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# Maturity model for the implementation of digital twins in a brazilian public health unit

## Modelo de maturidade para a implementação de gêmeos digitais em uma unidade de saúde pública brasileira

## Modelo de madurez para la implementación de gemelos digitales en una unidad de salud pública brasileña

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**Abstract**
The objective of this research is to present a study that helps to fill a gap in the literature by proposing a maturity model to assess the readiness of Brazilian public health units for the implementation of Digital Twins (DTs). DGs, as part of Industry 4.0 (I4.0) technologies, can optimize resource and process management in healthcare. The model was developed through a systematic review of Critical Success Factors (CSFs) for DG implementation and maturity model dimensions. CSFs were grouped into six conceptual classes, while maturity dimensions were categorized into four: Infrastructure, Organization, Processes, and Information Management—each with four levels: Initial, Basic, Intermediate, and Advanced. Preliminary validation was conducted in basic health units in two cities and two hospitals in the southern Fluminense region of Rio de Janeiro. Results showed the model's ability to differentiate organizational maturity levels, highlighting its potential for practical application. This study contributes to the field by offering a tailored tool for strategic planning and resource allocation in the implementation of DGs in the public health sector, with possible expansion to private units.
**Keywords:** Digital Twins; Unified Health System; Maturity Model; Digital Transformation.

**Resumo**
O objetivo desta pesquisa é apresentar um estudo que contribua para preencher uma lacuna na literatura por meio da proposição de um modelo de maturidade para avaliar a prontidão das unidades de saúde pública brasileiras para a implementação de Gêmeos Digitais (DGs). Os DGs, como parte das tecnologias da Indústria 4.0 (I4.0), podem otimizar a gestão de recursos e processos na área da saúde. O modelo foi desenvolvido a partir de uma revisão sistemática dos Fatores Críticos de Sucesso (FCS) para a implementação de DGs e das dimensões de modelos de maturidade. Os FCS foram agrupados em seis classes conceituais, enquanto as dimensões de maturidade foram categorizadas em quatro: Infraestrutura, Organização, Processos e Gestão da Informação—cada uma com quatro

níveis: Inicial, Básico, Intermediário e Avançado. A validação preliminar foi realizada em unidades básicas de saúde de dois municípios e em dois hospitais da região sul fluminense do Rio de Janeiro. Os resultados demonstraram a capacidade do modelo de diferenciar os níveis de maturidade organizacional, destacando seu potencial de aplicação prática. Este estudo contribui para a área ao oferecer uma ferramenta adaptada para o planejamento estratégico e a alocação de recursos na implementação de DGs no setor público de saúde, com possível expansão para o setor privado.
**Palavras-chave:** Gêmeos Digitais; Sistema Único de Saúde; Modelo de Maturidade; Transformação Digital.

**Resumen**
El objetivo de esta investigación es presentar un estudio que contribuya a llenar una laguna en la literatura mediante la propuesta de un modelo de madurez para evaluar la preparación de las unidades de salud pública brasileñas para la implementación de Gemelos Digitales (DGs). Los DGs, como parte de las tecnologías de la Industria 4.0 (I4.0), pueden optimizar la gestión de recursos y procesos en el ámbito sanitario. El modelo fue desarrollado a partir de una revisión sistemática de los Factores Críticos de Éxito (FCE) para la implementación de DGs y de las dimensiones de los modelos de madurez. Los FCE se agruparon en seis clases conceptuales, mientras que las dimensiones de madurez se categorizaron en cuatro: Infraestructura, Organización, Procesos y Gestión de la Información—cada una con cuatro niveles: Inicial, Básico, Intermedio y Avanzado. La validación preliminar se realizó en unidades básicas de salud de dos municipios y en dos hospitales de la región sur fluminense de Río de Janeiro. Los resultados demostraron la capacidad del modelo para diferenciar niveles de madurez organizacional, destacando su potencial de aplicación práctica. Este estudio contribuye al área al ofrecer una herramienta adaptada para la planificación estratégica y la asignación de recursos en la implementación de DGs en el sector público de la salud, con posible expansión al ámbito privado.
**Palabras clave:** Gemelos Digitales; Sistema Único de Salud; Modelo de Madurez; Transformación Digital.

## 1. Introduction

The Brazilian Federal Constitution of 1988 (Do Brasil, 1988) establishes that health is a right for all, and the State is responsible for ensuring this right through social and economic policies aimed at reducing the risk of diseases and providing universal and equal access to health promotion, protection, and recovery services. These principles were formalized in Law 8080 of 1990 (Júnior A & Júnior L, 2006; Pinto Junior et al., 2014; Almeida Botega et al., 2020), which serves as the legal framework for the Unified Health System (SUS, acronym in Portuguese). Ensuring the right to health is a shared responsibility of the three levels (Chieffi et al., 2017) of government in Brazil (federal, state, and municipal). Despite its principles of universality, comprehensiveness, and equity, it grapples with insufficient funding and an inefficiency of public expenditures that amount to 8% of the GDP (Schenkman et al., 2022).

