THE CONVERGENCE OF GEOGRAPHIC INFORMATION SYSTEMS AND BUILDING INFORMATION MODELING FOR CITY INFORMATION MODELING IN CURITIBA: AN INSTITUTIONAL THEORY-BASED APPROACH

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Abstract
This study examines the implementation of urban technologies in Curitiba, focusing on the convergence between Geographic Information Systems (GIS) and Building Information Modeling (BIM) for the development of City Information Modeling (CIM). The research highlights the necessity of developing organizational capacities and governance structures to foster this technological integration. The objective was to analyze the institutionalization process of GIS- and BIM-based initiatives in Curitiba through the lens of institutional theory. Methodologically, the study employed exploratory, descriptive, and confirmatory research, utilizing document analysis and interviews with key stakeholders. The findings confirmed hypotheses based on formal logic regarding the interaction between institutional pillars and stages of institutionalization, revealing varying levels of maturity: Metrogeo is at the objectification stage, while LaBIM/PMC is at the habitualization stage. Practical implications underscore the need for integrated capacity-building strategies, multilevel technical cooperation mechanisms, and alignment between procurement processes and emerging technological demands to implement urban technologies successfully.

Keywords: Urban Planning; Urban Technologies; Urban Governance; Institutionalization of Technologies;. CIM; GIS; BIM.

1. INTRODUCTION

Contemporary digital city models predominantly rely on Geographic Information System (GIS) technology to establish spatial connections and representations (Pereira et al., 2021; Xu et al., 2014). However, these models exhibit representational limitations (Biljecki et al., 2021; Stojanovski, 2013). In its current configuration, GIS does not achieve the same level of urban morphological detail that Building Information Modeling (BIM) provides at the building scale (Pereira & Prokopiuk, 2024b). Paradoxically, while BIM offers high-detail potential, its application remains confined to specific segments of urban morphology

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(Stojanovski, 2018). The contemporary challenge lies in developing organizational capacities (Gasco-Hernandez et al., 2022) and governance structures to enable the convergence of GIS and BIM, thereby accelerating the development and implementation of more comprehensive and integrated City Information Modeling (CIM) systems (Augusto Pimentel Pereira & Mario Procopiuck, 2022).

The sociotechnical dimension of GIS implementation has catalyzed innovations in urban management tools, particularly for infrastructure evaluation. As demonstrated by Sahay and Robey (1996), the social meanings attributed to technologies decisively influence their implementation and use. Local social dynamics, shaped by groups configuring specific institutional logics (Hayes & Rajão, 2011), are critical in developing effective implementing GIS and BIM strategies. These strategies enable the projection of future scenarios and the establishment of robust foundations for more integrated CIM systems.

Institutional theory emerges as a fundamental analytical framework for understanding technological innovation processes in sociotechnical contexts, engaging with transformations across political science, economics, sociology, and management (Hall & Taylor, 2003; Scott, 2014). Analyses of BIM and GIS adoption and implementation have benefited from this approach, particularly from its sociological and organizational perspectives (Augusto Pimentel Pereira & Mario Procopiuck, 2022). Within BIM/CIM/GIS ecosystems, sociotechnical perspectives are essential to ensure that the diffusion of these technologies does not merely replicate or exacerbate existing inequalities and inefficiencies in organizational structures but promotes positive transformations through the integrated consideration of technical and social aspects (Augusto P. Pereira & Mario Procopiuck, 2022). However, contemporary studies have primarily focused on cultural-cognitive elements, such as organizations' tendency to imitate perceived successful practices (isomorphic pressures), while neglecting broader analyses that also consider regulatory and normative aspects in shaping the broader urban governance contexts that emerge from BIM/CIM/GIS technology implementation (Augusto Pimentel Pereira & Mario Procopiuck, 2022).

This article analyzes the institutionalization process of GIS- and BIM-based initiatives in Curitiba through an institutionalist lens. The investigation is structured around two complementary hypotheses: H1 posits that the interaction between the regulatory, normative, and cultural-cognitive pillars (Scott, 2014), the stages of institutionalization—habitualization, objectification, and sedimentation (Tolbert & Zucker, 1996)—and the social meanings attributed to technologies (Sahay & Robey, 1996) provides an integrated analytical framework to understand how different institutional levels interact in the implementation and maturation of GIS and BIM technologies. H2 proposes that the manifestation of these elements in Curitiba's implementation and adoption processes, mediated by institutional logic shaping local social dynamics (Hayes & Rajão, 2011) and by organizational and technical changes (Sackey et al., 2015), reveals patterns of technological convergence that can inform future theoretical developments on institutional maturity in complex urban contexts.

The study contributes to the debate on information technologies in urban planning and management (McLean et al., 2016; Rezende et al., 2015; Shiode, 2000). Curitiba was chosen as the empirical case due to its innovative trajectory, and it was recognized for its leadership in the Brazilian digital city rankings (Duarte et al., 2014; Pereira & Prokopiuk, 2024a).

2. AN INSTITUTIONALIST PERSPECTIVE ON THE ANALYSIS OF URBAN TECHNOLOGIES

The epistemological approach of institutionalism has significantly contributed to fields such as management (Krapohl, 2007; van Raak & Paulus, 2008) and politics (Bursens & Deforche, 2010; Peters et al., 2005). However, its application to urban planning remains relatively limited despite its potential (Sorensen, 1999, 2017, 2018). Comparative studies demonstrate the value of institutionalism for understanding processes related to adopting and implementing technologies like GIS and BIM (Taylor, 2013). For instance, Pereira and Procopiuck (2022) have illustrated the utility of historical institutionalism in analyzing the development of urban technological ecosystems.

Institutionalism typically associates institutions with organizations and the rules or conventions issued by formal organizations. Institutions encompass official procedures, protocols, norms, and conventions embedded in various dimensions of an organizational structure, ranging from constitutional orders to operational procedures and conventions that govern stakeholder behavior (Hall & Taylor, 2003). Consequently, the definition of institutions includes formal organizations and informal rules and procedures within governance systems, influencing social agents' behavior over time (Thelen & Steinmo, 1992). Strategies and practices induced in a specific institutional context may become entrenched and, over time, constitute worldviews disseminated by formal organizations, shaping their agents' and stakeholders' preferences and decisions.

One specific way to observe the institutionalization process is to divide it into stages, beginning with the genesis of an innovation triggered by technological changes, regulatory milestones, legislation, or market forces. After emergence, three subsequent phases occur: habitualization, objectification, and sedimentation. Habitualization refers to the adaptation of organizational structures and agents' acceptance to integrate innovation. Objectification addresses the degree to which the innovation is embedded in the organizational context, marked by a consensus around it, especially among decision-makers. Sedimentation occurs when the innovation becomes fully incorporated into the organization, enduring over time and allowing for its evolution across generations (Tolbert & Zucker, 1996). CAD tools

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are an example of a technology that has reached sedimentation and now constitutes a barrier to other innovations, which pose significant challenges to implementing and adopting BIM (Babič & Rebolj, 2016).

In institutionalization processes, three foundational pillars condition practices and serve as strategic organizational bases. The first is the regulatory pillar, involving establishing rules, inspecting their compliance, and, if necessary, applying sanctions—coercive mechanisms of institutions. The second is the normative pillar, encompassing prescriptive, evaluative, and obligatory dimensions of social life, including values and norms. This pillar has empirical indicators, such as awarding certificates or seals by professional entities, which socially validate the institution. The third is the cultural-cognitive pillar, associated with shared concepts that constitute the nature and structures of social reality. Attention to this dimension helps identify interconnected organizations (Scott, 2014)forming sociotechnical innovation ecosystems articulated through multilevel governance systems (Procopiuck & Freder, 2020). Established sociological theories support this conception of institutions, such as Berger and Luckmann's (2014) social construction of reality and DiMaggio and Powell's (1983) institutional isomorphism.

