and interactions, not just in quantity or location, but in the quality of relationships between elements (Argota Sánchez-Vaquerizo and Zurera Gómez 2023; Carpentras et al. 2024).

SUEs represent an emerging paradigm that supports this challenge. As intelligent, digitally encoded urban objects, SUEs could guide users in real-time—highlighting spatial relationships, design requirements, and socio-ecological considerations. By embedding operationalized, anonymized citizen preferences in databases, they foster richer engagement with urban environments and facilitate informed decision-making across expert and non-expert stakeholders.

SUEs also address key limitations of current AI systems, particularly their underdeveloped spatial reasoning capabilities, which obstruct the collaboration with and among humans. By doing so, they enable a shift from overly simplistic or technocratic or simplistic planning approaches to more context-sensitive and integrated socio-technical urban visions (Argota Sánchez-Vaquerizo 2025).

A compelling application of SUEs in complex socio-technical contexts in cities lies in adaptive street infrastructure. Multi-agent reinforcement learning (MARL) algorithms have enabled street configurations that dynamically adjust to traffic flows and changing spatial needs (Dubey et al., 2024). For instance, connected vehicles (CVs) can adaptively utilize priority lanes, reducing congestion even at low CV adoption rates (Dubey et al., 2025).

These systems exemplify how SUEs could integrate empirical data and semantic modeling to enable intelligent, context-aware behavior (e.g., adjusting signal timings, lane configurations, or pedestrian amenities in real-time). This aligns with the four foundational SUE premises:

- Reality & Modality: Integrating real-world traffic and environmental data with simulated scenarios to enhance understanding.
- Transitivity & Validity: Creating reproducible protocols that formalize how spatial configurations relate to urban dynamics and allow consistent updates.

SUEs could thus transform traditional infrastructure into responsive, human-centric systems. Their continuous learning and adaptability support long-term planning and design feedback loops. Outputs such as optimal crosswalk timings or sidewalk widths can be formalized into design guidelines or policies, ensuring that knowledge is suitably reused across urban governance processes. In sum, SUEs offer a paradigm shift in favor of inclusive, intelligent, and adaptive urban design, bridging the expert–non-expert divide and enabling socio-technical co-creation in contemporary city-making.

Conclusion

Ultimately, with modeling technologies and methods increasingly penetrating the urban environment, the need will grow not only for standardization and comparability across contexts, but also for design methodologies that can respond to evidence, constraints, and feedback in transparent and reproducible ways. Accordingly, we position Semantic Urban Elements (SUEs) not as an abstract schema for classification, but as an enabling scaffolding that supports more evidence-based and responsive design practice. By making relevant constraints, evaluative knowledge, and multi-domain evidence explicit, interoperable, and machine-checkable, SUEs enable design exploration to be coupled to systematic checking and iteration while retaining human judgment and accountability. SUEs provide a method to represent and generate systems of the complex urban environment as Urban Elements with explicit relations, enabling hybrid human-machine workflows. This positioning resonates with Alexander's concern that design must achieve "fit" in complex, evolving contexts beyond purely formal procedures. To address the operational challenge of integrating Design and Science in such contexts, we articulated four prerequisites for an urban Design+Science approach and illustrated how the SUEs lens satisfies these criteria and extends existing work across Urban Analytics, Design Evaluation and Knowledge Representation, and Computational Social Science, supporting more responsive and human-centric urban systems.

Reflection

SUEs aim to operationalize the analysis of the built environment by considering the integration of multimodal data, different domain knowledge, and semantic relationships between urban (sub) systems and humans. The method attempts to make key components, relationships, and affordances of the city machine-readable, thereby allowing for hybrid intelligence between computers and humans.

Even though powerful, however, this concept still has limitations. First, in terms of scope, the SUEs method is neither exhaustive nor global; we pose it as an example of a Design+Science approach but it is not likely to be the only one nor does it cover every aspect of Urban Design and Science. It is even unclear whether the current Semantic Web standards, based on predicates, is powerful enough to cover every possible relevant domain or whether all relevant relationships (e.g., trust, reputation, and culture) can be explained within that framework (Carpo 2023). Moreover, SUEs aim to augment urban design knowledge and support human-in-the-loop workflows, not to fully automate design and deliver operational or deployment-ready infrastructure. Rather, we call for a more participatory design and co-creation approach in the future.

SUEs also does not provide native compatibility with existing design tools (e.g., BIM/GIS standards); rather, it supports semantic linking. Although SUEs are not digital twins themselves, it is a promising method to make digital twins of buildings and cities more meaningful by considering significant interactions between other urban solutions and human-centric applications, while being mindful of its limitations (Helbing and Argota Sánchez-Vaquerizo 2023).

As more data, better data, and new types of data are becoming available in cities, the analysis, planning, and design of cities improves (United Nations Development Group 2013). For instance, existing indicators for the level of achievement of the Sustainable Development Goals (SDG), as monitored by national, sub-national, and particularly local reviews, indicate a lack of interoperability standards and the challenge of describing the functioning of cities in interaction with their inhabitants better and more dynamically (Saner et al., 2020). This lack of standardization is where the potential impact of our proposition becomes most visible. SUEs as a novel representation framework that supports new data generation can help one to provide more grounded information about urban solutions for urban environments, connected to people's lives and needs.

Simultaneously, SUEs move the focus from data as a commodity to a framework able to reflect relevant aspects of life in cities and gather data aligned with paradigms of human development and capability approach paradigms (Sen 2012). SUEs aim to achieve this by relying on a knowledge model, representing the multi-domain data flows and the relationships with the urban solution at hand. We note, however, that data-driven approaches need to be developed and handled with care, as biased or incomplete datasets can lead to unfair or inefficient decisions. Additionally, over-reliance on algorithmic outcomes without transparency or stakeholder input may undermine public trust and equity. Like any technological advancement, successfully implementing SUEs requires a responsible innovation approach, building capacity across all levels of governance and decision-making. This includes a proper training and education of technicians, policymakers, and citizens, as well as capacity building within researchers to fully leverage this new paradigm.

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