A SOCIO-TECHNICAL PERSPECTIVE ON THE FUTURE OF CITY INFORMATION MODELLING

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Abstract
The concept of city information modeling (CIM) has advanced for almost two decades with considerable conceptual, ontological, and instrumental advances in modeling. However, there are limitations to developing more realistic and complete models that are in line with the demands of urban management. This article aims to analyze from the socio-technical perspective of institutionalization real cases of cities that apply CIM models in their management and planning processes. Methodologically, it is a multiple case study based on bibliographic, documental, and gray literature analysis techniques on the implementation process of 21 CIM projects in different global contexts. The results show innovative analytical perspectives of CIM ecosystems based on the concepts of institutes and socio-technical systems of multiple orders; the potentialities of CIM applications are dependent on the rapid technological development and local training; and the limitations relate to the capacity of the public power to enable the application, incorporation, and implementation of practical solutions. The conclusion is that implementing 3D models of cities in urban management and planning can benefit local governments and serve as reinforcement in proportion as it overcomes preexisting practices that hinder innovation diffusion processes.
Keywords: CIM. Urban Management. Multiple Case Study. Socio-technical Approach.

1. INTRODUCTION

The concept of city information modeling (CIM) is seventeen years old since it first appeared in a blog that dealt with the possibilities that the tool would bring to respond to disasters such as Hurricane Katrina (Khemlani, 2005). Although with considerable advances, CIM is still in an emergent stage of development and far from the utopia projected on its latent potential. However, cities have increasingly started to use CIM models to support their management and planning (Souza & Bueno, 2022), and its adoption and implementation can receive essential contributions from socio-technical approaches (Pereira & Procopiuck, 2022). Therefore, the objective of this article is to analyze, from the sociotechnical perspective of institutionalization, real cases of cities that apply CIM models in their management and planning processes. From a practical perspective, the study is justified by bringing global references for managers and urban planners interested in the informational modeling of cities. From a theoretical point of view, the justification is to contribute to advances in studies on CIM based on the concept of institutes (Menshikova & Pruel, 2019), sociotechnical models of multiple orders (Misa, 2003; Procopiuck, 2011), and innovation through institutionalization process (Tolbert & Zucker, 1996).

2. THEORETICAL BACKGROUNDS

The advances in urbanization and data science gave rise to a new realm of urban science (Duarte & DeSouza, 2020), and one of its forms of action is through CIM initiatives. CIM studies are part of a broader sphere of debates that involve other concepts (Gil, 2020), such as, e.g. three-dimensional city models (3DCM) and planning support systems (PSS). PSS are geo-referenced tools for technical, visual, and data-based support for planning process tasks such as handling, communicating, and analyzing information (Vonk & Geertman, 2008). 3DCM enables representations of the urban environment based on 3D geometries of its common objects and structures (Biljecki et al., 2015). A CIM can be achieved through 3DCM semantic enrichment (e.g. Park et al., 2019; Stavric et al., 2012; Xue et al., 2021) and decomposition by logical criteria in addition to graphics (Ruohomäki et al., 2018). 3DCM allows distinguishing objects for the human eye but not for computer systems, while CIM expands its ontological and analytical possibilities (Willenborg et al., 2018). The digital twin is an emerging concept related to CIM, which has gained traction in several disciplines and practical applications enabled by technological advances, data availability, and computational capabilities (Ketzler et al., 2020). The concept deals with a mirror image of a physical process or system, looking for exact correspondence with the operation of the physically developed process in real-time (Batty, 2018; Ketzler et al., 2020). The purpose of the digital twin is to create a reliable model of reality updated in real-time to represent changes in the built urban environment (Tomko & Winter, 2018). Ideally, the connection between the real and represented environment occurs through sensors that capture information to form the city's digital twin source on a real-time basis. The product of this dynamic (re)construction of the city tends to create an ecosystem as, e.g., a source for data analysis companies to configure and offer services (Ruohomäki et al., 2018), in addition to being a natural instrument for city planning through urban management.

In addition, building information modeling (BIM) and geographic information system (GIS) are modeling bases that can enable CIM models, mainly due to their combination (Gil, 2020; Souza & Bueno, 2022). Some authors consider CIM an expanded application of BIM on the urban scale (Amorim, 2015; Stojanovski, 2013). However, the dominant perspective is that CIM is the result of the semantic and conceptual integration between BIM and GIS (Argenziano et al., 2018; Correa, 2015; Correa & Santos, 2015; Dantas et al., 2019; Rua et al., 2013; Trento & Hardt, 2019; Xu et al., 2014).

Comparatively BIM tends to offer a greater wealth of geometric and semantic information about the life cycle of buildings, while the focus of GIS is on subsidizing decision making based on geovisualization and geospatial modeling (Song et al., 2017). The limitation of GIS is in the ability to represent the morphological structure of a more complex system (e.g., a city), as the limitation of BIM is in its focus on buildings, which is only part of urban morphology (Stojanovski, 2018).

The temporal proximity between the emergence of BIM and CIM seems to bring them together conceptually, technically, and operationally. There are, therefore, spaces to approach CIM as a macro analogy of BIM in urbanism (Amorim, 2015, 2016; Gil et al., 2011; Stojanovski, 2013, 2018) due to the expansion of the applicability scale. The connection between these two information technologies and urban planning and management technologies seems promising for understanding the formation of a technological ecosystem permeated by political, technological, and management dynamics. In this perspective, the focus shifts to analyzing a tool and its relationship with a set of norms and policies for urban management and planning in the macro-definitions of city information modeling and the city information model. This first macro-dimension deals more with the method and the combination of procedures, and the second with the result of applying such a method (Pereira & Procopiuck, 2022).

