Science of the Total Environment 956 (2024) 177269

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

A conceptual data model for IMM: A methodological interpretation of targets and indicators in SDG11

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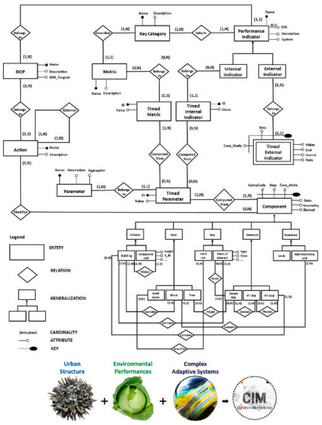
HIGHLIGHTS

- Sustainable Development Goals are tied to the performance of the built environment.
- Built environment is a complex system that is impossible to predict fully.
- There are complex links between urban structural and performance parameters.
- A reliable database design is needed to study this network of relationships.
- An Entity-Relationship model is the first step toward the database design.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Jacopo Bacenetti

Keywords:
Sustainable development goals (SDGs)
Entity relationship model (ERM)
Systems thinking, Urban Design
Morphological structure
Environmental performance

ABSTRACT

We are rapidly approaching the midpoint of the period set by the UN Agenda 2030 for transforming our activities on the planet Earth. Yet, many of the global issues we have begun with stand still while some of them took a much more severe course. The Sustainable Development Goals (SDGs) are unambiguous. What is unclear is the way to propel our socio-economic organizations into the desired performances. Regarding performance control, the built environment is arguably the most critical system. Every year, we add more urbanized land to the face of the planet without clearly envisioning its environmental effects and social outgrowth. As a result, we frequently find ourselves struggling with unpleasant consequences and unpredicted side effects. In our body of knowledge, there is a missing link between urban structure and performance. This paper offers a systemic breakdown of urban structural parameters and a coherent reading of its performance indicators intending to create a City Information Modelling (CIM) tool. The objective is to formulate the reciprocal relationship between the components of the built environment (as the designer's toolbox) and the system's outcome. To do so, this article moves from the Integrated Modification Methodology (IMM), exploring it through the lens of an Entity-

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https://doi.org/10.1016/j.scitotenv.2024.177269
Received 14 December 2023; Received in revised form 13 July 2024; Accepted 26 October 2024

Relationship (ER) schema, delving into its systemic approach to model the built environment as a Complex Adaptive System (CAS). IMM elucidates the intricate structure/performance relationships inherent in the complexity of the built environment. Building upon the successful IMM application in numerous urban transformation projects and retrofitting procedures, our focus is now on streamlining operational processes and accelerating workflow efficiency. Specifically, we seek to optimize the rapid assessment of correlations between structural changes and performance outcomes within the IMM framework. This work aims to operationalize the Agenda 2030, enabling a practical methodological interpretation of targets and indicators in SDG11.

1. Introduction

At the midpoint of the fifteen-year timeframe delineated by Agenda 2030, there is still ambiguity among the scientific community regarding the efficacy of current global endeavors aimed at securing a sustainable future (Moyer and Hedden, 2020).

For several reasons, the built environment seems to be the most appropriate context for studying the roots of this adversity. Environmental issues are strongly related to the urbanization rate. With only 3 % of the earth's coverage, cities are the chief cause of global warming and the deterioration of nature (Watts, 2010; Miller and Small, 2003; Mcdonald et al., 2008). Urban areas devour 80 % of the world's primary energy and emit up to 60 % of greenhouse gases (UN Habitat, 2008). The most polluting industries are either in the cities or directly serving them. In 2022, built-up lands covered up to 4.3 million square kilometers of the earth's surface. The constructed land increased globally by 50 % in only 20 years (Fig. 1). Asia and Africa saw 68 % and 73 % of built-up land expansions (Potapov et al., 2022).

The built environment is, moreover, the stage of severe socio-economic conflicts. Today, one billion people live in slum conditions worldwide, and by 2050 the world expects to see at least 70 % of its urban population in informal settlements (Arcidiacono et al., 2017).

Recent years witnessed a substantial proliferation of technological interventions in various urban domains like smart city technologies and urban data management driven by the objective of improving overall performance (Woods, 2020; Jin et al., 2019; Lombardi et al., 2012). The real issue, nevertheless, is less instrumental and more attitudinal (Mohammad Zadeh, 2020). The construction sector annually allocates approximately 10 trillion dollars toward construction projects (Nesticò and Moffa, 2018). Paradoxically, in many instances, the sector inadvertently exacerbates urban complexities by misattributing effects as root causes.

The built environment is a Complex Adaptive System (CAS) (Manesh and Tadi, 2011). In a CAS, non-linearity rules the systemic relationships, and every part is related to any other component (Holling, 2001; Vahabzadeh Manesh and Tadi, 2013). The actions in a CAS are often simultaneous. Therefore, its functioning mechanism is unlike simple systems where one can untangle the process in basic hierarchical steps. In the practical sense, the city is more akin to natural organisms rather than a man-designed system (Bettencourt et al., 2004). Complex systems involve synthetic reactions and simultaneous mechanisms (Holland, 2006; Hayenga, 2015; Miller and Page, 2009). Our understanding of them is always limited. Therefore, we cannot fully predict the full scope of their behavior.

Classical engineering is controlling performance by modifying the structure. In the complex system, however, it might produce unwanted consequences: many environmental issues are the side effects of structural modifications on the built environment through development projects (Mi et al., 2019). These repercussions are particularly conspicuous in regions undergoing heightened and rapid urbanization. Research indicates that the substantial urbanization rate observed in China since the late 1970s, with a 33 % increase from 1978 to 2011 (Yang et al., 2014), correlates directly with elevated levels of air and water pollution (Bayraktar et al., 2010), heightened energy demand (Davies et al., 2008), significant depletion of natural vegetation (Pei et al., 2013), reduced carbon storage (Churkina et al., 2010), the emergence of urban heat islands (Chen et al., 2014), and other adverse trends in local climate dynamics (National Bureau of Statistics of China, 2012; Oke, 1982). Analogously, similar effects are observable in Middle Eastern cities experiencing intensified urbanization. For instance, Beirut, recognized as one of the most rapidly urbanizing areas in the Middle East, exhibits notably low albedo values compared to other parts of the country (Kaloustian and Diab, 2015).

