

City Information Modeling – an expedient tool for developing sustainable, responsive and resilient cities?

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Abstract. When initiating a property development project, an extensive amount of information has to be collected and evaluated to derive a development concept that can meet the needs, requirements and demands prevailing in the given urban context. This data is commonly gathered via desktop research and is usually not comprehensive enough to depict the whole picture. The same is true for information on development restrictions, design principles to encourage sustainable behavior of city dwellers, and information on the surrounding built environment to foster local synergies. On the building level, Building Information Modeling (BIM) has proven to be a useful tool to overcome these problems of incomplete and disjointed information and requirements. In recent years, an effort has been made to apply the principles of BIM to the city level and establish City Information Modeling (CIM) as a crucial analysis and planning tool for the sustainable cities of tomorrow. The research questions are thus: Which data sets should be included for CIM to become an expedient tool for urban development? What requirements must CIM meet? And what added value can CIM offer to all involved parties? First results indicate that CIM can contribute to the development of responsive and resilient cities, covering numerous sustainability goals.

1. Introduction

In times of interrelated megatrends such as climate change, urbanization, digitalization and increasingly accelerating iterations in technological advancements, the German construction industry faces a volatile future market with an expectation of significant impacts on current business models and planning procedures. Breaking down the United Nations Sustainable Development Goals (UN SDGs) [1], the German government's Sustainable Development Strategy [2] sets the agenda in evaluating the upcoming dynamics in the construction industry.

The strategy comprises a reduction of built-up area and transportation infrastructure expansion from 63 hectares per day in 2014 to below 30 hectares per day in 2030 and a final energy consumption in passenger transport that is 20 percent lower than in 2005. Furthermore, CO₂ emissions are supposed to be as little as 5 to 20 percent of a 1990 baseline, whereas by 2030 the amount of emitted air pollutants should be halved from a 2015 baseline [2]. Cities are therefore strongly advised to rethink their current construction scenarios, taking into account the synergies between the UN SDGs and the complex urban realm in which they must be embedded. This paper uses different examples from practical use cases to outline the importance of digital planning methods in making evidence-based decisions. The digital



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planning tools considered in this paper are Building Information Modeling (BIM) and City Information Modeling (CIM), which serves as a further development of BIM that is more oriented towards neighborhood and city planning. Furthermore, it is argued that evidence-based could also mean more resilient, as dynamic data can enable the simulation of future scenarios and a faster responsiveness of city infrastructures to changing environmental influences.

2. Fundamentals of digital planning in the urban context

For life cycle assessment, including planning, constructing, maintaining and deconstructing different types of structures, Building Information Modeling (BIM) is an established digital tool for the construction sector. First, it represents a 3D model from which 2D floor plans and building shapes can be derived. Second, it contains the properties and characteristics of all building components. The use of BIM changes the planning and decision-making processes, as planning errors are detected at an early stage and can therefore be eliminated at reduced costs in contrast to planning without BIM [3].

City Information Modeling (CIM), also called Urban Information Modeling or Digital Urban Twin in literature [4], can be used for urban purposes that go beyond BIM. CIM produces a digital 3D model of a city including different types of information data, including geographic information system (GIS) data [5]. It is therefore only through CIM that the urban context is accessed, so it may be a supporting tool for achieving the targets of the German Sustainable Development Strategy as mentioned in the introduction as well as those of UN SDG 11 (Sustainable Cities and Communities) and SDG 13 (Climate Action). At present, however, it does not exist globally; only some cities have launched a digital representation of their existing buildings paired with supplemental information about the buildings [6].