Recognizing the existence of various examples of institutionalized technologies in urban management and planning, the institutionalist perspective offers a consistent analytical framework for examining how technological innovations are integrated into complex organizational structures. Adopting the theoretical-conceptual approach proposed by Tolbert and Zucker (1996), it becomes evident that although similar institutional forces may be present in different contexts, their manifestations and outcomes can vary significantly. This variation arises because of specific properties of local contexts, such as prior technological trajectories, existing organizational structures, and particular sociotechnical dynamics structure institutionalization processes. Thus, institutional analysis enables identifying how these contextual properties interact with the regulatory, normative, and cultural-cognitive pillars to configure distinct patterns of adoption and implementation of technological innovations in urban management and planning.

3. THE INSTITUTIONALIZATION PROCESS OF CIM, BIM, AND GIS

Technology adoption refers to the process by which an organization or its social agents decide to fully utilize innovation in their daily activities (Rogers et al., 2009). Essentially, it represents the decision to accept and apply the technology in everyday operations (Harun et al., 2016). On the other hand, implementation involves executing this decision by incorporating and actualizing the transformation within a specific context and timeframe. As such, organizational and technical changes must accompany actions related to technological implementation (Sackey et al., 2015). Ahmed and Kassem (2018) argue that adoption is a broader concept, driving the organization toward an advanced stage of technological internalization. Consequently, implementation is a result of technology adoption. The subsequent stage, diffusion, pertains to the rate of technology adoption and its workflows across different markets (Kassem & Succar, 2017) or within an ecosystem. Although these concepts are essential for understanding the processes and flows of technological implementation, they provide limited insight into the broader strategic and organizational decision-making environments in which they occur. Nor do they sufficiently address how these influences shape local decisions and practices, thereby highlighting the need for epistemological support to advance toward conceptual unification.

Institutional theory offers the necessary framework to complement and unify technological innovation and institutionalization processes. Implementation is the outcome of the adoption process, which can culminate in establishing an institution. This perspective links internal organizational decision-making and behavioral logic with temporally and socially constructed external logic, enabling a deeper understanding of the behaviors underlying sociotechnical ecosystems. The unifying epistemological support of institutional theory captures the breadth and complexity of these processes, serving as a didactic and operational facilitator to understand the multifaceted entanglements of CIM, BIM, and GIS technologies with complex management systems across diverse political contexts. Accordingly, institutional theory shows promise for understanding how these technologies are socio-politically constructed in different technical contexts of urban management and planning (Augusto P. Pereira & Mario Procopiuck, 2022).

In the unification process to form a coherent ontological foundation, the analogy between BIM and CIM technologies has been well-received in studies on urban digital technologies. Gil (2020) demonstrated that both operate in a virtual simulation context, constructing three-dimensional entities linked to information (Xu et al., 2014). This information interacts parametrically with the projected virtual reality (Beirão et al., 2009), enabling the projection of scenarios and simulation of current and future realities (Harun et al., 2016). This simulation capability gives managers a more tangible visualization of complex scenarios, supporting decision-making processes based on simulated evidence (Gil et al., 2011). Additionally, these three-dimensional models facilitate the exchange of intersectoral and interdisciplinary information (Harun et al., 2016). However, implementing these models is complex, requiring the interaction of policies, processes, and technologies to create a methodology that manages the lifecycle of simulated objects, particularly within the context of the built urban environment (Succar & Sher, 2012).

Given this complexity, implementing information technologies requires a robust methodological framework comprising a systematic set of ontologically consistent relationships and a straightforward conceptual design. Implementation effectiveness increases when linked to administrative concepts and practices, such as corporate strategy or urban management (Jung & Joo, 2011). In urban management and planning, this robustness is achieved by connecting technology construction to political variables that constitute broad organizational fields or sociotechnical ecosystems underpinning comprehensive first- and second-order urban systems.

Instrumentally, an important step is to incorporate this unified ontology of management systems and technologies into public policies to encourage the widespread adoption of resulting tools (Pereira & Prokopiuk, 2024a). This integration is crucial because merely disseminating these technologies is insufficient to ensure success in urban management. A critical challenge for public authorities is promoting the dissemination of these technologies and leading by example, adopting them as pioneers, establishing supportive connections with the cities' daily operations, and leveraging external resources and competencies. Moreover, adjusting organizational culture is essential to positively influence adoption, implementation, and diffusion processes, fostering new ways of thinking and acting in urban solution development (Liao & Teo, 2018). In the Brazilian context, one of the greatest challenges at this stage has been overcoming the rigid organizational culture of public institutions (Melati & Janissek-Muniz, 2017).

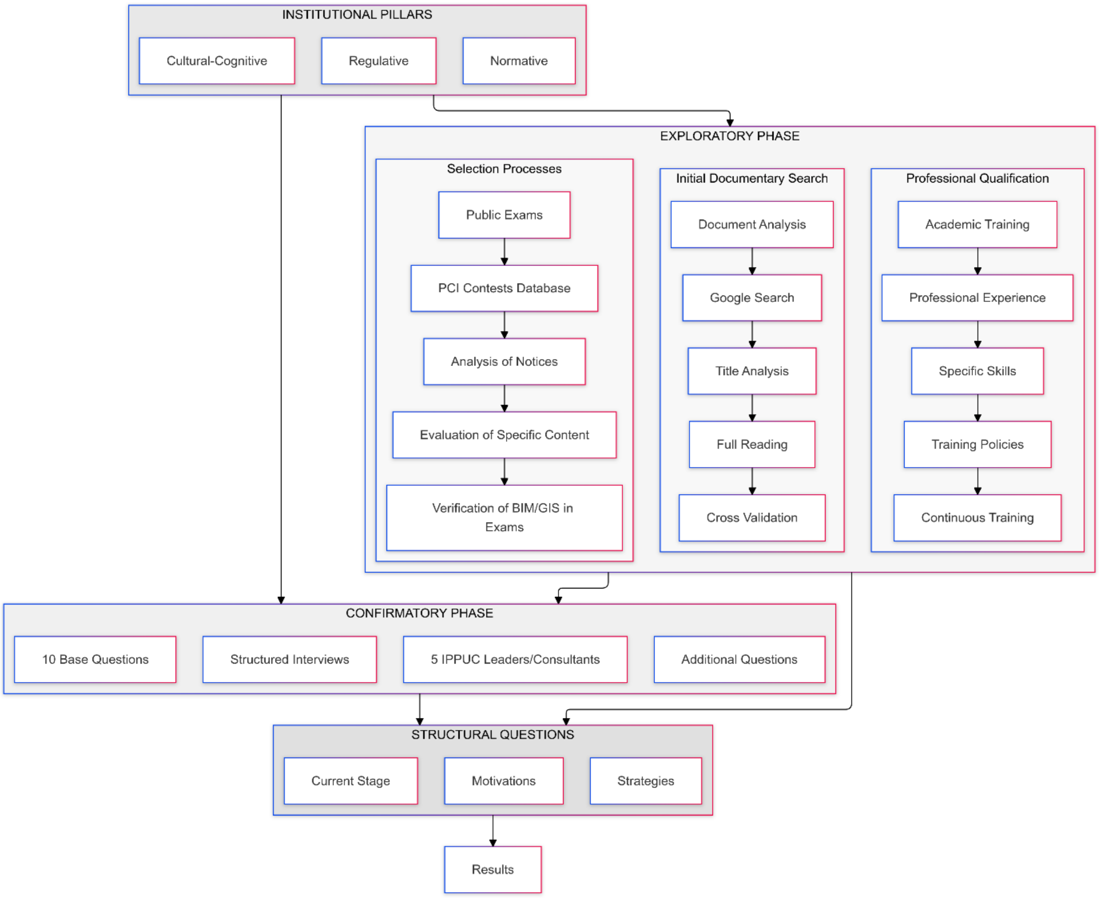
From an external perspective, assessing public sector readiness is necessary to understand governments' capacity to produce and deliver services based on advanced communication and information technologies (Ayanso et al., 2011; Harun et al., 2016). In addition to focusing on the organizational culture of public administration bodies, CIM technologies must be socially and politically legitimized in the urban context. In this regard, an organizational field or sociotechnical ecosystem offers an initial understanding of the social and technical infrastructure required to support new technologies adopted by local public authorities. It is also essential to consider the imposition of these technologies as a prerequisite for professional practices in fields such as engineering, architecture, and urban planning.