To break this vicious circle, we must accept the following:

1. The built environment is a complex system. We should stop considering it a simple man-designed fabrication subjected to classical engineering.

2. Our systemic understanding of the cities needs to be revised. We should change the paradigm and adopt a systems-thinking approach to study the relationships between structure and behavior in urban systems (Martin et al., 2005; Weisz, 2018).

The present paper aims to address both statements scientifically. It presents the Integrated Modification Methodology (IMM), a systemic process for modelling the built environment as a CAS. It breaks down the fundamental elements and interconnections within the IMM's procedures into an Entity-Relationship (ER) schema where the urban structure links to performance through some formerly neglected role players.

2. Theoretical background

Commencing from the Twentieth Century onward, urbanization underwent a transformative evolution. This shift was propelled by the convergence of advanced technologies and novel ideological paradigms, facilitating the accelerated expansion of urban centers. Furthermore, many planned cities have emerged from the ground up in studios (Jeffrey, 1990; Clark, 2014; Roberts, 2015). Hereafter, the designer

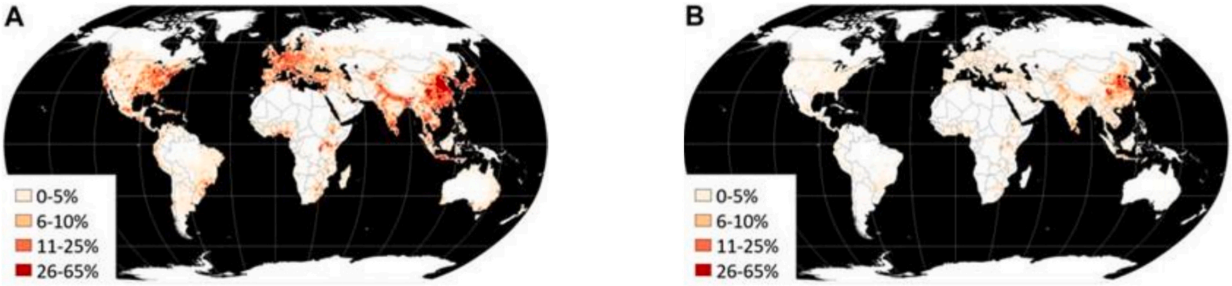

Fig. 1. A comparison between built-up lands in 2020 (A) and in 2000 (B) Source: Potapov et al. (2022).

faced an unprecedented task: to create a permanent habitation for numerous generations on the verge of frequent and unpredictable changes. Based on specific standards, needs, and ideologies, the designer had to define targets, design structures, and deliver performances (Peponis, 1989).

Historically, it is safe to say local governments and international organizations failed in this task. Although targets are often unambiguous, and the blueprints are promising, the desired performance is out of reach in the realized version.

Many times, the actual result is the exact opposite of the targets. The modern Utopian movements, like the Garden Cities, appeared at the beginning of the twentieth century to ensure self-sufficiency and social friendliness (Słodczyk, 2016; Friedmann, 2020; Howard, 2013; Hügel, 2017; Ward, 2005). They have turned out to be dilapidated suburbs in practice. Today, it seems that not much has changed. More than one hundred years after modernism, ambitious projects like Masdar City with sustainable promises have become extravagant no-man-lands (Crot, 2013). Numerous theories, methodologies, and exercises have risen to link goals and performance and have fallen empty-handed. New Urbanism produced the same suburban environment it intended to defy (Ellis, 2002; Marshall, 1999). Smart Growth has intensified the problems it aimed to solve in its intervention areas (Cox, 2002). All the failed practices have one faulty trait in common: they are component-based. However, the components are rarely the main issue, and the problem is attitudinal. The built environment is a complex system, yet urban design keeps neglecting its complexity. Designers try to control the result directly by modifying the components, knowing too little about the actual functioning manners in cities. Academia, too, needed to produce more science to affect the course of development in the built environment. Most studies ignore the systemic totality and pursue efficiency in individual parts or subsystems (Mohammad, 2020). The predicament is that they usually focus on singled-out mechanisms on divided scales (e.g., improving building material or upgrading traffic models) rather than considering the city as a simultaneous whole.

Significant progress has been made in enhancing building performance during both the construction and operational phases. Concurrently, urban transportation technologies have evolved comprehensively, continually fostering cleaner and more efficient transportation networks. Nevertheless, it would be premature to assert that these advancements in construction and transportation have led to the comprehensive resolution of social, economic, and environmental challenges associated with urban areas. The dynamic nature of urban environments entails those alterations, whether improvements or hindrances exert a profound influence on the overall urban structure.

In light of the multifaceted character of urban systems, it is prudent to advocate for an approach wherein the capacity and quality of the urban structure serve as the force for systemic modifications, rather than a scenario where the elements merely react to external changes. This orientation acknowledges the imperative of establishing a harmonious and coherent integration between the urban structure and its constituent elements, given the intricate interdependencies within urban systems.

Therefore, it is fundamental to change the paradigm and adopt a holistic approach. However, studying the built environment from a holistic standpoint is challenging. Countless parameters and role players concurrently govern the functioning of urban systems. Within and in between the buildings and other spatial entities, continuous and multidirectional dynamic processes are happening, and each mechanism is linked to any other in a contorted fashion (Schuster, 2005; Manesh and Tadi, 2012).

A full comprehension of complex systems is non-trivial (Bassett and Gazzaniga, 2011), but they can be modelled (Batty et al., 1999; Ellam et al., 2018; Batty and Longley, 1986). There have been numerous attempts to model complex biological, social, economic, and even urban systems with different scientific approaches and expectations (Bretagnolle et al., 2006; The Dynamics of Complex Urban Systems, 2008; Walloth et al., 2016). Each model is inevitably simpler than the modelled phenomenon: the model does not represent the actual functioning, and it cannot deliver direct and accurate readings of the performing parameters. However, from the system's perspective, one should not oversimplify the main elements and relationships that signify the complexity of that system (Holling, 2001). The role of the model, thus, is to portray the chief structural characteristics that influence performance.