2.1 Compatibility of BIM and CIM

For an implementation of BIM data into a CIM Model, several aspects must be considered: software compatibility, standards and regulations, and different quantities of data and information. Various papers [7–9] have already investigated the software compatibility of BIM, GIS and CityGML, an exchange format for open standardized data models for City Information Modeling (CIM); their results show that this issue is one of the biggest challenges for establishing CIM. The Industry Foundation Classes (IFC) standard could be a possible exchange format, as it is already an established open BIM format. As mentioned by Biljecki and Tauscher [9], various kinds of interoperability between different software and possible sources of errors have to be eliminated. Looking at current BIM standards available, there is a large variety from trade to trade and country to country [10]. The CityGML standard in Germany defines five Levels of Detail (LOD), ranging from simple 2D models of the terrain in level 0 to a more complex 3D representation of building blocks and interior structures in level 4. The different abbreviations in BIM and CIM represent a first challenge in communication between the two and can easily lead to misunderstandings [11]. Dantas, Sousa and Melo [12] have researched the compatibility of the ISO 37120 themes with BIM and CIM. They considered different themes and indicators, i.e., energy, safety and transportation, and compared the inherent indicators. Besides the low compatibility with different software tools used, the amount of relevant city indicators was insufficient for building the set of data that would be needed for a comprehensive City Information Model. Both BIM and CIM are, currently, mainly static models of the present situation and geometry. Only BIM 5D includes time and cost factors, but it is rarely used at the moment [11].

2.2 Static and dynamic data

To understand possible benefits of City Information Modeling using more dynamic data, it is important to understand the difference between static and dynamic models. A static model represents a specific output, such as a function or geometry of a building block at a certain point in time; this means there is no time dependency. By contrast, the factor of time is decisive for a dynamic model. Dynamic models describe a state of something changing over time, such as flows (e.g., energy input and CO₂ output) in a city [13]. Therefore, it is essential to consider the dynamic flows in a city for a future-proof sustainable urban development [14].

3. Dynamic city models for more responsive city planning

Taking into account that the current definitions of BIM and CIM are based on static data sets, describing one- to three-dimensional geographic and geometric information, the relationship between an infrastructural present state and a prospective future scenario that fulfills the UN SDGs is rather hard to assess. However, simulations could help predict potential effects of climate change on the built environment, as well as the effects of greenery and evaporation on the microclimate of a neighborhood [15]. Consequently, more dynamic models of urban systems are required in order to understand how urban infrastructures can move from one state to another [16], also taking into account the interplay between lifestyles, urban form and the resulting environmental impact [17].

Hypothesis: This paper argues that the organic nature of cities and their metabolic input-output flows requires digital planning processes to be extended by dynamic data in order to reach more resilient city performances.

4. Methodology

To identify potential applications of CIM and the respective system requirements CIM must fulfill in order to implement dynamic data, requirements management, as part of requirements engineering [18], shall be used in a simplified manner. Therefore, two relevant research projects at Fraunhofer IAO were chosen as use cases (section 5) to outline potential applications of a comprehensive dynamic data base in urban real-life settings. Furthermore, eight expert interviews and a quantitative online survey with 72 participants were conducted to validate the impact dynamic CIM could have on further projects in real-life settings. In order to realize the identified benefits of CIM in urban planning applications, section 6 introduces the concept of urban metabolism to systematically structure the necessary key components. To complete the requirements management approach, the use case analysis and consequent literature is followed by a requirements analysis, clearly outlining specifications CIM must adhere to in order to enable planners and further stakeholders in building a widely usable dynamic data base with system-wide effects (section 7) [19].

5. Use case analysis and potential applications of City Information Modeling

The following use cases show challenges in two chosen projects at Fraunhofer IAO that reflect potential applications of CIM in real-life settings. The conceptual analysis was supplemented by expert interviews and a quantitative survey, in order to validate the identified potentials and devise a structural proposal for a consequent data base in section 6.

5.1 Use case 1: Data management for evidence-based city planning

Within the initiative ZUKUNFT BAU, Fraunhofer IAO accompanied several housing projects from early planning to their actual construction. Throughout the process, researchers began to gain insights into the adjoining mobility infrastructure, urban design, demographics, dominant energy production and commuter traffic. As a consequence, it was discovered that although the architect's suggested building layouts met the investors' requirements, they did not address the apparent system requirements of the surrounding urban context. The average floor plans in the original design were too large, breaching the actual demands of 1- to 2-bedroom apartments, which could have resulted in a different number of apartments, delivering a more efficient use of space on the ground floor. Additionally, changes in mobility behavior, such as the increasing use of micromobility and mobility apps for intermodal transport, were not incorporated into the initial plans. Given the expected demand and the lack of consideration of already existing public parking within walking distance of the premises, the misallocation would have led to the construction of a parking garage underneath the building, causing sunk costs over the lifetime of the building. Some of these variations between the planning and the actual demand of the surrounding socio-technical system were caused by the investors' blueprint requirements that were based on experiences with the characteristics of the building stock, not on the current state of the system the buildings will be based in. Consequently, obsolescent assumptions shaped building designs that would have been outdated from day one. Scarce financial resources turned out to be one of