4. METHODOLOGICAL PROCEDURES

The institutionalist approach often associates institutions with organizations and the rules or conventions that constitute and operationalize them (Hall & Taylor, 2003, p. 196). Building upon these foundations, this exploratory, descriptive, and confirmatory study employed document analysis and interviews with key stakeholders to understand the dynamics of BIM and GIS implementation processes in Curitiba, as illustrated in Figure 1. It aimed to construct a documented narrative.

4.1. Exploratory Phase: Document Analysis

The primary data sources utilized during the exploratory phase included detailed reports on the stages of the implementation process and legal, regulatory, and normative instruments related to GIS and BIM technologies, as outlined in Appendix I. These reports provided insights into project development, challenges encountered, and strategies adopted. Additionally, municipal and state selection examinations for hiring engineering and architecture professionals were analyzed, focusing on including questions related to the technologies mentioned earlier. This analysis assessed whether the required knowledge in these examinations aligned with the current technological needs of the organizations.



Source: Own processing

FIGURE 1 – RESEARCH PROCESS

The final stage of document investigation involved evaluating the profiles of professionals hired to join municipal technical teams responsible for implementing and operating GIS and BIM technologies. This assessment considered their academic backgrounds, professional experiences, and specific skills, verifying their ability to contribute to ongoing technological innovation projects. Furthermore, the training and capacity-building policies offered to new hires and the continuity of these practices were examined to ensure professionals' constant adaptation and development in response to new technologies.

To align empirical findings with theoretical foundations, data collection was structured around Scott's (2014) three institutional pillars: regulative, normative, and cultural-cognitive. The rationale for using these analytical categories lies in two key points: (i) these concepts provide a comprehensive framework for various approaches by addressing critical issues across this diversity, and (ii) this structure encompasses

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both formal organizational aspects (regulative and normative pillars) and informal rules and procedures (normative and cultural-cognitive pillars), which tend to be constructed and developed over time in each specific context. This study includes the adoption, implementation, and diffusion of GIS and BIM technologies. Table 1 presents the indicators organized by pillar.

TABLE 2 - INDICATORS OF THE THREE INSTITUTIONAL PILLARS (ADAPTED FROM SCOTT (2014))

Pillars of Institutions	Regulative	Normative	Cultural-Cognitive
Indicators	Rules, Laws, Sanctions	Certification, Accreditation	Common beliefs, Shared logic of action, Isomorphism
Mechanisms	Coercive	Normative	Mimetic
Basis of legitimacy	Legally sanctioned	Morally governed	Comprehensible, Recognizable, Culturally supported
Affect	Fear, Guilt/Innocence	Shame / Honor	Certainty / Confusion

Source: Own processing

The exploratory phase began with collecting documents through the Google search platform, using the keywords shown in Table 2 to ensure a necessary distance from the discursive practices and inducements provided by project agents. Document evaluation was based on adherence to the research's central theme. Initially, titles were analyzed, followed by a complete reading of the selected documents to validate and cross-reference information. Comprehensive readings were also conducted on laws and regulations related to the investigated technologies' adoption, implementation, and dissemination. The investigation sought evidence of the characteristics listed in Table 1 in Curitiba's BIM and GIS adoption processes. It aimed to identify how these technologies were integrated, their challenges, and their implementation and diffusion strategies.

TABLE 2 – SEARCH KEYWORDS

Units of Analysis	Keywords used in the search
Implementation of GIS / Metrogeo	"Metrogeo" AND "IPPUC"; "GIS" AND "IPPUC"; "Metrogeo" AND "PMC"; "GIS" AND "PMC"
Implementation of BIM / LaBIM/PMC	"LaBIM" AND "IPPUC"; "BIM" AND "IPPUC"; "LaBIM" AND "PMC"; "BIM" AND "PMC"

Source: Own processing

In the second phase, the investigation sought information about public examinations for hiring architecture and engineering professionals in municipal and state agencies that comprise the sociotechnical ecosystem responsible for integrating and managing ICTs in Curitiba. In Brazil, public examinations are essential selection processes for public administration at municipal, state, and national levels. These exams aim to democratize access to public positions, ensure impartiality, and prevent political appointments. By implementing meritocracy, the best candidates are selected for public tasks through rigorous evaluations, including exams and tests, following legal and public notice rules.

To obtain technical content used in these processes, the study relied on the document database from the preparatory platform "PCI Concursos" (2021), one of the most comprehensive information sources for technical hiring in Curitiba and the Metropolitan Region. The analysis focused on the specific knowledge sections of the exams, identifying questions related to BIM and GIS to generate an external comparative analytical reference to organizational operational dynamics.

4.2. Confirmatory Phase: Structured Interviews

In the third phase of this research, of an affirmative nature, structured interviews were conducted with five leaders and consultants from the Curitiba Institute of Urban Research and Planning (IPPUC), all of whom were directly involved in the Metrogeo or LaBIM/PMC projects. Participant selection was guided by criteria ensuring the validity and reliability of the collected data. Priority was given to professionals affiliated with IPPUC or partner entities, such as the Municipal Infrastructure Department, who were directly involved in planning, implementing, or managing the analyzed projects. The sample included individuals with relevant professional backgrounds and proven expertise in GIS and BIM technologies, encompassing managers and technicians at different hierarchical levels to provide a comprehensive view of the challenges and solutions associated with the initiatives. The selection process was based on consultations of organizational records and institutional contacts provided by project managers. This resulted in a diverse group of interviewees representing various roles within the BIM/GIS ecosystem.

This phase aimed to validate and deepen the data collected during the exploratory phase based on contextualized document analysis. The interviews sought to connect findings, either confirming or refuting previously obtained information, while offering a more detailed understanding of the projects' managerial and technical aspects. Initially, ten critical questions were posed to the interviewees, with additional questions added as the interviews progressed to enrich data collection and ensure a more comprehensive analysis.

Table 3 outlines these ten initial questions and their relationship to the institutional pillars. The structured interview process, detailed in Table 3, followed a logical sequence of questions exploring different aspects of the institutional pillars: regulative (R), normative (N), and cultural-cognitive (C). For example, P1RNC sought to identify the primary motivators for realizing the LaBIM and Metrogeo projects, while P2C addressed the influence of other projects or organizations. P3NC explored partnerships between Metrogeo and LaBIM, and P4RNC examined the primary BIM/GIS diffusion strategies adopted. P5NC assessed the influence of IPPUC's prior geoprocessing expertise on the LaBIM project. P6RNC investigated the use of external consultancies and their areas of contribution. P7RN reviewed the practice of consulting on BIM or GIS topics for public hiring examinations. P8NC evaluated the technological competencies of newly hired professionals at IPPUC. P9RNC discussed the participation and engagement of other BIM/GIS ecosystem agents. Lastly, P10RNC assessed the current implementation stage of the projects. This progression enabled a comprehensive and detailed analysis of the factors influencing the institutionalization and implementation of BIM and GIS technologies in Curitiba.