From the point of view of urban morphology, the goal of the CIM would be to establish a platform to provide libraries with typologies of elements and urban design patterns that incorporate qualitative information to support urban planners with forecasts and scenario composition (Souza & Bueno, 2022; Stojanovski, 2018). Alongside this artefactual base, the perspective of management and urban planning seeks to analyze, design, and manage the urban space, allowing the visualization and evaluation of results in decision-making processes on urban projects (Beirão et al., 2015) and urban problems (Chen et al., 2018). Compared with previous city models, the CIM concept shows a fundamental difference in the potential of semantics to build a multifunctional and integrated management system with more complete and consistent data and modeling. One of the key points of its efficiency is the richness of the projected image of the city as a source of multisectoral information exchange, covering the management process vertically and horizontally (Xu et al., 2014). In theory, these qualities would open the way to responsive and adaptive urban management (Duarte, 2019) and interactive by applying dynamic tools in an interoperable ecosystem to enhance collaboration and participation between stakeholders (Gil, 2020) from the social construction of a common informational base of the city or its fundamental aspects.

2.1. Construction and Application of CIM Models

A CIM model extends the richness of data and detail in the virtual analytics environment over mesh models (Willenborg et al., 2018). These models have assumed nomenclatures, e.g., digital twins, the

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city's 3D models, and the virtual version of the city itself (e.g., Virtual Singapore) (Schrotter & Hürzeler, 2020). Local governments around the world already utilize GIS, BIM, and CIM technologies, with the combination of GIS and BIM processes being a key to achieving CIM models (Charlton et al., 2015; Ketzler et al., 2020; Sai et al., 2020). Smart cities projects in large Brazilian cities, e.g., show trends towards materialization by updating practices and processes through the intensification of the application of digital technologies. Smart cities projects in large Brazilian cities, e.g., show trends to materialize by updating practices and processes with the intensification of the application of digital technologies (Fariniuk et al., 2020). The risk of building solutions with isolated actions further reinforces the fragmentation characteristic of urban planning and management processes (Firmino & Frey, 2014), mainly because of the current diversity of technologies, tools, and languages to create city models.

The insertion of the CIM in the management and urban planning processes seems to open up opportunities to use guiding indicators for its adoption and expansion of uses. On the other hand, these technologies can find resistance in the habits and behaviors of individuals and organizations (Baptista, 2009), creating obstacles to the incorporation of innovations and the adoption of new processes (Linderoth, 2017). This type of problem can be aggravated when there is a close relationship between the continuity of preexisting technological solutions, and there is a demand for structural change in the logic to address everyday processes, as occurs, e.g., with the replacement of two-dimensional drawings and CAD tools by BIM (Babič & Rebolj, 2016). At this point, paths can emerge from organizational approaches that reveal a panorama for managers and municipal leaders to guide the development of public policies for technological innovation.

Despite the broad and heterogeneous universe of insertion of the CIM, current research and practical applications already show essential signs to delimit the technical reality covered, but still with limitations to consider CIM as a scale adjustment between GIS and BIM technologies in the face of strategies, also in constant evolution, related to urban management and planning.

2.2. Construction of CIM Ecosystem Analysis Bases

CIM models are possible realizations through the combination of technologies to represent the whole or part of the territory, with the presence of agents benefiting from their adoption and implementation. The multiplicity of actors is an inherent condition of innovation processes, as well as trends of equity and relational reciprocity (Aka, 2019). This socio-technical composition has been the basis for examining the intensity of social and technical components since, as an ecosystem, the CIM results from the action of partnerships involving organizations working together in search of mutual advantages (Kon, 2016). These advantages are not necessarily financial but in line with the organizations' objectives that make up such an ecosystem.

Under the social aspect, the public, private, and civil society organizational agents are usually organized in fields of activities or task environments. Succar (2009, 2010) presented the analytical framework for BIM, defining these fields as technological, process, and political. Although such agents do not act exclusively in one of the fields, the relational complexity and their positioning within the respective fields form an ecosystem that affects the implementation and operation of a CIM model, especially from an organizational point of view. Each agent and field tend to contribute differently to the sedimentation of the model through research and development, sale of software and hardware, creation of public policies, rules, and norms to assist in disseminating the CIM practice, or the establishment of adequate infrastructures.

There are various useful tools for creating a CIM model and processes to capture data to feed the model from a technical perspective. Another crucial point is the infrastructure required to enhance the approach to the CIM utopia, being responsive, adaptive, integrated, and multisectoral. The availability of public goods and collective equipment and the acquisition of goods and services dependent on access to information networks is part of this process and conditions the effectiveness of implementing these technologies in the urban context (Rezende & Procopiuck, 2018). Implementation effectiveness depends on organizations' strategies to create consistent patterns of workflows and information exchange (Tan et al., 2019). This refers to social issues by creating a cycle of interdependence between the factors, highlighting the need for socio-technical approaches to carry out innovation processes, such as the adoption and implementation of the CIM.