Consequently, there is always a missing link between the modelled structure and the actual behavior. This missing link in the complex systems causes much uncertainty about the performance. The model, hence, should methodically include as many structural parameters as possible to reduce ambiguity (Schuster, 2005; Ellam et al., 2018; Rouse, 2015). More importantly, it should offer reliable processes for reading the outcomes based on structural parameters. These characteristics add room for design retrofitting, and they also progressively uncover much about the missing structure/performance link.

The number of persuasive attempts at holistic modelling and studying the structure/performance relationship leading to feasible applications is unsatisfactory. One can only find relative practices under the umbrella of Smart Cities (Zygiaris, 2013). In Smart Cities, technology provides the decision-makers with potentially valuable data. However, data is not enough by itself: data is only a tool, not a methodology, i.e., a knowledge-based procedure that sets goals and uses tools to achieve results. Without a robust outlook, it is more plausible to get lost in the magnificence and abundance of data. Smart Cities usually have clear-cut objectives and expectations: they, however, set different prime goals and naturally get different results.

From the urban design perspective, it is critical to unveil the complex mechanisms caused by the urban system and read the behavior accordingly. Since the indicators express the urban performance numerically, the model should also identify the structural role players and articulate them as numerical values.

Within the realm of urban design, numerous scholars have endeavored to unravel the intricate mechanisms governing urban systems, subsequently elucidating urban behavior through a systematic lens. Some studies have adeptly harnessed quantitative methodologies and metrics to examine, assess, and enhance the domain of urban studies (Bettencourt et al., 2004; Walloth et al., 2016; Batty, 2013). The escalating rate of urbanization intensifies the demand for methodological frameworks that possess the capability to integrate theoretical insights with pragmatic design practices. This need is driven by the imperative to effectively navigate and respond to intricate and evolving challenges posed by urban environments.

The goal of a competent methodology would be to unveil the complexity of urban systems by extracting the major structural parameters and performance indicators. The expected result is to find relationships between the two with a toolbox of data and computer algorithms.

2.1. Integrated modification methodology

The Integrated Modification Methodology (IMM) is an appropriate base for building such a model. With a systems-thinking approach, IMM models the complex nature of the city into several dimensions called Key Categories (KC). Each Key Category indicates an influential functioning mechanism of the built environment and is represented by a combination of maps and numerical metrics. Furthermore, the methodology includes an extensive list of performance indicators extracted from the literature. As IMM is a design methodology, it offers tools for evaluation and modification both for the given context and design scenarios (Tadi et al., 2020).

In this regard, IMM is principally oriented toward the evaluation and enhancement of urban environments and the associated urban design processes. IMM contributes to the domain of urban design by offering a methodical and comprehensive framework that indirectly enriches the capacity for predicting and comprehending urban behavior through the following mechanisms:

1. Holistic Perspective on Urban Environments: IMM promotes a holistic vantage point, taking into account a spectrum of variables that shape urban dynamics. This approach encompasses a broader spectrum of influences, enhancing our comprehension of urban behavior.
2. Iterative Design Scenario Testing: The iterative nature of IMM affords the opportunity to rigorously assess various design scenarios. This iterative process allows for the exploration of multiple design alternatives, enhancing the decision-making process in urban design.
3. Support for Evidence-Based Decision-Making: IMM serves as a foundation for evidence-based decision-making in the realm of urban design. By emphasizing the integration of empirical data into the decision-making process, IMM enhances the likelihood that design choices will be firmly rooted in empirical evidence and data-driven insights.

Presently, IMM employs performance indicators to assess the existing contextual conditions. This evaluation comes alongside the KCs and paints an overall picture of the structure/performance relationship. Although such a relational scheme is unprecedented, it is still not direct. Hence, it is up to the designer to interpret it. To minimize the risks, IMM offers a retrofitting phase in which the design scenarios undergo an evaluation, too (Biraghi et al., 2022). The structural metrics are naturally available as the designer redefined them. However, one can only estimate the indicators in a hypothetical situation.

The procedure of modification through IMM is based on four integrated phases (Fig. 2).

1. Investigation.
2. Formulation.
3. Modification.
4. Optimization.

Based on its systemic properties, the actual urban form is studied through the Key Categories in the first phase. In the same step, the performance indicators of the actual state gathered and their relevance to the KCs are analyzed. This phase is called the diagnosis. In the next phase, the meta-project, the systemic problem is identified. This problem is expressed through the KCs in which the malfunctioning of the urban system is rooted. They are called the Catalysts of transformation. Accordingly, Design Ordering Principles (DOPs) devise the modification strategy. The DOPs are a set of design guidelines curated from the literature that are in accordance with the principles of sustainability. By ordering them based on the local necessities and design goals the modification strategy will be formed. The mentioned strategy translates into the design proposals (usually in the form of a master plan). This happens with the designer interpreting the Actions emerging as the result of the previous steps. The design state is a new system structure that could go through the same phasing system up to the third phase. This iteration is stopped by arriving at a best-performing design proposal. Then, by optimizing the local elements (buildings, management systems, etc.) in the final phase, the structure of the system is to a new urban form.

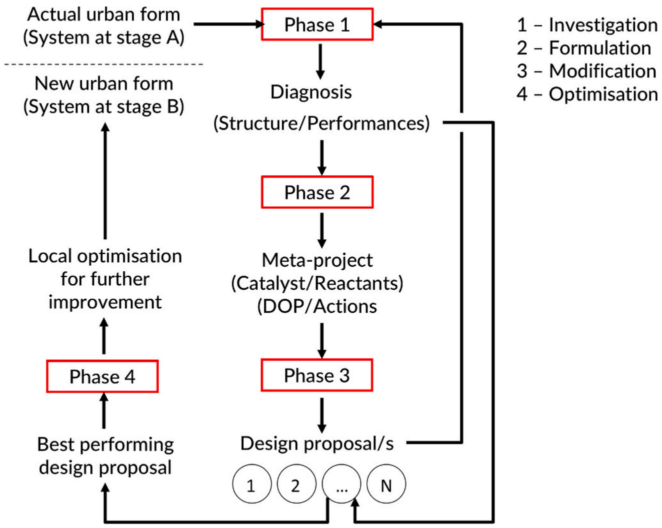

Fig. 2. Phasing process of the Integrated Modification Methodology.