the main reasons why such evidence-based decision-making was hindered in the early stages of planning, even when higher costs (in the example of the parking garage) were able to be avoided in the long run. Nonetheless, the use case shows that the time and effort put into such comprehensive analysis of the surrounding socio-technical dynamics can have significant effects on the building's design. So far, there is no central data platform that provides sufficient data on the city system level for planning purposes on the district and building level.

5.2 Use case 2: Functional integration for resource efficiency

Another research project at Fraunhofer IAO and the University of Stuttgart deals with lightweighting in the urban system, thus demonstrating the possibilities of saving resources by applying the principle of functional integration, which in turn can contribute to the fulfillment of SDG 13 (Climate Action). Through the integration of several functions that consider different sectors such as mobility, climate adaptation and building construction, a reduced use of resources is possible. To evaluate, three different use cases were described: a Mobility Hub with gastronomy, living, co-working and urban farming; urban surfaces with an integrated public interface; and adaptive public space with flexible usage and resilience adaptation. Results showed that resource savings from 5 percent up to 80 percent are feasible. This can only be successful by using digital tools for planning and surveying the life cycle of not only a building but the whole city system. Through a workshop with experts, it could be validated that a combination of BIM and CIM are a prerequisite for the consistent use of lightweight construction principles and thus for a holistic approach to the planning and evaluation of a city or neighborhood. Therefore, CIM must be integrated to quantify the effects of saving resources through functional integration within a city system [20].

5.3 Further potential of CIM

Extending the identified needs for data-based planning methods to allow evidence-based decision-making on the building and district scale, a survey (N=72) was conducted to verify the potential benefits of using CIM in city planning, specifically targeting planning experts, development companies and district researchers. When asked about the benefits of CIM, 69.4 percent of the participants rated the simulation of planning projects in the digital urban environment as beneficial. Other major benefits identified were easy access to a digital urban model (66.7 percent) and central access to data (58.4 percent); one third also saw benefits in CIM as it could speed up planning procedures (38.9 percent). More specifically, respondents stated that, on average, 24.6 percent time savings could be had when using CIM in planning procedures in their organizations [6]. Nonetheless, in current literature, few concepts address the generic system architecture that would be necessary to implement CIM as an easily accessible planning tool comprising static and dynamic data sources beyond the representation of single urban objects [21]. Hence, the following theory of urban metabolism will be introduced as a guiding theoretical framework in mapping static and dynamic data in urban systems.

6. Urban metabolism for more dynamic City Information Modeling

The previously described research showed the effect data can have on decision-making in planning and on the resource efficiency of final outcomes. The concept of urban metabolism goes a step further and augments the static view on the urban system and its socio-technical components by adding dynamic data on input and output variables as well as the flows in between. Therefore, not only can this broader set of data provide the opportunity to build in a more context-specific and resource-efficient way, but it can also simulate future scenarios to understand how urban infrastructures can adapt and move from one state to another over time [14, 16]. The ability to adjust to ever-changing environments or, in other terms, to become more resilient, will be essential in both mitigating and adapting to climate change and extreme weather events in cities, directly addressing the UN SDG 11 (Sustainable Cities and Communities) and SDG 13 (Climate Action)[1, 22].

According to Minx et al. [17], an urban metabolic system consists of three core values, representing the reciprocally connected aspects of urban drivers (e.g., land use planning and infrastructure decisions), urban patterns (e.g., urban form and land use connectivity) and lifestyles (e.g., types of housing, demographics, and mobility behavior). The supplementing dimension input, in the form of energy & matter, as well as output, materializing as waste & emissions, show the physical exchange between the inner urban system and its environment, which is itself represented by the ecological support system that provides ecosystem services. Hence, looking at the urban metabolism shows interdependencies between different sources and sinks that are connected via distinctive flows of energy, material and people, passing through the given urban structure (figure 1).