These innovation processes can be approached from the perspective of institutional theory, considering institutions as human restrictions that guide the dynamics of life (North, 1991), that usually occur from cultural contexts and shared value systems (Baptista, 2009), like ecosystems. Formal or informal institutions (North, 1991) result from the sedimentation of sets of rules and indicators of the maturity of the institutionalization process itself (Scott, 2014). Thus, innovation tends to be consecrated by fulfilling stages of the institutionalization process (Tolbert & Zucker, 1996). The formalization of institutions in laws, corporate standards of companies and associations, or social norms gives rise to institutes (Gerasymchuk & Averkyna, 2012). As regulatory support bases institutionalized at the local level, the institutes contribute to the effective implementation of information systems for urban management (Leonteva et al., 2018). Thus, GIS, BIM, and CIM tend to behave as institutes at some stage of institutionalization processes. As institutes, these technologies originate in complex structures supported by technologies, processes, and

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policies operated by individuals and organizations for the collective construction of specific forms of formal or informal interaction (Menshikova & Pruel, 2019), as exemplified in Figure 1.

Figures 1 and 2 show how complex socio-technical systems tend to establish relationships with each other and with smaller systems. In this composition, systems that involve other systems are called second-order systems, and those involved are called first-order systems (Misa, 2003; Procopiuck, 2011). GIS, CIM, and BIM technology systems and their immediate relational wrappers are first-order. BIM can compose one of the CIM subsystems at a more detailed level, thus assuming a third-order position.

In a broader perspective, GIS, CIM, and BIM systems can act as interconnected and complementary tools with other socio-technical systems with specialization directions, such as e.g., urban management. The observation of a broad perspective arrangement shows that urban management would assume the position of a fourth-order system (Garrison & Levinson, 2005).

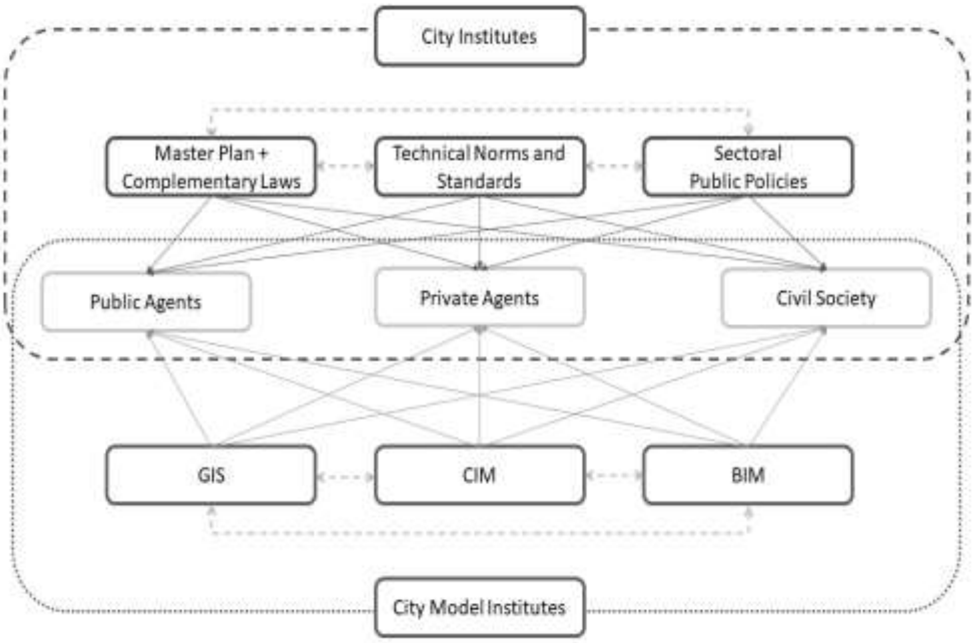

FIGURE 1 – SCHEMATIC EXAMPLE OF THE RELATIONSHIP BETWEEN CITY INSTITUTES AND CITY MODEL INSTITUTES

Understanding the scalar hierarchical organization of these technologies lies in the difference in data representation and granularity required for each level. Models focused on macro representations, such as city zoning, capture urban attributes uniformly distributed in geographically delimited regions (Wegener, 2001), leaving nuances and relationships relevant to the understanding of the urban of interest for more punctual analyzes to understand, e.g., the effects of planning and management norms (Taleai et al., 2014).

Consequently, the amplified and multi-scale vision of organizations is crucial for the establishment and operation of a city model based on the CIM, especially given the latent potential of the tool to be a means of avoiding the fragmentation of actions in urban planning and management (Almeida & Andrade, 2018). This vision tends to bring significant challenges to promoting multidisciplinary integration between territorial planning sectors generally thought of in a macro perspective as fundamental to meet the supply of services, which arise from micro scales and with much greater data granularity.