Martins and Waclawovsky (2015) conducted a literature review based on a retrospective analysis of scientific articles, documents, and books published between 1994 and 2014 with the aim of identifying the challenges and difficulties in healthcare management. The authors identified key topics to be addressed, which include: lack of planning and managerial deficiencies, comprehensiveness of actions, interaction among multiprofessionals and the quality and resolution of care, collective work, equity, universalization, financing, institutional model, the healthcare model, workforce management, and social participation. Other issues highlighted in their study encompass the misunderstanding of the SUS mission, bureaucracy, decentralization, public participation, the double-door system, access regulation to healthcare, human resource management, regulation, control, evaluation, and auditing, and, finally, service quality management. The identified focal topics can serve as starting points for proposing digital solutions (van Velthoven et al., 2019) that optimize the use of public resources, considering the strategic role of existing digital technologies. This aligns with the vision that digital transformation in healthcare is a strategic field (Dal Mas et al., 2023).

The focal points emphasize the need for agility, flexibility, structured organization, planning, control, and ongoing technical-scientific training in public healthcare management to enhance service delivery and optimize the use of public resources. With the advancement of digitization, the public sector is undergoing a necessary transformation to address societal, economic, and educational changes, as indicated by data from the European Commission showing increased quality and use of digital public services (Banhidi et al., 2020). Furthermore, digitalization in Brazil has resulted in substantial savings for the federal government (Porrua et al., 2021).

Since the 1990s, rapid technological advancement has instigated profound changes in production processes, heralding the onset of the fourth industrial revolution (Zhou et al., 2015), commonly referred to as Industry 4.0 (I40). This transformative wave, encapsulated as I40, involves the convergence of technologies to enhance, automate, and optimize manufacturing, giving rise to the concept of the ”smart factory.” The advantages of heightened efficiency, performance, quality, and productivity stemming from I40 have swiftly extended to other sectors of society. Key technologies associated with I40 encompass the Internet of Things, Big Data, Cloud Computing, Simulation, Virtual and Augmented Reality, Robotics and Autonomous Collaboration, Additive Manufacturing, Cybersecurity, and Cyber-Physical Systems (Kamble et al., 2018; Min et al., 2019).

A subset of I40 tools is the Digital Twin (DT), which represents a cutting-edge application at the forefront of the convergence of I40 technologies. Bolton et al. offering a definition of DT as “a realistic digital representation of assets, processes, or systems in the natural or built environment”. Its definition remains a work in progress (Barricelli et al., 2019). In order to identify potential solutions for public healthcare management (Erol et al., 2020) processes and the success of adopting a DT based approach, this work proposes the development of a maturity model for DT implementation in a public healthcare unit. This initiative is motivated by the absence of models specifically dedicated to assessing the maturity of public healthcare units. The conceptual framework of the model will be constructed through an extensive review of literature in relevant knowledge fields and a systematic literature review (Dziopa and Ahern, 2011) of the critical success factors (CSFs) necessary for the effective implementation of a DT in a given healthcare unit, while also taking into account dimensions from existing maturity models (MM). The growing adoption of advanced technologies in healthcare, such as system simulation, machine learning, and digital twins, is reshaping the management and delivery of healthcare services in both the public and private sectors (Semeraro et al., 2021). However, the successful implementation of DT in Brazilian public healthcare units requires a higher level of organizational and technological maturity. This study is justified due to the lack of research specifically focused on DT implementation in public healthcare and the need to identify critical success factors and maturity models to support this process. The proposed framework will enable healthcare unit managers to assess organizational readiness, identify areas for improvement, and develop action plans. This will lead to significant advances in public resource management, increasing operational efficiency in healthcare units and resulting in financial and material savings. In summary, this study is relevant for driving digitalization in public healthcare management, benefiting society as a whole.

The objective of this research is to present a study that helps to fill a gap in the literature by proposing a maturity model to assess the readiness of Brazilian public health units for the implementation of Digital Twins (DTs). This article is divided into five chapters, followed by its bibliographic references at the end. Section 2: The theoretical framework of this dissertation addresses the essential concepts related to the study’s topics, including the structure of the healthcare system, critical success factors for its implementation, and the organizational maturity model. It also explores the concept of the digital twin and its relevance in the healthcare sector. Section 3: The methodology used in this work is presented, including the data acquisition tools, the taxonomy used for classifying critical success factors and maturity model dimensions, the roadmap for developing the maturity model, and its validation through field research. Section 4 The obtained results are presented along with their implications and limitations. Finally, in section 5, the study’s discussions are presented, and the next research steps are outlined.

## 2. Theoretical Framework and Research Hypotheses

In this section, we briefly examine the documentation and the current state of research on the DT and its application in healthcare management. Then, we clarify the fundamental principles of the approach used to define the MT for implementing a DT in a SUS healthcare unit.