TABLE 3 – INTERVIEW SCRIPT

Code	Question	Regulative Pillar	Normative Pillar	Cultural-Cognitive Pillar
P1	Based on your experience with LaBIM/Metrogeo, what were the main motivators for the project's realization?	x	x	x
P2	Did you notice any influence from other projects or organizations in the development or implementation of the project?			x
P3	Did Metrogeo develop any initiatives in partnership with LaBIM?		x	x
P4	What are the main BIM/GIS diffusion strategies adopted by LaBIM/Metrogeo?	x	x	x
P5	Do you believe IPPUC's prior geoprocessing knowledge influenced the LaBIM project?		x	x
P6	Did the project involve external consultancy? In which areas did they assist?	x	x	x
P7	Were you consulted about BIM or GIS topics or questions for recent public hiring examinations? Is this a regular practice?		x	x
P8	Have the new professionals hired at IPPUC already mastered BIM/GIS technology?		x	x
P9	How do you perceive the participation and engagement of other agents in the BIM/GIS ecosystem within the project?	x	x	x
P10	Regarding the project's progress, what is the current stage of Metrogeo/LaBIM? Do you believe implementation is ongoing?	x	x	x

Source: Own processing

The unified analysis of the information obtained in the exploratory and confirmatory phases sought to answer three structural questions: (i) What were the motivations for creating the LaBIM and Metrogeo organizations? (ii) What strategies were employed in the institutionalization process of these organizations? (iii) What is the current institutionalization stage of each organization? Integrating the collected information allowed for a deeper understanding of the factors influencing the adoption and implementation of GIS and BIM technologies in Curitiba, offering a consolidated view of initial motivations, institutionalization strategies, and progress.

5. RESULTS AND DISCUSSION

The findings from the exploratory phase revealed a fragmented landscape for the development of the LaBIM and Metrogeo projects, highlighting the absence of consolidated initiatives and the disconnection between the organizational context and the hiring process. The document collection and analysis of legal and regulatory instruments uncovered significant discrepancies in the management of territorial information and in the strategies for implementing GIS and BIM technologies.

In the subsequent phase, the analysis of public hiring examinations exposed a misalignment between technical requirements and organizations' contemporary technological needs. This underscored the lack of clear criteria for selecting professionals qualified to address these innovations.

Finally, the confirmatory phase, through structured interviews with IPPUC leaders and consultants, corroborated the initial perceptions raised during the document analysis while adding insights into the operational and managerial challenges encountered daily. The interviews detailed the cultural, normative, and regulatory influences shaping the adoption and implementation of these technologies, providing a more comprehensive view of the institutional dynamics at play.

The following sections delve deeper into these discussions, offering a detailed understanding of the institutional and operational context of the analyzed projects.

5.1. Contextualizing Technological Initiatives in Curitiba: Metrogeo and LaBIM

Curitiba is home to two significant initiatives related to territorial information modeling and georeferencing: the GIS platform Metrogeo and the BIM diffusion laboratory LaBIM/PMC, both integrated into the municipality's public administration (PMC). These projects are the primary analysis subjects in this investigation, forming the foundation for subsequent discussions and studies.

Metrogeo is an interactive GIS system developed in partnership with the Coordination of the Metropolitan Region of Curitiba (COMEC) to consolidate geographic, cartographic, tabular, and image data for the Metropolitan Region of Curitiba (RMC) (IPPUC, 2017). This system standardizes and consolidates geographic information across the RMC municipalities, fostering more homogeneous governance (MundoGEO, 2014; PGP-PR, 2019). The system is managed by a committee comprising technical representatives from five towns, with technical coordination provided by IPPUC, which oversees monitoring, planning training sessions, and validating the data input into the platform (IPPUC, 2017). The goals of Metrogeo's implementation include establishing a georeferenced information network across the RMC and equipping teams to interact with and utilize the technology in the region's 29 municipalities

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(PGP-PR, 2019), serving an estimated population of 3,693,891 people and spanning an area of 16,581.21 km² (IBGE, 2020).

LaBIM/PMC is a laboratory dedicated to BIM technology, established by IPPUC to serve as a training center for all technical personnel in the Municipality of Curitiba (IPPUC, 2020). Funding for equipment acquisition, software, and training for managers, IT technicians, engineers, and architects was provided through the Pro-Cities program, financed by the Inter-American Development Bank (IDB) (IPPUC, 2019a). The implementation plan follows a phased timeline, beginning with the partial adoption of BIM in pilot projects and working groups involving various departments related to urban management and planning (Rizzardo, 2019). The initial actions focused on BIM adoption, representing the first phase of the process, followed by implementation and dissemination. This approach contrasts with the Brazilian federal government's strategy, which began with disseminating the technology.

Although these phases are reversed, the establishment of LaBIM/PMC was motivated by the BIM-BR Strategy, which designated BIM as a federal public policy in May 2018 (Brasil, 2018, 2019). This policy mandated the use of BIM technology in the direct or indirect execution of construction and engineering services, placing the responsibility for implementation on federal public administration entities (Brasil, 2020). The diffusion of BIM nationwide has already gained momentum through academic research, market studies, and initiatives by professional associations. Its inclusion as a public policy objective significantly increased its importance. Unlike older technologies such as CAD and GIS, BIM has become a central focus of public policy. When the state adopts a clear stance on BIM, establishing specific management capacities for this technology within governmental structures tends to be a logical consequence. However, it is noteworthy that the development of such supportive capacities is not uniform across administrative policies and often reflects the priorities of different governments (Souza, 2017).

It is important to note that Curitiba's adoption of BIM does not stem solely from the need to comply with the federal decree, as this does not directly apply to Brazilian cities. BIM adoption in Curitiba appears to be a mimetic process (DiMaggio & Powell, 1983), aligning with the national strategy for BIM diffusion and progressing toward effective adoption and implementation. This strategy aligns with the regulative pillar of Scott's (2014) framework, wherein normative mechanisms act as drivers of innovation. Document analysis revealed that the primary motivation was compliance with the federal standard and the process leader's recognition of the benefits BIM implementation could offer (IPPUC, 2019a).

5.2. Driving Factors for Technological Implementation

The analysis of documents and news regarding the implementation of Metrogeo revealed its origins as indirectly tied to the Curitiba Digital project. Initiated in the late 1990s, this project provided CD-ROMs containing city street maps with official names, developed based on the cartographic database (MundoGEO, 1998). By the mid-2010s, Metrogeo encountered significant challenges in information exchange due to a lack of interoperability in managing territorial data, with no standards or structures to harmonize geographic data across municipalities in the Metropolitan Region of Curitiba (RMC) (PGP-PR, 2019).The project also benefited from the support of ParanáCidade, a state agency supporting municipal planning, whose contribution was crucial for assembling and consolidating the database system.

Interviews revealed that Metrogeo originated from IPPUC technicians' realization that many RMC municipalities frequently and systematically requested GIS support. In response to this demand, efforts were made to establish a knowledge-sharing project among the cities, culminating in a formal, comprehensive agreement materialized as a unified and open database (PGP-PR, 2019). Additionally, as reported by the interviewees, IPPUC's prior experiences with geoprocessing and implementing CAD tools contributed to the consolidation of LaBIM/PMC and the adoption of BIM.