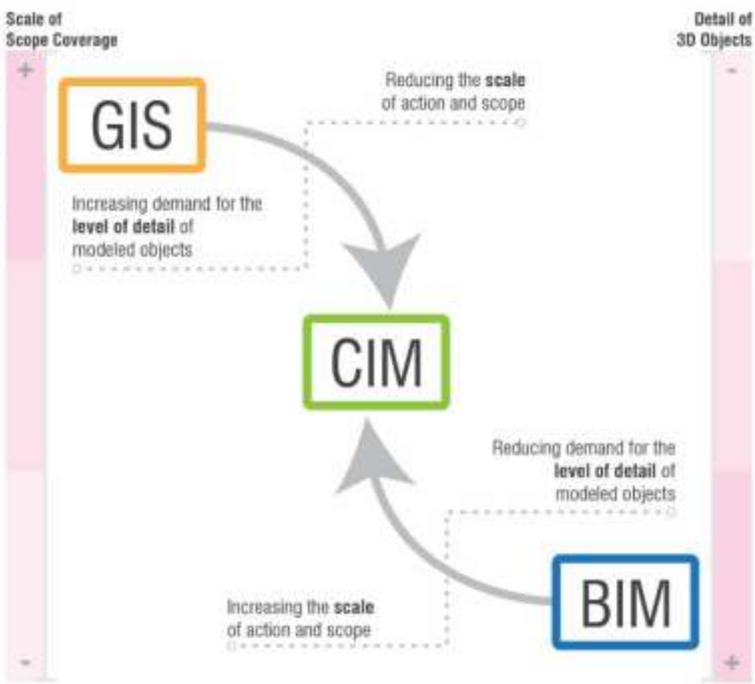

FIGURE 2 – THE RELATIONSHIP BETWEEN GIS, BIM, AND CIM FROM THEIR COMPREHENSIVENESS SCALE AND THE DETAIL LEVELS OF THEIR THREE-DIMENSIONAL OBJECTS

3. RESEARCH METHODOLOGY

The investigation is based on a multiple case study and is structured in two main stages. The first stage is descriptive and supported by documentary and bibliographic research, complemented, in the case of Curitiba/PR, with an interview with the person responsible for the geoprocessing sector of the Institute for Research and Urban Planning in the city. In the first phase, descriptive forms were built to record the cases, which can be read in full in Appendix 1 and the references of consulted documents are in Appendix 2. The second stage is analytical, and it crosses and confronts the first results with the literature. The analytical structure of the discussion is organized based on (i) the latent potential in the use of tools such as 3DCM and CIM; and (ii) the challenges and limitations that exist in the search to extract the maximum from these potentialities.

4. RESULTS PRESENTATION AND DISCUSSION

The research raised 21 cases of 3DCM and searched for data on the applications foreseen by the agents involved in its viability and on the sectors in which the agents operate. To reach this analytical approach, we first built a theoretical framework that connects the institutionalist approach with the establishment of technological institutes surrounding the CIM ecosystem in its various fields of action.

The different levels of a process of institutionalization of technologies through the promotion of innovation (Tolbert & Zucker, 1996) can happen in their most varied aspects, from political, organizational, procedural, or essentially technological issues (Succar, 2010). In addition, as noted before, CIM is composed of a complex and multi-technology ecosystem, as it interacts directly with GIS and BIM, preexisting technologies (Gil, 2020, Pereira & Procopiuck, 2022). In this sense, if we try to observe this reality to establish a taxonomy, we have that for the CIM ecosystem, it is possible to assess the levels of institutionalization for each of the technological, procedural, and political domains (Figure 3).

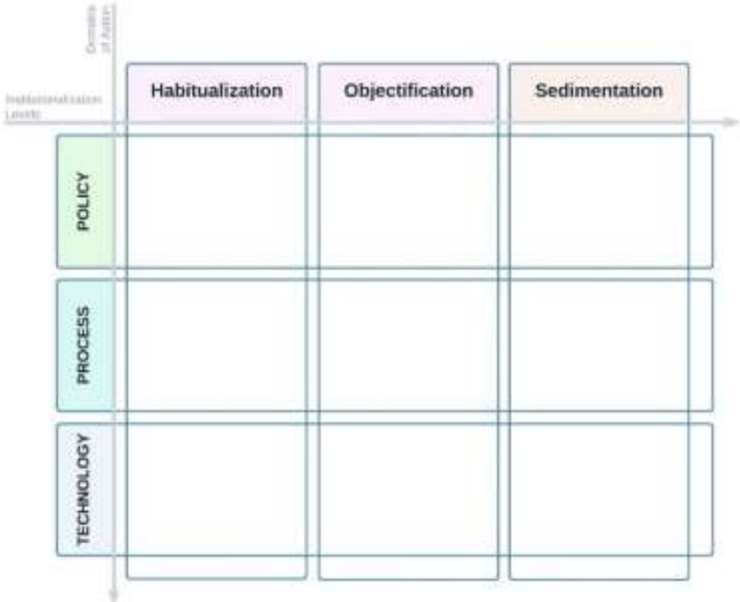

FIGURE 3 – LEVELS OF INSTITUTIONALIZATION VS. DOMAINS OF ACTION OF AGENTS FOR GIS, CIM, AND BIM

Note that what Succar (2009, 2010) calls "fields" of action, we instead call "domains" of action. Such change is proposed based on the multiple-order systems hierarchy and that GIS, CIM, and BIM have their own fields of action if we look from a broader vantage point. The technologies assume the bonding role for all the agents involved in their social-technical fields.