IMM is not merely a conceptual framework awaiting validation. On the contrary, it has already undergone extensive testing and validation through its application in diverse urban settings. IMM has been successfully implemented in cities such as, Milan, Dakar, Quelimane and Rio de Janeiro, among others (Biraghi et al., 2022; Biraghi et al., 2023; Tesfaye et al., 2024; Biraghi et al., 2024), sometimes including training activities for local technicians about it. These real-world projects serve as concrete examples of IMM's viability and efficacy in addressing complex urban challenges, making it a valuable tool for urban planners, policymakers, and researchers.

For the optimal execution of this procedure, automated algorithms should be employed to conduct numerical analyses impartially. The results of these analyses should then be presented to the designer as a tool that facilitates decision-making in the context of design and subsequent modifications.

At this stage, the challenge is to enhance the operational aspects of IMM, optimizing workflow efficiency by leveraging ICT and digitalization to automate processes and streamline decision-making. The IMM conceptual model needs now to be translated into a practical, operational framework and the development of an Entity-Relationship (ER) schema serves as a crucial step in this process, facilitating a more systematic and efficient approach to urban transformation.

In particular, the main IMM limit lies in its inability to effectively compare numerous potential design scenarios based on their individual performance, as assessed through a comprehensive set of interrelated performance indicators. IMM's existing process lacks the capability to seamlessly evaluate the performance of various design alternatives in real-time, hindering the identification of the optimal scenario. This limitation stems from the methodology's reliance on a static evaluation approach, which assesses each design scenario separately. As a result, we are unable to make informed choices based on real-time feedback and are often constrained by the constraints of traditional planning and design processes. To address this challenge, IMM needs to evolve into a more dynamic and iterative framework that enables continuous feedback loops and adaptive decision-making, prioritizing the most effective design solutions that align with sustainability goals.

Anticipating urban behavior poses inherent challenges and uncertainties owing to the convoluted mechanisms underpinning urban systems. Urban systems encompass a multitude of interdependent factors, such as land use, transportation, demographics, economics, and social dynamics, which collectively engender the complexity of the urban environment. As a result, the task of generating precise predictions is extremely difficult. Nonetheless, researchers and urban planners employ diverse models and theoretical frameworks to facilitate informed predictions pertaining to urban behavior.

Given the objective of attaining an optimized design scenario, it is paramount to meticulously estimate the performance of the altered state with a high degree of precision. Thus, the model needs to employ a reliable prediction mechanism. Such a mechanism could be translated into reliable prediction tools based on a data-driven digital twin of the urban system.

This mechanism does not exist yet. To build it, one must study the logical links between the measurable entities within the model. Uncovering the entire network of relationships in a complex system is impossible. But one can investigate the representatives of this network in a model. Computer algorithms and data come into play only after realizing IMM's ER schema.

2.2. Methodological interpretation within the framework of agenda 2030

The above-mentioned attempt would also be a decisive contribution to Agenda 2030. The SDGs deal with complex systems too. Targets and desired performance are the basis of the goals, and there is a missing link between the two. The realization of what this paper pursues can become the initial steps toward a methodological outlook with the ability to link targets to the indicators.

Uncovering the systemic relationships between Goals in Agenda 2030 has become one of the most trending research topics in recent years (Koch and Krellenberg, 2018; Roy et al., 2021; Pizzi et al., 2020). The United Nations' Agenda 2030 (Transforming Our World, 2018) focuses on 17 general goals named Sustainable Development Goals. The SDGs cover the three pillars of sustainability (economic viability, environmental protection, and social equity) in individual categories. Each goal comprises several targets linked with measuring indicators. Scholars agree that implementing the SDGs involves numerous operational issues (Gusmão Caiado et al., 2018). Moreover, the structure of Agenda 2030, especially the current arraignment of the indicators, makes it prone to become the base of reductionist interpretations (Mair et al., 2018).

Ten targets and 15 indicators set up SDG 11 in cities. They embody almost a complete range of urban issues of the present day: slums, housing quality, accessibility to transportation and services, natural heritage, air pollution, urbanization, and much more. Targets and indicators are crystal clear and well linked to each other at the conceptual level.

Practically, however, the targets are much more complicated to hit. According to the most recent SDG report issued by the UN, the preeminent problems that Agenda 2030 targeted at the beginning are still there. Six years after the briefing of the SDGs, one billion people live in slums worldwide, and 99 % of the world's urban dwellers breathe in polluted air (World Health Organization, 2015). The overall situation in critical regions like South and Central Asia and Sub-Saharan Africa is immensely worrisome. Cities are growing, and with them, the problems of waste management, accessibility, and social equity grow.

The divergence of cities from Sustainable Development Goals (SDGs) can be proved with specific examples demonstrating the global severity of this issue. SDG 11, which aims to make cities inclusive, safe, resilient, and sustainable, highlights various indicators where many urban areas fall short. For instance, cities like Delhi, Dhaka, and Milan consistently exhibit high levels of air pollution, exceeding the WHO's recommended PM2.5 limits. Mumbai and Manila struggle with inadequate waste management, significantly impacting the environment and public health. Additionally, Kolkata, Mumbai, and Lagos have substantial portions of their populations living in slums.

Accessibility to public transport is another critical area where many cities fail to meet SDG 11 standards. Only 15 % of urban residents in low-income countries have convenient access to public transport, with Bangkok and Mexico City serving as notable examples of this shortfall. Limited public spaces in cities such as Cairo and Jakarta further hinder residents' quality of life. Moreover, the critical need for effective disaster risk reduction strategies is underscored by the vulnerabilities observed in New Orleans and Venice (https://ec.europa.eu/eurostat/web/products-eurostat-news/w/edn-20231009-1, 2024; United Nations Human Settlements Programme (UN-Habitat), 2020; https://unstats.un.org/sdgs/metadata/, 2024).

These examples are not isolated incidents but represent a broader trend affecting cities globally. Data indicates that approximately 60 % of cities are not on track to achieve SDG 11 (Our World in Data team, 2023), highlighting the widespread and urgent nature of these sustainability challenges.