A noteworthy aspect of federal regulation is that the use of BIM in the direct or indirect execution of construction and engineering services by federal public administration entities is part of a National Strategy for BIM Dissemination. While this technology is promising for improving the quality of public engineering services, the foundational strategy appears to overlook its full potential. The federal government seemed more focused on promoting the BIM product than adopting it as an effective user. For instance, the decree established that, during the first dissemination phase beginning in 2021, BIM would be used solely for managing and developing new architectural and engineering construction projects considered of great relevance for BIM dissemination. This dissemination focus continues into the second phase, starting in 2024, with the incorporation of significant renovations. In the third phase, beginning in 2028, BIM is expected to be applied to construction or renovation projects deemed of medium or high relevance for dissemination. Interviewees also highlighted the facilitative role played by the IDB in the LaBIM/PMC project.

The federal government's strategy for BIM dissemination was aimed at the Ministry of Defense and the Ministry of Infrastructure, but it exhibits institutionalization weaknesses. These weaknesses stem, for example, from the strategy being established through a presidential decree without federal legislative participation. As a presidential directive, the plan lacks robust institutional support, especially compared to legislation passed and approved by Congress. Furthermore, the strategy limits BIM dissemination to

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direct administration entities, excluding organizations within the indirect public administration. Brazil's indirect administration includes public companies wholly owned by the government, such as the Brazilian Post and Telegraph Company, and companies with shared ownership between the government and private entities, such as Petrobras.

From a theoretical perspective, this federal decision contradicts the adoption, implementation, and dissemination processes, as discussed by Ahmed and Kassem (2018). It also diverges from the view that adoption represents when an organization decides to accept and apply technology in daily operations (Harun et al., 2016). The federal government's dissemination strategy seems more focused on promoting the technology market outside the public administration, mandating that engineering and architecture service providers internalize BIM rather than having public entities adopt it directly. Thus, the strategy emphasizes stimulating market supply for technology insertion rather than creating demand for BIM solutions within the public administration.

Nonetheless, the intention to disseminate BIM through the national strategy represents an important symbolic mechanism within the overarching multilevel governance system. This mechanism creates institutional pressure, encouraging municipal and state public administration technical bodies to advance in adopting, implementing, and disseminating this technology by promoting BIM as a national public policy—albeit more symbolically than practically—the federal government establishes a standard and expectation that influences subnational levels of government. This influence is reinforced by the need for normative compliance and recognition of the benefits associated with the technology, such as greater efficiency and transparency in engineering and architectural processes.

Moreover, the national strategy contributes to building institutional capacities, laying the groundwork for a more robust and coherent integration of these technologies into administrative practices in the future. Despite its limitations and weaknesses, the national strategy plays a significant role in creating an environment conducive to innovation and modernization of public processes, aligning with the theoretical principles of adoption and implementation discussed by Ahmed and Kassem (2016) and Harun et al. (2016).

5.3. Strategies and Implementation Mechanisms

The objectives of Metrogeo's implementation include enabling integrated territorial management, standardizing the structure of georeferenced information within the metropolitan context, sharing information, experiences, knowledge, technologies, and tools, and training municipal teams in the use of this information (PGP-PR, 2019). To achieve these goals, one strategy involved organizing various training courses and events for technicians from the municipalities of the Metropolitan Region of Curitiba

(RMC) (Aprendere, 2016a, 2016b; Bem Paraná, 2013, 2014; COMEC, 2013; IPPUC, 2016a, 2016b; MundoGEO, 2014; Piraquara, 2014). Curitiba assumed the role of project manager and signed cooperation agreements with other RMC municipalities (Click Riomafra, 2013; Curitiba, 2013). The interviews confirmed that the primary implementation strategy for Metrogeo was conducting training cycles in cities across Paraná, including some outside the metropolitan area. While the most consistent agreements were established in 2013, when the project gained greater visibility and dissemination, internal negotiations began in the late 2000s.

IPPUC led these initiatives as the agency responsible for system management, with support from other municipal technical bodies, such as the Municipal Secretariat for Metropolitan Affairs (SMAM) and the Municipal Institute of Public Administration of Curitiba (IMAP). The courses and agreements relate to Scott's (2014) cultural-cognitive pillar, promoting the dissemination of common beliefs and shared logic of action among the various agents operating and feeding data into the system. This effort to construct a shared understanding is essential for increasing the potential for technology dissemination and alignment, reducing uncertainty and confusion among technical and political agents regarding innovation. However, it is worth noting that training alone may be insufficient for effective technology adoption and implementation, as Harun et al. (2016) highlighted in their study on Malaysia's strategy.

The document analysis and interviews revealed that IPPUC's strategy for implementing LaBIM/PMC involved an agreement with an international development agency, establishing an extensive multilevel sociotechnical governance system. This agreement was formed with the state coordinating body for the Metropolitan Region of Curitiba and the national BIM dissemination policy. IPPUC signed a contract with the Inter-American Development Bank (IDB) to secure funding under the Pro-Cities program, enabling the acquisition of technological equipment and software while creating conditions for contracting projects partially executed in BIM (IPPUC, 2019a, 2019b; Rizzardo, 2019).

This allocation of resources highlights another institutionalization strategy for BIM: conducting pilot projects to apply the knowledge acquired during formal training programs in practice. These training programs constituted the third strategic axis of IPPUC's efforts to implement LaBIM/PMC, including formal training sessions, creating technical groups with other municipal departments, and technical meetings to align teams (IPPUC, 2019a, 2020).

The fourth identified strategic line was the creation of a BIM Development Plan to formalize the municipal technology dissemination strategy (Rizzardo, 2019), representing a mimetic process relative to the federal government's policy. Interviewees emphasized that widespread dissemination is promoted by establishing a municipal committee involving other departments formalized through a municipal decree (PMC, 2022).

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The fifth strategic line was establishing a technical cooperation agreement between LaBIM/PMC and LaBIM/SEIL (the BIM Laboratory of Paraná's Secretariat of Infrastructure and Logistics). Created in 2015 (LaBIM, 2015) with a consolidated trajectory, LaBIM/SEIL achieved significant results, such as publishing the BIM Handbook, which provides guidelines for public building project development using BIM (Lima, 2018).

This fifth strategy resulted in numerous references to LaBIM/SEIL in research on LaBIM/PMC, underscoring the technical cooperation between these organizations. The laboratories' names suggest that mimetic mechanisms position LaBIM/PMC within Scott's (2014) cultural-cognitive pillar. Beyond the isomorphic behavior adopted by the municipal laboratory, this technical cooperation facilitated the creation of common beliefs and shared logic of action among agents from both organizations, illustrating the association of isomorphism with the cultural-cognitive pillar.

LaBIM/SEIL is considered a benchmark laboratory, achieving notable milestones such as publishing the BIM Handbook (Lima, 2018) and completing its first pilot project to implement BIM (Edificações, 2019). Cooperation with this reference organization to support LaBIM/PMC's initiatives can be viewed as a form of certification or quality endorsement, positioning the laboratory within Scott's (2014) normative pillar.

The interviews also revealed that access to robust funding allowed LaBIM/PMC to adopt another strategy: hiring external consultants. These consultants contributed at multiple levels, including training technical staff and drafting terms of reference for new BIM project contracting modalities.

5.4. Institutionalization Stages of Metrogeo and LaBIM/PMC

In 2019, Metrogeo was awarded the Paraná Public Management Award (PGP-PR, 2019) for its role as a provider of training services and events directly aligned with its organizational objectives. This recognition was a normative indicator in the institutional analysis; certification validated and legitimized Metrogeo's implementation process.