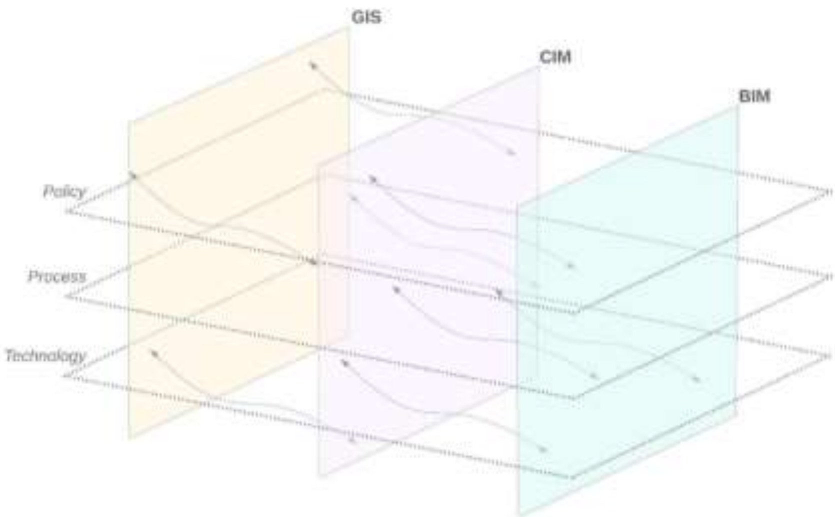

FIGURE 4 – MULTILEVEL AND MULTISCALE INTERACTIONS BETWEEN GIS, CIM, AND BIM FIELDS THAT PRODUCE TECHNOLOGICAL INSTITUTES

Aware of the interrelationship between GIS, CIM, and BIM, we can also understand that levels of institutionalization can exist for each of these concepts, creating a three-dimensional superposition of these indicators, which can be understood as the institutional maturity of each technology and ecosystem, consequently (Figure 5). Among the socio-technical fields of GIS, CIM, and BIM, the relationships materialize the technological institutes in different domains of action and different levels of action, covering different scales of action at different levels of granularity of three-dimensional data (Figures 4 and 5).

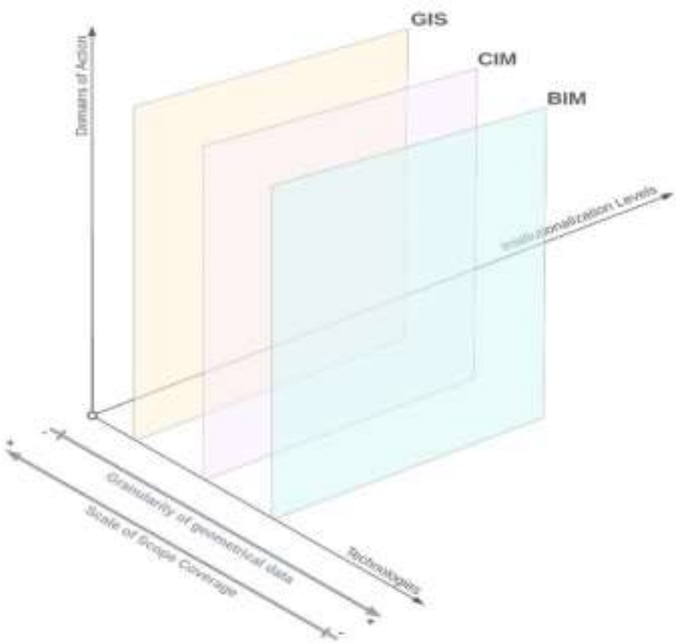

FIGURE 5 – ANALYTICAL FRAMEWORK OF THE CIM ECOSYSTEM CONSIDERING THE TECHNOLOGICAL FIELDS DELIMITED FOR GIS, CIM, AND BIM.

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As shown in Figure 2 and 5, for the analytical framework of the ecosystem, it is also possible to make the axis of technologies behave bidirectionally, changing its growth direction when dealing with the scales of the scope of coverage or the granularity of the geometric data of the models. The BIM, GIS, and CIM institutes emerge from the interaction between the sheets represented by each concept. These interactions can happen in the form of pressures, tensions, collaborations, or simple information exchange, and with top-down, bottom-up, and middle-out directions, with the first two having hierarchical distinction and the last referring to agents positioned at the same level of the hierarchical pyramid (Succar & Kassem, 2015). Furthermore, pressures can have multiple natures, formal and informal, through norms, rules, or behavioral patterns culturally established in the relationship between organizations or agents. The plurality of agents involved in the process is also a relevant factor that must be considered in socio-technical analyses of these ecosystems. Finally, the way in which agents relate to each other can happen for different purposes and is closely associated with the intention of application of these tools. These applications can be organized into three large groups: the visualization and public access, the planning and simulation of scenarios, and the monitoring and maintenance of the urban built environment.

The resulting dynamics of multisectoral pressures, applications, and benefits shape the ecosystem behavior of the CIM socio-technical field, as shown in Figure 6. This notion of field for sociological studies has its origin in previous studies of electromagnetism, precisely because they represent a system that generates forces that encompass objects or agents that are subject to the vectors of these forces (influences) depending on their location in the field and their relationship with the field's other agents as well as with the broader structure where the field is inserted (Scott, 2014). Bourdieu (1977) understands these fields as social arenas governed by different approaches and values, giving special attention to the process of internalization of cultural rules. Thus, GIS, CIM, and BIM will have their own fields with their vector dynamics of pressures and specific influences generating cultural rules (or institutes) specific to their multiscale functioning. Taking the CIM as the focal point of analysis, the performance of the GIS and BIM fields must be considered, and the same will happen if we look at the fields from the latter two. This is the character of interdependence established by these technologies (Figure 4).

The analysis focused on obtaining data about the diversity of agents involved in the enablement and implementation processes of the models and their applications. From the observations of how these models have been applied and who has been involved in these projects, it is possible to make inferences for future practical and theoretical developments of CIM, locally and globally.