All this happens in a period in which the built environment development is skyrocketing. The global size of the construction market in 2021 increased by almost one trillion dollars from 2020 (from 6.4 to 7.3 trillion dollars). According to some estimates, it will grow to 14.4 trillion dollars by the end of the UN Agenda deadline in 2030 (Next Move Strategy Consulting, 2022).

These figures clearly illustrate that the execution of Goal 11 is fundamentally feeble and ineffective. Some of the other decisive SDGs see a similar trend. As all SDGs are naturally connected, these directions are threatening red flags warning us about the route we are taking to sustainability.

This situation accentuates the necessity of a comprehensive predictive model for modifying complex systems. However, the problem is not solely methodological. It lies deep in economic and political systems too. Thus, the world needs a sophisticated multidirectional pursuit of resolution.

The present study suggests an advanced reading of the urban systems and the intrinsic structural parameters that might influence the performing patterns. Hence, it could eventually develop into an execution blueprint for SDG 11. The same logic could lead to an integrative model for all SDGs which would be able to link them both in evaluation and modification. Considering the relevance and necessity of such inquiries for approaching sustainability, the present study underscores the requirement for a methodological integration encompassing the various facets of SDGs. By illustrating the structural elements and the parameters of performance within the totality of an integrated system model, this paper can add to resolving the internal and external link between goals, targets, and performance patterns.

3. Methodological discussion

Explainable Artificial Intelligence (XAI) is dedicated to the development of elucidative techniques aimed at enhancing stakeholders' comprehension of the behavioral patterns and rationale underlying artificial intelligence (AI) and machine learning models (ML) (Meske et al., 2022). Despite the recent surge in XAI's growth, it has garnered criticism for its technocentric orientation, characterized by XAI researchers predominantly crafting explanations based on their own discretion rather than comprehensively assessing the future users' requirements. It is noteworthy that the approach proposed herein adopts the broader definition introduced by Miller, wherein an explanation is construed as a response to a "why question." (Miller, 2017) This perspective underscores the imperative of extending explanations to non-technical individuals who will be interfacing with AI-powered systems. The adaptation of explanations to align with users' specific needs, competencies, and expertise is a key consideration.

The question emerges: Should this imperative be integrated into the early phases of a digitalization process? In pursuit of an answer, the last decade has witnessed a convergence of Information Architecture (IA) and AI into the paradigm of Human-centered AI (HAI) within the domain of Human-Computer Interaction (HCI). HAI is envisioned as a framework that endeavors to prioritize the human element throughout the entire development process of intelligent interactive systems. This aspiration is encapsulated by the concept of HAI, a design methodology that systematically incorporates end-users into the developmental trajectory of these systems (Shneiderman, 2020).

Correspondingly, the primary objective of this part of the present study is to investigate avenues through which a human-centered design approach can be proficiently integrated into the conceptualization of an Entity-Relationship (ER) schema for IMM. This research aims to advance the existing state-of-the-art methodologies applied to the evaluation of performance in urban structures, while concurrently incorporating principles of explainability within the framework.

The inquiry advances through a human-centered approach (Giacomin, 2014) that encompasses investigating stakeholder needs and eliciting corresponding requirements. This process unfolds in the following sequential steps:

1. an initial round of four comprehensive interviews conducted with domain experts, aimed at delineating the analytical intricacies of the IMM phasing. This phase seeks to elucidate the challenges inherent

in the process and the extant solutions employed by experts to mitigate these challenges.

2. a subsequent systematic elicitation process employed to distill the identified challenges into formalized requirements to be integrated into the framework.

A total of four unstructured interviews (Patton, 2002; Chambers, 1996) were conducted, engaging both the developers of the Integrated Modification Methodology (IMM) and expert users. In addition to an introductory phase and the collection of demographic data, the interviews were primarily structured around the investigation of three key dimensions:

1. Examination of the workflow encompassing the activities routinely undertaken by each interviewee within their respective domains.
2. A thorough exploration of the prevailing challenges encountered by the subjects in the course of their daily professional activities, coupled with potential strategies and solutions employed to address these challenges.
3. Probing into the prospective modalities of interaction envisioned by domain experts when contemplating the utilization of cutting-edge technologies in their domains.

The overarching aim of these interviews was to amass qualitative data regarding the challenges and requisites faced by domain experts during their professional processes, as well as their articulated expectations concerning the provision of explanatory insights through a tool.

The outcomes of the initial two rounds of interviews underwent independent analysis by the research team, culminating in a final session dedicated to achieving consensus in the identification of challenges.

The examination of the data unveiled the presence of implicit knowledge concerning the relationships between various indicators and the Key Categories, residing as a collective cognition within the group of architects yet to be formalized. Subsequently, manual data analysis was conducted, notwithstanding the inherent limitations associated with precision, scalability, and system efficiency.

In the context of performance assessment and decision-making, the absence of a well-structured decision-making framework posed considerable challenges when discerning between comparable alternatives and subsequently articulating the rationale behind the selection of specific choices.

Furthermore, consideration was given to the varied stakeholders who may engage with the system during its various phases, underscoring the necessity to anticipate and provide diverse forms of explanations elucidating the rationale underpinning different decisions made throughout the process.

The elucidated methodology serves as an initial stride in the pursuit of crafting a human-centered platform tailored for the evaluation of urban performance within the framework of the Integrated Modification Methodology (IMM). The primary focal point of this endeavor was to attentively examine the challenges and requisites encountered by domain experts, with the overarching aim of enhancing the support mechanisms for the digitalization of the IMM phasing process.

In the initial phase of this process, it was confirmed that a pivotal prerequisite was the formalization of knowledge. The carried-out inquiry helps to conclude that the adoption of an Entity-Relationship (ER) schema was the most judicious course of action. Such a schema can comprehensively encapsulate the logical sequencing and interrelationships among diverse elements employed in the assessment of sustainability and performance metrics. The conceptualization of this process into an ER schema constitutes a fundamental stepping stone toward effectively addressing the aforementioned challenges.