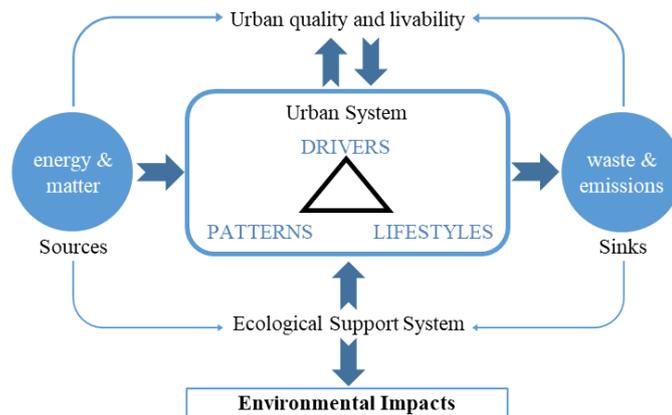


Figure 1. Extended urban metabolism (Minx et al. [17]; own illustration)

As the analysis of urban metabolism and the functionality of its sources, flows and sinks can only be as good as the gathered data, comprehensive data availability will play a crucial role. The following indicators provide a first framework in the given dimensions of the concept which could consequently be used to enhance CIM. Each of the described components of urban metabolism comprises a set of indicators, categorizing the flow and use of resources throughout the metabolic process within city systems. Table 1 exemplifies a simplified summary of such indicators, which have already been tested to gain an overarching picture of metabolisms in several exemplary cities.

Table 1. Relevant indicators in the extended urban metabolism concept [17]

Metabolic dimension	Indicator categories	Description
Urban Flows	Energy and climate change	Urban flow indicators represent the physical metabolism of a city. The indicators describe metabolic in- and outflows to and from the urban system. Exemplary indicators: metric tons of CO ₂ emissions per capita per year; share (%) of solid waste recycled.
Urban Patterns	Land cover	The use of city territory is important for aspects of urban ecosystem provisioning and for analysis of infrastructural design, which influences other metabolic dimensions. Exemplary indicators: share (%) of land used for residential and commercial use; increase in soil sealing on urban territory by type of converted land over five years.
Urban Patterns	Transportation network	The urban transport network provides incentives for city residents regarding modal choice. Exemplary indicator: length of public transport network in kilometers per capita.

Urban Drivers	Transportation	The city's modal split and traffic volume determine its dependency on external energy resources and have an impact on local air quality. Exemplary indicator: total vehicle kilometers per capita.
Urban Drivers	Lifestyles	The way in which people live and consume has an effect on their environmental footprint and use of the physical infrastructure. Exemplary indicators: gross domestic product (GDP) at city level; GDP per capita.

Realizing the first employment, Minx et al. [17] proved that the empirical use of urban metabolism can generate valuable insights into the environmental pressures associated with the flow of goods and services in cities. Furthermore, it sets the crucial links between spatial patterns and societal behavior, resulting in certain inputs, throughputs and consequent outputs that are directly connected to the livability of cities and the use of services provided by the surrounding environment. Analyzing cities in the context of their ecosystem is a helpful addition to the academic discourse, especially when taking into account imminent environmental risks in times of climate change. The authors also describe the outcomes as being sufficient to identify general trends in urbanization, no matter where the set of indicators was applied. Scalability would therefore be given, even with almost no costs for updating the models once the concept is implemented [17].

However, some limitations occurred in the availability of publicly accessible data. Key areas of the indicator set could therefore not be taken into account, with variations in every city. It is of great importance to close those gaps and provide data of high quality and high spatial resolution.

7. Data sources and requirements for evidence-based planning tools

Addressing the lack of dynamic data in facilitating CIM turned out to be one of the major challenges in realizing the proposed application of urban metabolism. Especially the urban flow indicators outlined by Minx et al. [17] are not covered in major European cities, not to mention cities in less developed parts of the world, where data availability may even be worse. Necessary dynamic data must thus be collected in innovative ways (7.1) and meet certain standards and requirements (7.2).