According to the proposed timeline for Metrogeo's implementation phases in 2021, activities included the operational integration of urban cadastral databases and the continuation of training initiatives. Preceding the formalization of partnerships, critical activities encompassed system development, operator training, the launch of the Metrogeo portal, the creation of a reference road network, the development of a thematic database, the establishment of a metropolitan road network, and the importation of rural cadastral data. These findings, derived from documentary sources and previously published works (e.g., Alves, 2020), indicate an advanced implementation stage.

However, based on documentary findings, the project is currently stalled, with its online platform unavailable and no recent updates regarding its progress. Interviews confirmed these observations, revealing that the project has been paralyzed. Despite this, Metrogeo remains a topic in municipal government plans, reinforcing its high level of institutionalization and the presence of normative and regulatory pillars. While Curitiba's robust technical workforce sustains long-term technological implementation perspectives (Pereira & Prokopiuk, 2022), smaller municipalities face different challenges. Many metropolitan cities rely on commissioned or temporary staff for geoprocessing roles, leading to training courses with expiration periods tied to political cycles and election outcomes. Metrogeo has recently become politically contentious in Curitiba, being removed from the current administration's government plans.

To reconcile theory with practice, this study presents evidence of Metrogeo's institutionalization stage, aligning it with the phases proposed by Tolbert and Zucker (1996). This analysis makes asserting that the project is currently in the objectification phase plausible. In this stage, there is consensus among leaders about its value, and its adoption by organizations is increasing. To progress to the sedimentation phase—when routines and practices are externalized and naturally transmitted (Baptista et al., 2010)—the project must withstand the test of time, embedding itself into historical continuity and enduring across generations (Tolbert & Zucker, 1996). The recent disruptions caused by political interests reinforce this classification.

TABLE 4 – SYNTHESIS OF PROJECT CLASSIFICATIONS ACCORDING TO THE APPLIED EPISTEMOLOGY

Institution	Identified Institutional Pillars (Scott (2014))	Institutionalization Stage (Tolbert & Zucker (1996))
Metrogeo	Regulative: Rules and inspections. Normative: Certifications and awards, such as the Paraná Public Management Award. Cultural-Cognitive: Creation of shared beliefs and a shared logic of action.	Objectification (stalled): Consensus on the project's value; increasing organizational adoption; need for continuous testing to achieve sedimentation; the impact of political disruptions.
LaBIM/PMC	Regulative: Legal framework and national strategies such as the BIMBR Strategy. Normative: Formation of technical groups and creation of a BIM Development Plan. Normative: Formation of technical groups and creation of a BIM Development Plan.	Habitualization evolving toward objectification: Early formation and promotion of new organizational arrangements; primary forces (technological change, legal basis, and market forces); inter-organizational interaction and early implementation; pilot project execution and work completion required to conclude the objectification phase.

Source: Own processing

By comparison, according to Tolbert and Zucker's (1996) framework, LaBIM/PMC is at an earlier stage than Metrogeo, currently in the habitualization phase. In the institutionalization process of BIM, three primary forces drive innovation: technological change, the legal foundation for its adoption, and market forces acting as catalysts for change. IPPUC has begun forming, promoting, and formalizing new organizational arrangements, materialized in LaBIM/PMC and its Development Plan. The transition to the objectification phase is underway, evidenced by inter-organizational interactions and the commencement of implementation strategies. This phase's completion will depend on the execution of pilot projects and the finalization of construction works. Interviewees corroborated these observations, noting that municipal-level diffusion remains in its infancy while internal implementation progresses consistently.

5.5. Hiring Policies and Competency Development

The two analyzed organizations' training approaches for technical staff in the core technologies varied significantly. While Metrogeo relied on internal intellectual capital, with IPPUC employees and outsourced agents conducting the training, LaBIM/PMC exclusively depended on external agents for this capacity-building. These distinct approaches highlight the level of internalization of knowledge in each organization, suggesting that the development of the cultural-cognitive pillar is more advanced in Metrogeo than in LaBIM/PMC.

Competency development in both cases could be accelerated if the hiring processes for technical staff were aligned with organizational planning and kept pace with innovations. The investigation emphasized evaluating technical knowledge exam content used in public hiring processes and identifying questions related to information technologies used in the built environment. This assessment was relevant because, in Brazil, public servants tend to remain within an organization for several years, allowing groups of employees to establish criteria for admitting future generations of professionals. This trend provides an additional measure of the level of technology internalization within Brazilian public organizations, as exemplified by IPPUC.

For instance, selection exams conducted by PMC in 2010 and 2019 for hiring architects included questions on AutoCAD commands (NC-UFPR, 2010, 2019) but did not address BIM or GIS technologies. Similarly, the examination for hiring a junior architect at Curitiba's COHAB featured two questions on AutoCAD (FUNTEF-UTFPR, 2009), while the exam for COHAPAR did not assess AutoCAD proficiency at all (PUCPR, 2011). However, all these exams included questions on architectural design and spatial understanding, project management, project implementation, and construction oversight. These questions could be contextualized to include aspects related to BIM.

Similarly, GIS could be integrated into land use and zoning legislation questions. Interviews revealed that Metrogeo and LaBIM/PMC technicians were not consulted during the preparation of hiring exams. Nevertheless, interviewees noted an increasing influx of technicians proficient in these technologies—not due to exam requirements but through their market-driven initiatives. This evolving maturity of the context positively contributes to developing basic technological skills.

None of the interviewees reported being consulted during the exam preparation process. They observed that new hires, particularly younger professionals, tend to show greater interest in new technologies. However, they believe the alignment between individuals and their positions occurs more by chance than by strategic design. This condition reflects the fragmentation often highlighted by urban management and planning scholars, particularly regarding technology integration (e.g., Firmino & Frey, 2014). In response, interviewees reported that department leaders and technical teams monitor the skills of new staff to reposition them in roles better suited to their expertise.

While it is understandable that hiring exams do not exclusively focus on current technologies, emphasizing technologies that are becoming outdated highlights a disconnect between hiring practices and the management of adoption, implementation, and dissemination processes for strategic technologies. One of these exams occurred after federal legislation established BIM as public policy. Furthermore, all these evaluations aimed to recruit professionals specializing in urban management and planning—fields that utilize GIS as a decision-making support tool.

Table 5 illustrates the internalization of competencies and technologies in Metrogeo and LaBIM/PMC, highlighting the regulative, normative, and cultural-cognitive pillars according to Scott’s (2014) framework and the institutionalization stages proposed by Tolbert and Zucker (1996).

For Metrogeo, the dominance of the regulative pillar and the lack of consultation with technicians during hiring processes indicate a misalignment between emerging technological needs and recruitment practices, reflecting a stalled objectification stage. Despite increasing organizational adoption and normative recognition, political interruptions hinder its sedimentation.

Conversely, LaBIM/PMC, still in the habitualization phase, heavily relies on external agents for training but shows progress in forming new organizational arrangements and executing pilot projects. Integrating continuous training policies and including emerging technologies in hiring exams is essential to align technical expertise with current demands, facilitating a more effective transition to objectification.

Both organizations require more structured and integrated strategies to overcome cultural and operational barriers, ensuring continuous evolution and robust competency development in urban management and planning.