Furthermore, it is expected that this ER schema will provide a common foundational framework from which we can devise and implement advanced AI techniques and novel interaction modalities. For example, by leveraging machine learning techniques, AI can also identify patterns and trends in urban data, providing valuable insights for informed decision-making and adaptive planning. Overall, AI has the potential to enhance the efficiency, effectiveness, and adaptability of IMM by enabling dynamic feedback loops and data-driven decision support. This strategic approach aims to harmonize and better cater to the multifaceted needs of the diverse stakeholders involved in the evaluation process.

4. Theoretical proposition

This article investigates the relationships between the procedural elements of the Integrated Modification Methodology (IMM). IMM quantifiably breaks down the structural parameters of the urban systems and offers an extensive list of indicators to size their performance. Thus, it may furnish the methodological foundation for the structure/performance predictive model posited in the preceding sections.

IMM models the urban structure through physical and immaterial components and investigates the functioning patterns influenced by them. Based on sustainable design principles, it also suggests a locally adjustable list of actions leading to design scenarios. Therefore, it involves analysis, evaluation, and modification tools.

As briefly mentioned, Key Categories are the chief analysis tools of IMM. They are described by different groups of structural factors. These factors are numerical values (metrics) that come together and express specific functional patterns of urban systems. They cover systemic qualities of spatial geometry, mobility, natural systems, and the distribution of points of interest (Mohammad Zadeh, 2020).

The evaluation tool of IMM is a developing list of verified indicators, including those belonging to SDG 11, grouped into 12 families. For instance, SDG indicators such as 11.1.1, 11.2.1, 11.6.1, and 11.6.2, focusing on criteria like suitable housing, inclusive accessibility to public transportation, and waste management, have been delineated into numerous indicators addressing these domains. This approach facilitates a multifaceted exploration of the associated structural and infrastructural challenges. Drawn from the scientific literature, these indicators are meticulously chosen to enhance the contextual granularity of the performance metrics delineated in Sustainable Development Goal 11. (Ellam et al., 2018). IMM interprets SDG 11 targets through the lens of Design Ordering Principles (DOPs) and Actions, the modification tools of IMM. By using these Principles, IMM provides a practical approach for cities to work toward the SDG11 targets of making cities more sustainable, resilient, inclusive, and environmentally friendly, which are key objectives of the SDGs.

4.1. Entity relationship model

The ER (Entity-Relationship) model is one of database design's most established conceptual models (Chen, 1976). Data design, a fundamental phase in any computer system's life cycle, identifies the database's organization and structure. Underlying it is a process of abstraction, i.e., that mental process that highlights specific properties relevant to the application and excludes properties irrelevant to it. ER schemas — the product of the data design — are usually used to express the requirements of a system for an information technologist, and they are:

- formal, i.e., expressed in an unambiguous but adequate manner to capture the fundamental characteristics of the world to be described.
- integrated, i.e., they refer to the totality of the environment (non-sectoral);
- independent of the physical realization of the database.

A conceptual schema is a representation of a database that defines the rules that govern it. This model portrays the key concepts to be represented and their relationships. In contrast, A database schema refers to the logical and visual configuration of the entire relational database and an instance is the data stored in a database at a given time. Fundamental elements of the ER model are:

- Entity: represents a class of real-world objects of interest to the application. Objects can have a material reality (e.g., cars, employees, students) or be immaterial objects (e.g., bank accounts, university courses). Each entity is characterized by a name and graphically represented with a box. Names are singular but can represent more instances.

- Relations: represents a logical link between entities of interest to the application. Each instance of a relation is a tuple between individual instances of the entities involved (e.g., the link between a car and its owner). Each relation is characterized by a name (preferably a neutral name) and graphically represented with a diamond. There may be different relations between the same entities.
- Attributes: They represent characteristics of the entities and relationships of interest to the application. Each entity and relationship instance has a value for each attribute. Each attribute is characterized by a name; graphically, it is linked to the entity or relationship it is associated with.

In general, if the concept is significant for the application context, it is an entity; if the concept is marginal and describable simply, it is an attribute; if the concept defines a link between entities, it is an association (relationship).

Another fundamental notion for developing sensible ER models is that of cardinality. Cardinality refers to the number of times a given entity instance must or may participate in the relation. Notable cases are the following:

- (1,1): compulsory, only once
- (1,n): compulsory, at least once
- (0,1): optional, one-time only
- (0,n): optional, n times

Attributes may also have cardinality. Attributes may be scalar, have only one value, or are multi-valued, wherein their cardinality must be specified (e.g. (1, n)). Each entity has an attribute called the identifier, i.e., that attribute uniquely identifies each instance of the entity. This attribute is called a key and is represented differently from the others in the diagram, with a circle at the end of the graphical link to the associated entity or relationship. A key must have a unique, non-zero, and exact value.

4.2. Entity-relationship model for phasing of IMM

Fig. 3 depicts the ER schema of IMM. The entity Component (bottom-right) represents the elements of the built environment, A CompCode, a Case Study, and a Step identify all the Components. The attribute Step tracks the built environment's evolution over time, while the boolean attribute Elected denotes whether that Component is part of elected as the transformation catalyst at least once. The Component entity is a