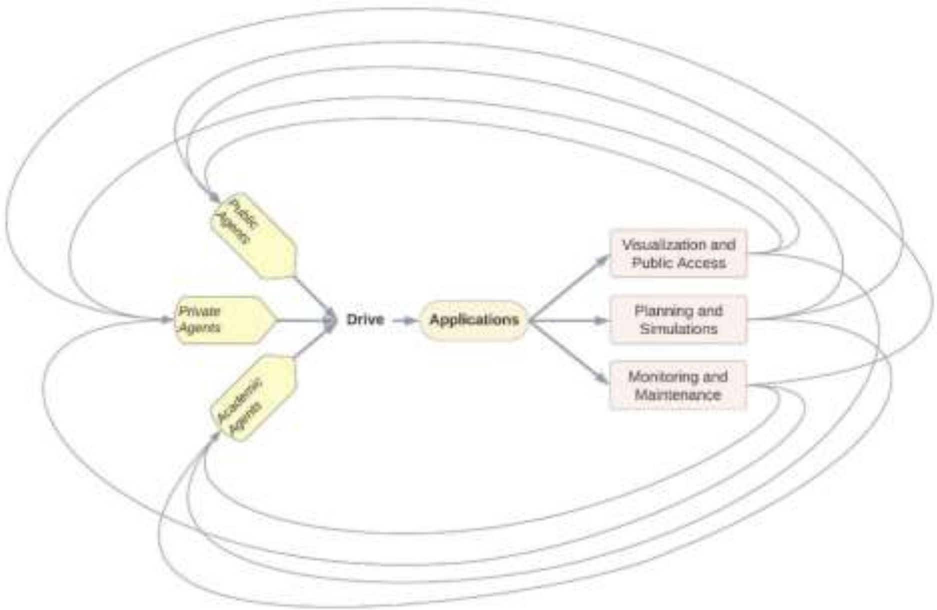

FIGURE 6 – DYNAMICS OF THE FUNCTIONING OF THE CIM TECHNOLOGICAL FIELD: MULTISECTORIAL PRESSURES, APPLICATIONS, AND BENEFITS DENOTE THE ECOSYSTEMIC CHARACTER OF THE FIELD

In a broad panorama, several cities had initiatives to implement technologies that preceded 3DCM. In Angers, Curitiba, Singapore, and the United Kingdom, e.g., there were already initiatives to disseminate BIM. Cities such as Boston, Curitiba, São Paulo, and Bremen, e.g., already had initiatives in the field of GIS to support territorial planning and management. The cities of Rotterdam and Gothenburg drew attention for initiatives with 3DCM in 2010 and the 1980s, respectively. In general, among the cases studied, the implementations of CIM and digital twin models began in the second half of the 2010s, and the models were effectively implemented in the transition from that decade to the 2020s. Thus, a great majority of these models are recent, with concretions happening in the first years of the current decade. In the cases of cities belonging to the Global South, such as Curitiba and Amaravati, the search for international partnerships was perceived to consolidate the projects.

4.1. Visualization and Access to the Public

Table 1 shows that in 95% of cases, the model promotes interaction between managers and the population through visualization and public access to interactive, whether models or not. The models with the function of visualization and access to the public are the ones that allow external interaction by interactive navigation, visualization, or data download. There is, therefore, a hierarchical order that may suggest levels of institutional maturity for the adoption and implementation of the CIM in this regard. A model like São Paulo's, e.g., that allows the visualization of the point cloud captured by LiDAR without a previous treatment or a refinement of the modeling, could be at an initial stage of opening for visualization and access to the three-dimensional data of the city. On the other end, the Helsinki model allows the downloading of three-dimensional, geographic, and specific sectoral data to promote research and development from the CIM model. These two examples illustrate two extremes of a possible scale for open model maturity levels. One of them with a very early level of development (LoD) modeling and without linked information layers or non-existent information level (LoI). On the other side, there is a high LoD model, with semantically enriched geometries combined with mesh geometries, in addition to a series of information layers that guarantee a high LoI. In technical terms, the levels of detail (LoD) of the models can be aligned with the stages of technical maturity of this model, and the levels of information (LoI) can be linked to the respective levels of political and organizational maturity.

TABLE 1 - PRACTICAL APPLICATIONS OF THE CIM - SYNTHESIS TABLE OF THE CASES FOUND

Application Case	Visualization and Public Access	Planning and Simulation	Monitoring and Maintenance
Amaravati, India	x	x	x
Angers, France	x	x	x
Berlin, Germany	x		
Boston, USA	x	x	
Bremen, Germany	x	x	
Curitiba, Brazil	x	x	x
Glasgow, Scotland	x	x	
Gothenburg, Sweden	x	x	x
Helsinki, Finland	x	x	x
Japan (56 cities)	x	x	
Munich, Germany		x	x
Newcastle + Gateshead, UK	x	x	
Porirua, New Zealand	x	x	
UK, Dublin, and New York	x	x	
Rennes, France	x	x	
Rotterdam, Netherlands	x	x	x
Sant Cugat del Vallés, Spain	x	x	x
Sao Paulo, Brazil	x		
Singapore	x	x	
Toronto, Canada	x	x	
Zurich, Switzerland	x	x	x
TOTAL	20 (95,23%)	19 (90,47%)	9 (42,85%)

The cooperation between authorities and citizens shown in Table 1 seems to contribute to the development of civil society, decision-making supported by information, social involvement in public life, and more effective local, regional, and national governance (Szarek-Iwaniuk & Senetra, 2020). Public participation has been traditional in institutionalized planning, and the advent of the digital universe brought new logics (Batty et al., 2012) and challenges related to access to information and key issues such as, e.g., privacy (Susila et al., 2020). The demand for channels to establish communication between the public power and citizens to promote transparent management and governance of cities exists

(Leonteva et al., 2018) and, even from a different analytical perspective, it seems to strengthen the combination of public management and ICTs as an enabler of participation (Flores & Rezende, 2018).