TABLE 5 – EVALUATION OF TECHNOLOGY INTERNALIZATION PROCESSES IN THE ORGANIZATIONS

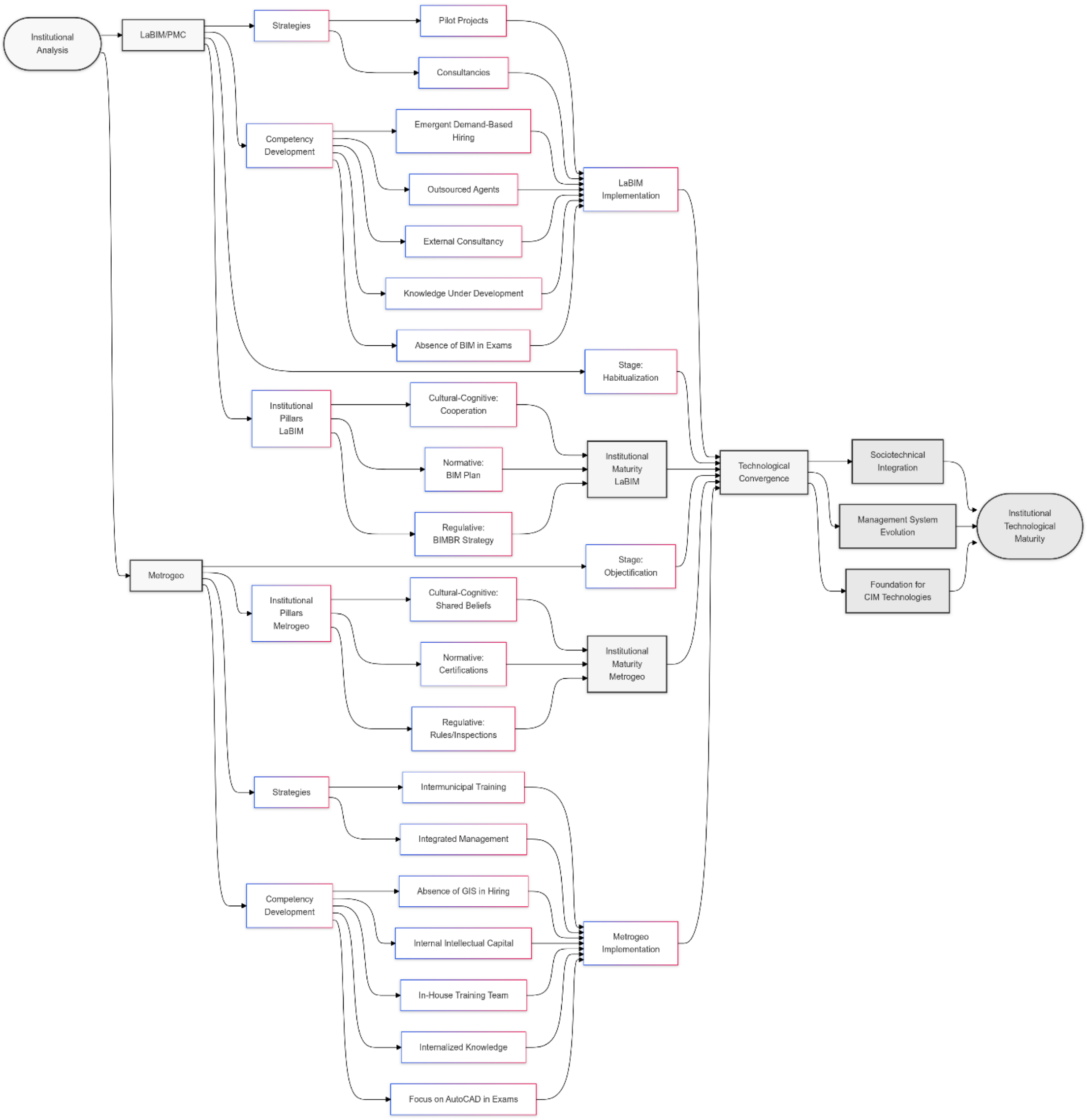
Organization	Identified Institutional Pillars (Scott (2014))	Institutionalization Stage (Tolbert & Zucker (1996))
Metrogeo	**Regulative:** Hiring exams focus on AutoCAD without addressing BIM or GIS; lack of consultation with Metrogeo technicians in exam preparation. **Normative:** Training courses and events for municipal technicians; certifications and awards like the Paraná Public Management Award. **Cultural-Cognitive:** Hiring professionals proficient in new technologies occurs primarily due to individual initiative; there is a need for a more structured strategy to align positions with technology usage; future inclusion of BIM and GIS in hiring exams and development of continuous training policies; and reliance on internal intellectual capital and external agents for training.	**Objectification (stalled):** Consensus on project value; increasing organizational adoption; need for ongoing testing to achieve sedimentation; political disruptions impede progress; necessity for organizational adaptability and technological competence to ensure project evolution and robust skill-building.
LaBIM/PMC	**Regulative:** Lack of strategic alignment between hiring processes and the need for emerging technological competencies. Normative: New hires demonstrate interest and knowledge in emerging technologies through individual initiative; assessment of hired professionals shows positive trends in developing basic technological skills; the importance of continuous training policies to align technical expertise with emerging technological demands. Cultural-Cognitive: Exclusive reliance on external agents for training; use of external consultants for training and drafting reference terms.	**Habitualization evolving toward objectification:** Formation of new organizational arrangements; driving forces include technological changes and market forces; execution of pilot projects; completion of construction projects required for a complete transition to objectification; contextual maturity positively contributes to essential technological skill development.

Source: Own processing

5.6. Technological Convergence and Institutional Maturity: A Comparative Analysis

Figure 2 provides a synthesized representation of how institutional analysis diverges into two technological initiatives in Curitiba: Metrogeo and LaBIM/PMC. Each initiative is structured through four fundamental dimensions: institutional pillars (regulative, normative, and cultural-cognitive), institutionalization stage (objectification for Metrogeo and habitualization for LaBIM/PMC), implementation strategies, and competency development. These dimensions interact to produce two intermediate outcomes: institutional maturity and the specific implementation of each project.

The convergence of results from both initiatives materializes through the interaction between institutionalization stages, institutional maturity, and implementation processes. This technological convergence yields three primary outcomes: establishing the foundations for CIM technologies, promoting the evolution of management systems, and enabling sociotechnical integration. Combining these three elements culminates in establishing institutional and technological maturity, constituting the institutionalization process's ultimate goal.



Source: Own processing

FIGURE 2 – FLOW TOWARD INSTITUTIONAL TECHNOLOGICAL MATURITY

LaBIM/PMC, currently in its habitualization phase, is characterized by the implementation heavily reliant on external agents (consultants and contractors) and a competency development process still in progress.