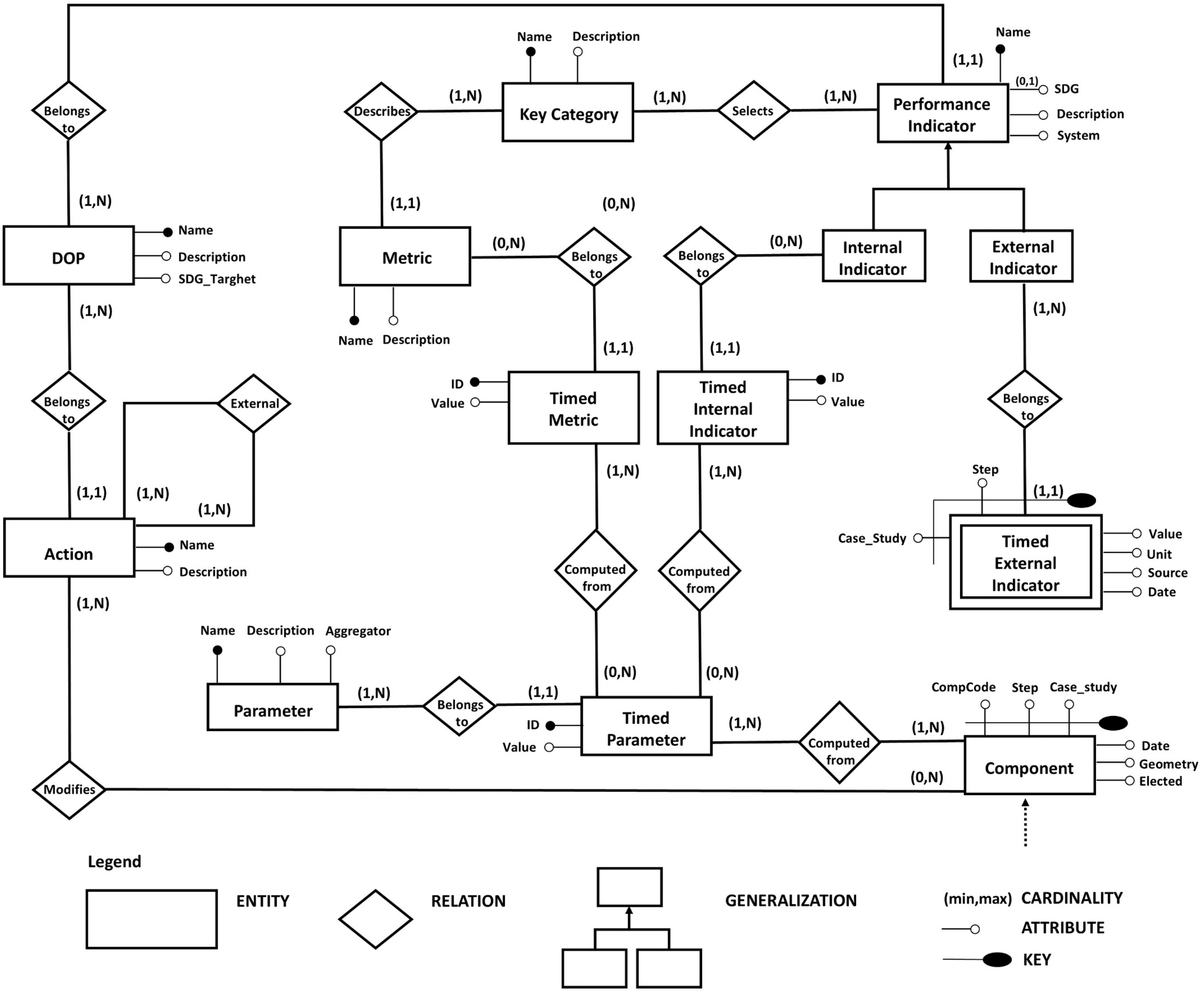

Fig. 3. The Entity Relationship Schema (ERS) of IMM.

nested generalization (Fig. 4). It is first made of Volume, Void, Uses, Network, and Boundary that, in turn, represent a generalization of more precise elements corresponding to input GIS layers (e.g., Building, Block, Point of Interest, Street link, and Administrative unit). These entities have relations showing how modification occurring in one can also have consequences on one or more of the others. Fig. 4 shows only part of the existing relations to avoid redundancy, ensuring a clearer reading. However, some relationships can be inferred. For example, because Block contains Building and Building contains one or more Point of Interest, it is possible to infer which points of interest are present in a block without including an explicit relationship in the schema. In addition to the attributes belonging to the parent entity Component, each entity that is part of this generalization has its additional attributes (e.g., Height for Volumetric unit, Area for Block, Type for Point of Interest, Speed limit for Street Link, and Population for Administrative unit). Their number it's so high that it can't be properly displayed in a single image, keeping a good readability. So, only a few examples of Volumetric unit and Point of Interest entities have been shown.

Components' attributes are aggregated to calculate Parameters and then combined to compute Metrics and part of the Performance Indicators (Internal indicators). We note that there are two types of entities for Parameters, Metrics, and Indicators. The first group of entities, Parameter, Metric, and Performance Indicator, describes each element's concept. A second entity type, Timed Parameter, Timed Metric, and Timed Performance Internal Indicator, is used to describe the evolution of these elements over time. These entities have a Value attribute, are identified by an ID, and their evolution over time is tracked through the relationships between the Timed Parameter and the Component, the Timed Parameter and the Timed Metric, and between the Timed Parameter and Timed Performance Indicator. For what concerns Performance Indicators, we also defined a hierarchy. A performance indicator can be an Internal Performance Indicator (i.e., calculated from the Component) or an External Performance Indicator (i.e., acquired from external sources). This last entity has a special notation — the double-box — because it is a weak entity, i.e., it is an entity that cannot exist independently without another entity as its attributes cannot uniquely identify it and rely on the relationship with another entity. In our case, external indicators are identified by the indicator name, step, and case study. Its key is composite, consisting of the Name of the Performance Indicator and the Step and the Case_study it refers to. We also add the Date attribute that refers to the date of the indicator collection\calculation. This attribute can be compared with the Date of the Component entity to double-check the correspondence between entities Step and Case_study.

Key Categories select the specific set of indicators. Indicators elect DOP and consequently activate a set of Actions. The entity Action can