Given the importance of opening data to minimally stimulate community participation, only a few cases did not have their bases available. The non-opening of the models to citizens may be related to factors, e.g., the non-identification of the official platform of the local government providing the data. This was the case in Munich, where the model was not found through the municipality base. In the project description of the digital twin of the city, there were no direct mentions of public participation, but the 3D model was available on a private platform (3DCityDB, 2021b). In the case of Curitiba, the availability of the consultative model is still limited by technical aspects, especially related to the size of the database for storage and processing. The Helsinki CIM model, which has a much smaller territorial area than Curitiba, reached, e.g., the mark of 11 TB of information being processed by a farm of 10 computers (Geo Week News, 2017; Higgins, 2017). Finally, another possibility occurs when projects are born focused on specific applications and end up restricting their view to it, as in the case of Angers, who aimed to use the model to support planning through simulations. This bias, as seen in the opening of the discussions, may be the result of external pressures or the multisectoral agreements that make the model viable.

4.2. Planning and Simulation

The models applied for planning and simulations considered were those related to implementing urban plans, projects, or analysis of environmental impacts, for example. The number of cases with this application also exceeded 90%. With increasing complexity, decision-making in the planning, design, construction, and management of urban space needs to have increasingly refined, visual, dynamic, and integrated information (Gao et al., 2021), which seems to reinforce why this is a more recurrent application. Also, as the root of urban planning and management tends to be physical-territorial (Ultramari et al., 2016) and quite reclusive in its area of knowledge (Firmino & Frey, 2014), this ends up being the domain in which most of the innovative actions motivated by planners turn.

The cases that did not clearly demonstrate use had different motivations. The city of São Paulo still does not apply its model in planning and simulation actions, as it still looks pretty embryonic. Possibly this is a temporary condition. The city of Berlin uses its model as a platform to attract new businesses and promote economic development in the city. In this sense, it is possible that the model is the implementation of an economic plan action but ends up not being used directly in urban planning and simulations.

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4.3. Monitoring and Maintenance

Compared to the other two categories of applications used in the investigation (Table 1), monitoring and maintenance functions had a much lower incidence, with less than half of the cases. Channels for monitoring and maintaining cities are not new. Paris, e.g., installed QR codes on city equipment and furniture so that citizens themselves could report the state of conservation to the municipality (Biseul, 2021). Curitiba has the 156 app as a channel for the city's janitor so that, in the same way, citizens can participate in the process of maintaining the built space (ICI, 2019). However, its connection with a 3D model and the new technological possibilities promoted, e.g., by big data and IoT, expand the opportunities in this scenario (Jin et al., 2020). Combining ICTs with artificial intelligence (AI) in cities creates information and big data fed into the CIM model, connecting them with abstractions and representations of the city (Stojanovski et al., 2020). The monitoring stage is related to the capacity to capture and store data within the model. In this sense, the amount of investments in sensors or other technological devices tend to be even more significant than those for assembling the model.

Thus, moving towards a dynamic model requires great capacity on the part of the public authorities and their eventual partners to enable a CIM. In addition to the financial capacity, it demands the realization of broad projects with the implementation of physical infrastructure, and tools, updating the knowledge of the technical staff, and learning of the population to interact with the new devices. Among the cases that already consider this application are cities with a tradition of promoting innovation, such as Angers, Curitiba, Gothenburg, Helsinki, Rotterdam, and Zurich. There are also cases where monitoring is part of the initial technology adoption and implementation package, as in Amaravati, Munich, and Sant Cugat del Vallés. The evidence found in the present investigation, regardless of the previous aspects, shows a movement that demands a high amount of financial resources and that, in most cases, is obtained with collaborations between public and private sectors, as shown in Table 2.

4.4. Cross-sector collaborations

The majority of the cases analyzed have models that result from intersectoral collaboration actions. The prevalence is in the partnership of private and public agents. In this sense, observing companies involved in some of the cases analyzed, we noted that the delivery of their services has a lot of adherence with what the academy has discussed regarding the application of three-dimensional models of the city. Virtual City Systems, for example, lists 13 functions it offers for its models (VC, 2021). The list presents similarities with the applications in the cases shown above, as well as in the themes that the academy has been debating. Furthermore, the Virtual City Systems (VC, 2022), the AAM (AAM, 2022), and the 3DCityDB (3DCityDB, 2021a) are companies that participate in models surveyed in this research, presenting features in their systems to make them public models, reinforcing what studies point out about the potential of such models to make management more participatory and democratic. In the case of Brazilian companies, two of those involved in creating Curitiba's model, Engefoto and Esteio, offer GIS registration and cartography services but do not detail the functionalities incorporated into these bases (Engefoto, 2022; Esteio, 2022).

The provision of services in line with users' and applicators' expectations demonstrates an alignment between the services offered in the city modeling segment and the demands addressed by their application. However, the process of exchanging information, or the focus on integration between sectors, does not receive as much attention from the documents analyzed. Creating and maintaining a 3DCM is closely related to the challenges of strategic collaboration between different organizations and the applications given to such a model (Horne et al., 2014). In this sense, the collaboration between industry sectors (especially construction and technology) and public authorities is crucial in ensuring these tools' success (Ketzler et al., 2020).