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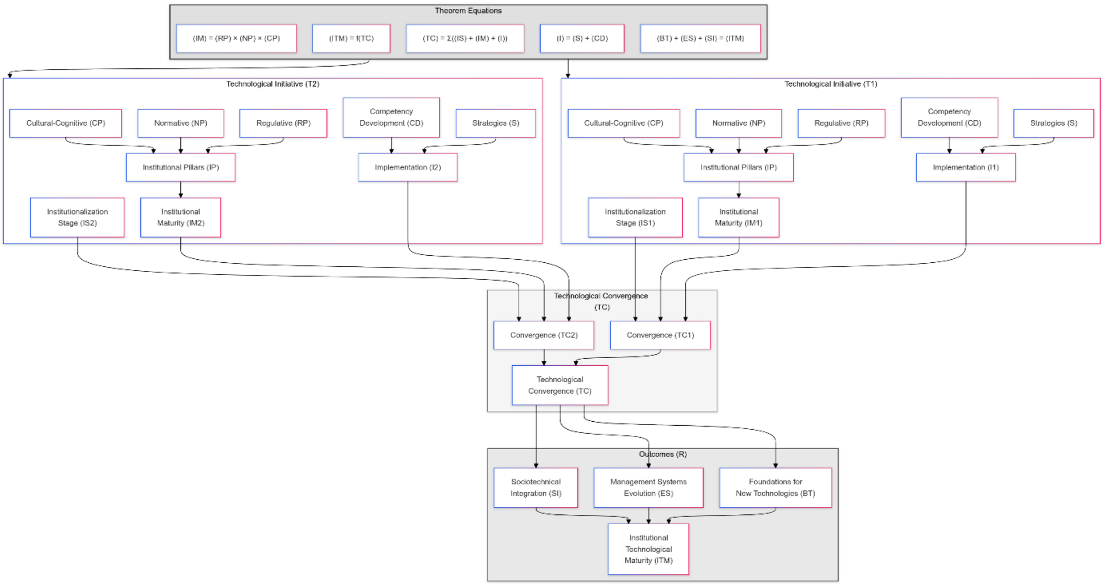
This reflects an early stage of institutional maturity, where practices and routines are yet to be solidified. Conversely, Metrogeo, in its objectification phase, demonstrates a more consolidated implementation with internal intellectual capital and in-house training teams, signaling greater institutional maturity. However, it continues to face challenges, such as lacking GIS-related considerations in hiring processes and a persistent focus on legacy technologies like AutoCAD.

An Institutional Convergence Theorem for Technological Maturity can be proposed using formal logic. The logical structure underlying Figure 2 posits that, in an urban management system where multiple institutional technological initiatives (T) coexist, institutional technological maturity (ITM) is a function of technological convergence (TC), which emerges from the interaction between different institutionalization stages (IS), institutional maturity (IM), and implementation (I) of each initiative. This convergence, in turn, produces three fundamental outcomes: foundations for new technologies (BT), evolution of management systems (ES), and sociotechnical integration (SI).

For each technological initiative T, institutional maturity (IM) is determined by the interaction of the regulative pillar (RP), the normative pillar (NP), and the cultural-cognitive pillar (CP), while implementation (I) results from the combination of strategies (S) and competency development (CD). The institutionalization stage (IS) evolves from habitualization to objectification and eventually sedimentation, directly influencing technological convergence (TC). Thus, $ITM=f(TC)$, where $TC = \sum(IS+IM+I)$ for each initiative T.

When two or more institutional technological initiatives converge, even at different institutionalization stages (e.g., habitualization and objectification), institutional technological maturity (ITM) emerges from the interaction between BT, ES, and SI. A necessary condition for this convergence is the presence of established institutional pillars and active implementation processes in each initiative, irrespective of their institutionalization stage. A sufficient condition is the system’s capacity to generate BT, ES, and SI simultaneously and synergistically.



Source: Own processing

FIGURE 3 –LOGICAL FLOW OF THE INSTITUTIONAL TECHNOLOGICAL MATURITY THEOREM

Figure 3 expresses the graphical visualization of the theorem's logical relationships. This Institutional Convergence Theorem for Technological Maturity is grounded in institutional theory as a unifying epistemological framework, as proposed by Scott (2014). This framework identifies the regulative, normative, and cultural-cognitive pillars as the structural elements of organizational practices. Pereira and Procopiuck expanded upon this framework through the perspective of urban technological ecosystems (2022).

The theorem's logical construction incorporates institutionalization stages defined by Tolbert and Zucker (1996)—habitualization, objectification, and sedimentation—demonstrating how distinct technological initiatives can converge despite varying levels of institutional maturity, particularly in contexts with a historical trajectory of innovations (Augusto Pimentel Pereira & Mario Procopiuck, 2022).

A sociotechnical perspective supports this convergence (Sahay & Robey, 1996) (and an analysis of BIM/CIM/GIS ecosystems, where sociotechnical approaches help prevent the diffusion of these technologies from reinforcing existing structural problems within organizational fields (Augusto P. Pereira & Mario Procopiuck, 2022). The theorem aligns with technological adoption and implementation processes as described by Harun et al. (2016) and Ahmed and Kassem (2018), where adoption signifies the decision to utilize innovation in daily operations, and implementation realizes this decision in specific contexts.

Ultimately, this convergence aligns with what Pereira and Procopiuck (2022) describe as a methodology for managing the life cycle of projects in dynamically constructed urban environments. It culminates in forming sociotechnical innovation ecosystems articulated through multilevel governance systems.

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6. CONCLUSION

This study confirmed its two initial hypotheses and achieved its investigative objectives. The first hypothesis (H1) was validated by demonstrating that the interaction among institutional pillars (regulative, normative, and cultural-cognitive), institutionalization stages, and the social meanings attributed to technologies provides a logically consistent analytical framework for understanding the implementation of GIS and BIM Curitiba. The second hypothesis (H2) was also confirmed, revealing that the technological convergence patterns observed in the implementation and adoption processes, mediated by local institutional logic and organizational changes, contribute to theoretical advancements in understanding institutional maturity in complex urban contexts. This logically articulated convergence became particularly evident in the comparative analysis of Metrogeo at the objectification stage and LaBIM/PMC at the habitualization stage, illustrating how different levels of institutional maturity can coexist and complement each other in urban technological evolution.

The empirical analysis revealed distinct characteristics in the institutionalization processes for the technologies in Curitiba, depending on the initiative. Metrogeo, despite its greater institutional maturity and position in the objectification phase, faces significant challenges related to political discontinuity and fragmentation of technical competencies among municipalities in the metropolitan region. Conversely, LaBIM/PMC, still in its habitualization phase, exhibits a more structured implementation process, benefiting from international support, technical cooperation agreements, and a clear development strategy. This dynamic illustrates how different institutionalization trajectories can emerge within the same urban context, influenced by political and institutional arrangements, installed technical capacities, and available financing mechanisms. The analysis also underscored the critical importance of continuous competency development and the alignment of hiring processes with contemporary technological needs, which proved determinant for the sustainability of the initiatives.

The practical implications of this study offer essential guidance for urban managers and planners involved in implementing urban information technologies. Curitiba's experience, in particular, highlights the importance of establishing a balanced approach between technical and institutional aspects when implementing GIS and BIM technologies. The findings indicate that the success of such implementations depends not only on investments in infrastructure and software but fundamentally on building institutional capacities and articulating multiple levels of governance. For other cities, both in Brazil and internationally, the findings suggest the need to (i) develop integrated competency-building strategies that transcend political cycles, (ii) establish multilevel technical cooperation mechanisms to enhance the sustainability of initiatives, (iii) align hiring processes and professional development with emerging technological demands, and (iv) consider technological convergence as a gradual process requiring institutional maturity across different levels. Curitiba's experience also demonstrates that the successful implementation of urban technologies requires a delicate balance between technical innovation and institutional stability. Thus, it offers an adaptable model for cities aiming to modernize their urban management and planning practices.

As inherent limitations of a single-case study, the results reflect the specificities of Curitiba's institutional context, a city with a consolidated trajectory of innovation in urban planning and management. However, the analytical framework developed from the empirical analysis and grounded in consistent theoretical foundations advanced toward a conceptual structure that can be tested and expanded in different urban contexts. Future research may apply this framework to analyze technological implementation processes in cities with varying levels of institutional maturity, validating and refining the identified relationships among institutional pillars, institutionalization stages, and technological convergence patterns. Additionally, comparative investigations across multiple cities using the proposed framework can contribute to developing more precise metrics for institutional and technological maturity and identifying critical success factors in implementing urban technologies within diverse sociotechnical contexts.

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