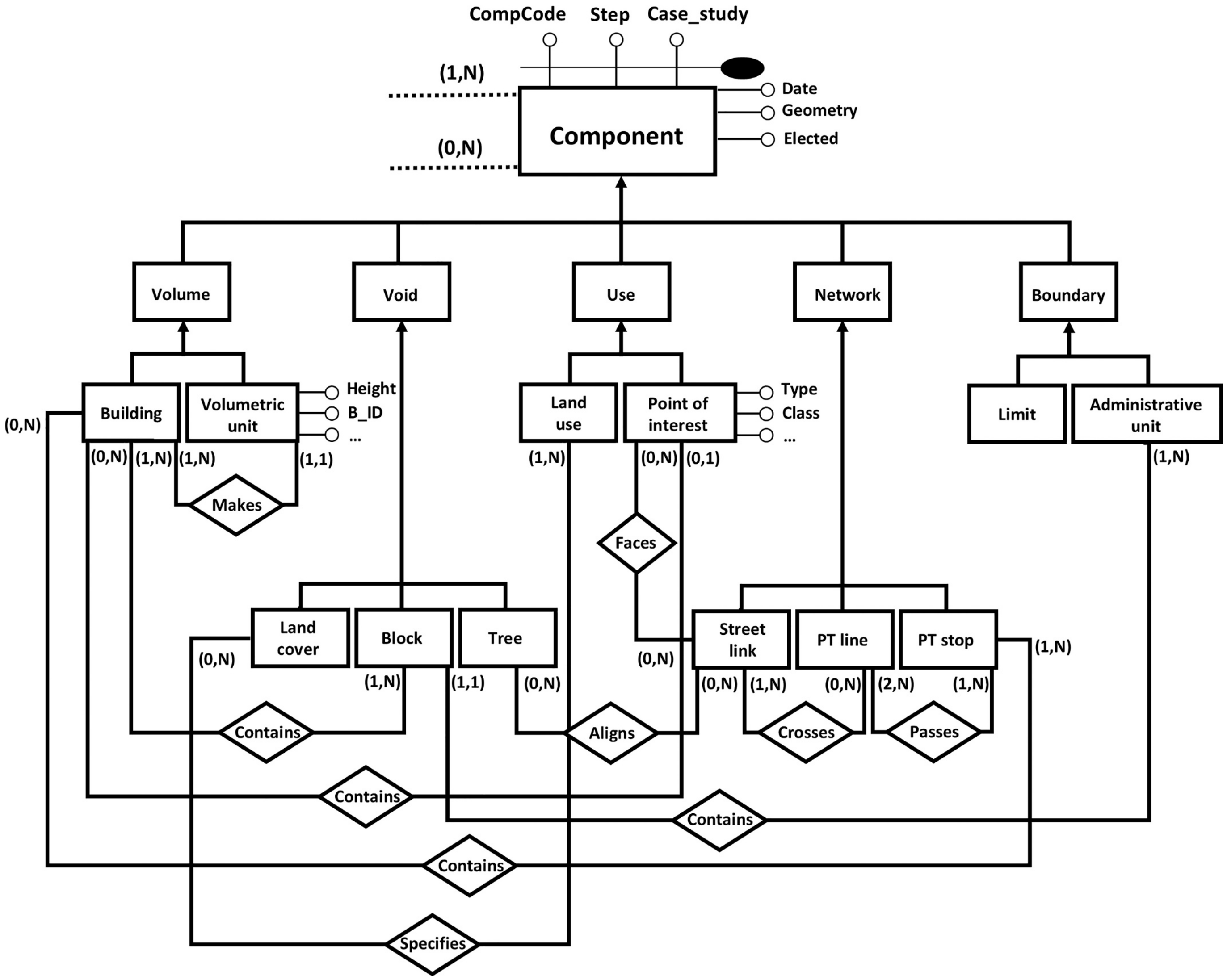

Fig. 4. Generalization of the Component entity and its internal relations.

relate to itself (self-loop) to define those actions associated with each other, even if they belong to different DOPs. This means that the weaker indicators need to be tackled by intervening in the urban system by modifying its Components according to the evidence that emerged from the diagnostic process. Cardinality and attributes were chosen consistently with the IMM structure.

The Entity-Relationship (ER) schema establishes a foundational framework for transforming IMM phasing into a data-driven methodology. While this approach holds significant promise in facilitating robust evaluation and rigorous formulation, it simultaneously presents inherent risks associated with human participation in the decision-making procedures. To mitigate these potential challenges, it is crucial to integrate methodologies that actively engage prospective users of intelligent systems at every stage of the design process.

In response to this concern, the current investigation proceeds with a scientific inquiry to explore the prospective integration of the ER schema with Explainable Artificial Intelligence (XAI) in forthcoming endeavors.

5. Conclusions

We are living in an era in which the environmental reactions to our development manners do not give us time for trial and error. On the other hand, our official plans to tackle climate change issues and approach sustainability, like Agenda 2030, are not necessarily defined in a way that addresses all aspects of complexity in economic, social, and environmental systems. Therefore, alongside Sustainable Development Goals, we need methodological interpretations like Integrated Modification Methodology to embrace the complex structure of the humane and natural systems into the framework of the SDGs. IMM is a systemic and performance-oriented modelling methodology for studying the built environment through sustainability principles. As the built environment is considered one of the most critical role-players in the future of our planet, it is vital for any studying method to approach it with a high sensitivity to its immense complexity. IMM does it by confronting deep structural mechanisms with the performance indicators of the urban systems both in the investigation and design phases.

With expanding knowledge about the intrinsic relationship between structural parameters and performing patterns, studying systems like IMM could act as methodological plug-ins to SDGs and free them from subjective interpretation of executing bodies. Moreover, such knowledge could uncover the critical patterns of relationships between different SDGs. Hence, it would be a gateway to sustainability through interdisciplinary strategies and prevent the destructive lateral effects of one practice on others.

The Entity-Relationship (ER) schema presented in this paper summarizes the initial attempts at deepening the systemic relationship between the parameters and procedures of IMM. This schema is defined to uncover the links that would enable us to read the performance of an urban system directly through its structure.

Notably, the methodology retains adaptability to potential procedural alterations in mapping techniques or metric measurements pivotal to shaping key categories. Additionally, the indicators are perceived as an open and modifiable inventory. Consequently, the ERschema is structured to reflect this flexibility inherent in the methodology.

The future steps of this research may include defining operational criteria for acquiring and managing data, carrying out experiments on an appropriate number of study cases, and comparing the results.

CRediT authorship contribution statement

Hadi Mohammad Zadeh: Writing – original draft, Conceptualization. **Emilia Lenzi:** Writing – review & editing, Visualization, Investigation, Formal analysis, Conceptualization. **Tao Dong:** Resources, Investigation, Conceptualization. **Carlo A. Biraghi:** Writing – review & editing, Investigation, Conceptualization. **Emanuele Pucci:** Writing – original draft, Validation. **Federico Cerutti:** Writing – review & editing, Validation. **Massimo Tadi:** Writing – review & editing, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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