TABLE 2 - VIABILIZATION OF MODELS BASED ON THE PARTICIPATION OF SECTORS

City	Public	Private	Academy
Amaravati, India	x	x	
Angers, France	x	x	
Berlin, Germany	x	x	
Boston, USA	x	x	
Bremen, Germany	x	x	
Curitiba, Brazil	x	x	
Glasgow, Scotland	x	x	x
Gothenburg, Sweden	x	x	
Helsinki, Finland	x	x	x
Japan (56 cities)	x	x	
Munich, Germany	x		
Newcastle + Gateshead, UK	x		x
Porirua, New Zealand	x	x	
UK, Dublin, and New York	x	x	
Rennes, France	x	x	
Rotterdam, Netherlands	x	x	
Sant Cugat del Vallés, Spain	x	x	
Sao Paulo, Brazil	x	x	
Singapore	x	x	x
Toronto, Canada	x	x	
Zurich, Switzerland	x	x	
TOTAL	21 (100,00%)	19 (90,47%)	4 (19,04%)

The cases where the academy was involved draw attention due to the more significant amount of information available, especially because they are the basis for producing research and scientific articles. Again, the case of Helsinki stands out at this point, especially in research in the field of energy efficiency and the feasibility of a digital twin in real-time (Rossknecht & Airaksinen, 2020; Ruohomäki et al., 2018).

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This evidence reinforces the key role of academia in promoting technological development and its applications.

The emphasis on integration is not evident in most of the data analyzed, especially between the organizations and people involved in the processes. The case of Rotterdam is an example of the breakdown of the existing logic in the georeferenced data management process. In this case, there are reports on how the technicians who manipulate the model easily adhered to the change (Business Geomatics, 2019). At the heart of this acceptance is recognizing the value that innovation can bring to their activities by each individual involved in the process, which tends to be a relevant driver for the implementation of new technologies (Bosch-Sijtsema et al., 2017).

Software developers also play a crucial role in the dynamics of the CIM ecosystem, especially in driving the state of the art of model design and application. Bentley and Esri, e.g., have several actual cases of the application of their tools, such as the optimization of water distribution systems, in the city of Rotterdam (Bentley Systems, 2022c), in the construction of the Helsinki digital twin (Bentley Systems, 2020, 2022a, 2022b) and the Plateau Project in Japan (MLIT, 2021). The application possibilities of these models are diverse, based on intersectoral partnerships, as in the case of Helsinki.

From a technological point of view, integration is made possible with the construction of components based on accepted standards, that some extensions exist and spread, but above all that, these are applied by users and as software applications (Gil, 2020). This is the central topic of the technological debate, the standards and extensions created by the Open Geospatial Consortium (OGC), the CityGML (OGC, 2021), and ISO, the Industry Foundation Classes (IFC) (ISO/TC-59/SC-13, 2018). With the current advances in research and technological development, this barrier tends to vanish over time.

From an organizational point of view, we noted that in some cases, such as Curitiba, actions to implement the CIM occur parallel with other BIM or GIS initiatives (sometimes promoted by the same public authority). In this sense, understanding how the innovation processes began is of fundamental importance in mapping the processes of technological diffusion (Geroski, 2000), as well as understanding their development over time once established. Thus, identifying those responsible, relevant agents and the pressures that have driven a technology adoption or implementation process can be crucial to understanding the nature of the institutes that result from such a process. These pressures can be vertical or horizontal. Vertical pressures can be felt from the top-down, motivated by government agents or regulatory bodies, or from the bottom-up, inspired by small agents or organizations. On the other hand, horizontal pressures occur between agents with the same position in the hierarchical pyramid but belonging to different ecosystems, the so-called middle-out pressures (Succar & Kassem, 2015). These dynamics are not interdependent, and movements provoked in either direction will have effects at the other end (Rogers et al., 2005). This behavior is characteristic of complex ecosystems such as the one formed by the CIM and feeds the hypothesis that good collaboration between sectors and organizations is one of the ways for the tool to be adopted and implemented with greater chances of success, as can be seen in cases such as Helsinki and Gothenburg.

5. CONCLUSIONS

In terms of theoretical structuring, the CIM ecosystem, as well as for other technologies, is divided into the three most active sectors in its development, implementation, operation, and maintenance: the public power assuming the centrality for being responsible for the promotion of public policies for dissemination technological and self-beneficiary of the realization of the innovation, exerting normative and regulatory pressures of technological diffusion; the private initiative with a relevant role in the diffusion of technology and exerting pressure on the public power through the action of companies and service providers that have already incorporated the technologies or of software developers in search of state of the art in technological development and varied applications; and academia contributing with these two sectors in developing research and basic knowledge to support public policies and technological innovations. This mutualist structure has generated the bases to understand the current stage of technology application and to act in the promotion of innovation.

The main potentialities found ended up being in the technological field, where the development of information and communication technologies (ICTs) have played a driving role. Another potential aspect is the ability of the 3DCM to be tools to strengthen democracy, allowing closer interaction between public power and the population. The challenges and limitations end up having great adherence to the performance of local governments and its capacity to make feasible incorporate and implement technologies in their realities. These contexts in which adoption and implementation take place are complex and permeated by multiple agents that, as seen, are usually involved in making these processes viable. Among other traditional barriers faced by urban planners and managers is the fragmentation of actions. Thus, the implementation of 3DCMs in urban management and planning processes can be very beneficial and an element of reinforcement to preexisting practices that hinder innovation diffusion processes. This may indicate why the cases studied, with few exceptions, fall far short of the tool's real potential, with the most prominent cases showing characteristics of being multisectoral and multi-scalar. In this sense, multilevel, multisectoral, and inter-organizational collaboration seems to be a valuable strategy in adopting and implementing three-dimensional models of cities.

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