7.1 Potential data sources in urban infrastructure

Consumer electronics such as smartphones are often underutilized sources of real-time data that could be fed into urban metabolism studies. Replica, a subsidiary of Alphabet's Sidewalk Labs, uses de-identified data to visualize travel behavior models [23]. The resulting trip patterns help planners to make evidence-based decisions on infrastructure investment. Besides smartphones, iBeacons are another way to map people's movement in the urban realm. Once attached to a wall or street furniture, the Bluetooth-based technology connects to smartphones passing by and maps people's movement [24]. Further data sources arise with upcoming technologies such as 3D-printing and structurally integrated sensory systems. The Amsterdam-based company MX3D printed an entire steel bridge with integrated data sensors using robotic arms. The sensors will deliver data to create a digital twin of the bridge to monitor its health, including, for example, pedestrian use and corrosion, extending the reach of urban metabolism to the actual state of currently-used infrastructure [25].

7.2 Relevant requirements for utilizing the added value in using CIM

To ensure the qualified use of gathered data, it is important to integrate a function to automatically check that the data is without contradiction [26]. Such an automated query could lead to time- and therefore cost-saving planning processes. Furthermore, consistent plans are an essential requirement, and a further step is an automated query of legal framework conditions, fire protection, sound insulation, regulations on the overall energy efficiency of buildings, accessibility and many more topics in the field of sustainable and resilient urban planning. To establish a system that not only supports sustainable and resource-efficient urban planning but also is versatile, a high degree of user-friendliness is necessary. This is achieved through the cooperation of software developers, software-savvy users and software-

averse users. For this it is essential to coordinate functions, processes and design and to evaluate them in several test runs by different user groups [16].

On the software side, it would be useful if CIM bases itself on the open BIM Standard IFC to reduce implementation problems. The advantages of using CIM can largely be derived from the advantages of using BIM. Therefore, an open-source solution can guarantee a continuous information flow in BIM as well as in CIM [27]. All aforementioned data is building related, but to increase the benefits of CIM it is necessary to implement dynamic data from urban flows mentioned in 7.1. A better collaboration of the different departments collecting the specific data is a major requirement [6], then only by combining data from all different aspects of an urban system, i.e., mobility, climate and human interaction, will CIM become an expedient tool for resilient and sustainable city planning. Using CIM as an analyzing tool for urban developments, a higher quality of data can be an assured compared to the current manual analysis; furthermore, an increased schedule control and cost control is possible [27]. In the mentioned survey, close to 70 percent of respondents indicated that “simulation of planning projects in the (digital) urban environment” would generate major benefits in their organization [6].

So if the model becomes dynamic, it enables a more forward-looking planning, as the system is able to visualize different future scenarios and their effects, making them visible and understandable for the user. In addition, data collected from various sources is then used to make evidence-based planning and thus to respond to the possible needs of citizens in the future. Cities could benefit from integrating different types of public services into a CIM, i.e., the monitoring of public waste bins and a resulting optimized route for waste disposal, or the surveying of real-time traffic flows.

8. Conclusion

In summary, this paper has argued that Building and City Information Modeling work statically. Although this may be in line with static sustainability targets set by the German Sustainable Development Strategy, the UN SDG 11 (Sustainable Cities and Communities) and 13 (Climate Action) demand resilient city infrastructures that are able to adapt to fast-changing environmental circumstances. Two use cases from current research undertaken at Fraunhofer IAO extend the potential benefits of more comprehensive data analysis to evidence-based city planning and a more resource-efficient construction industry overall. In preparing the implementation of more dynamic data sources into static City Information Modeling, the concept of urban metabolism has turned out to be helpful in structuring the vast complexity of data occurring in city systems. It is suggested to establish further sensory systems to gather relevant data on urban flows, which should then be shared on an easily accessible data platform for simple integration into digital planning tools. Going beyond the availability of sufficient data, it is argued that City Information Modeling software has to be enhanced by improving the compatibility between different software suppliers, such as PTV Visum for traffic simulation or Space Syntax for analyzing spatial relationships and user behavior. In summary, realizing the requirements for data and software tools could lead to the following advantages: increased transparency, growth, reduced risks, higher flexibility, quality and efficiency [28], as well as faster planning procedures [6]. In general, the availability of dynamic data means knowledge on urban flows that can then be simulated, optimized and consequently controlled, which makes City Information Modeling more evidence-based and less generic. By using data on the actual functionality of cities and their imminent flows of goods and people, urban solutions can be specifically targeted to address locally occurring issues.

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