### 2.1 *Existing technical and technological structure*

The SUS is one of the largest and most complex global public health systems, providing free access to comprehensive services for everyone in Brazil, from basic care in family health units to complex procedures in research hospitals. SUS assistance is a right for all Brazilian citizens, regardless of income or professional situation, covering from conception to the end of life, with a focus on health, quality of life, prevention, and health promotion. The organizational principles of SUS are based on three pillars: regionalization and hierarchization, decentralization and single command, and popular participation. Regionalization and hierarchization require the organization of services according to complexity, limited to a geographical area, planned based on epidemiological and population criteria. Decentralization and single command aim to redistribute power and responsibility among the three levels of government, with health responsibility delegated to municipalities. This principle is supported by the constitutional concept of a single command, where each level of government is autonomous, respecting general principles and social participation. The axis of popular participation emphasizes the need for society's involvement in the system's daily activities, promoting the creation of health committees and meetings to develop strategies, monitor, and evaluate the implementation of health policies.

The primary, secondary, and tertiary are divided levels of care the SUS. Primary care is provided by general practitioners, family health teams, and community health agents, focusing on basic health services and community health education. Secondary care, provided by specialized hospitals, includes more complex procedures and treatments. Tertiary care, delivered by highly specialized hospitals and clinics, encompasses highly specialized procedures and treatments. This complex organizational structure poses challenges in a country with over 5,500 municipalities and 27 federative units, requiring effective negotiation mechanisms between government spheres, such as intergovernmental committees.

To ensure the proper functioning of SUS, intergovernmental committees were established, such as the tripartite committee at the federal level and bipartite committees at the state level. These entities negotiate decisions to be implemented, highlighting the need for an information system dedicated to SUS. An information system is a collection of technologies, people, and processes working together to collect, store, process, and distribute information. Its elements include hardware, software, data, and people, with the central role of system users, designers, developers, and administrators (Castro et al., 2019). Within this Health Information System ecosystem, the identification of users in the SUS is essential, accomplished through the use of the National Health Card (CNS) as mandated by the Ministry of Health. The CNS contains personal information, contacts, and documents of users and enables the computerized recording of health services provided at all levels, including primary health units, hospitals, pharmacies, and laboratories. The CNS features a QR code that can be scanned by Health Information Systems with available interfaces. This unique identification for SUS users serves as a facilitator for integrated management initiatives, streamlining data consolidation, such as the creation of a comprehensive medical record documenting the user's entire interaction history with SUS. Nevertheless, a major challenge for the NHC lies in integrating different HIS implementations within the Health System, given their fragmentation resulting from distinct concepts, purposes, and objectives (Castro et al., 2019).

Initiatives to centralize data collected by various Health Information Systems began in 2015 and culminated in the Conecte-SUS platform, launched in 2019. Among its various actions, Conecte-SUS promotes the digital transformation of healthcare in Brazil, providing access to data across the entire SUS network. This infrastructure is crucial for proposing the implementation of a Health Data Warehouse GD (Sacks et al., 2020; Liu et al., 2019). The establishment of interconnected network structures through an Information System serves as the primary bridge for transitioning healthcare management into the era of digital health and precision medicine (Croatti et al., 2020).

### 2.2 *Critical success factors and maturity models*

Critical Success Factors (CSFs) are essential elements to achieve specific goals in projects, programs, or initiatives. Their categories range from setting clear and measurable goals to the need for effective leadership, adequate resource allocation, open communication, risk management, flexibility, continuous improvement, stakeholder engagement, alignment with corporate strategy, and strong governance. These CSFs provide a comprehensive framework, crucial for guiding and assessing progress, ensuring the effectiveness and overall success of any endeavor (Freund, 1988; Rad et al., 2022).

To illustrate the modern use of Critical Success Factors (CSFs), a search was conducted in the Web of Science database over the past five years using the terms ”critical success factors” or ”key success factors.” The search yielded 3,308 publications, with the areas of Management, Industrial Engineering, and Business comprising approximately 50% of the articles. Environmental Sciences and Green Sustainable Science Technology represent 20% of the publications. This result shows that CSFs are being studied and are relevant across various fields and applications. The distribution of publications by country also revealed that Brazil is among the top ten countries with the highest output: India 452 (13.664%), People’s Republic of China 452 (13.664%), USA 306 (9.250%), England 293 (8.857%), Australia 257 (7.769%), Malaysia 251 (7.588%), Brazil 179 (5.411%), Saudi Arabia 117 (3.537%), South Africa 116 (3.507%), and Germany 109 (3.295%).

The methods for identifying Critical Success Factors (CSFs) can be divided into those that use surveys and interviews with system experts and those that rely on literature reviews. Both approaches categorize the collected data into classes with similar properties. According to Zhou et al. (2015), and Todorovic´ et al. (2015), the current literature lacks systematic identification of CSFs. Ika et al. (2012) explore CSFs in World Bank projects, highlighting the multidimensionality of CSFs, summarized into five main factors: monitoring, national coordination, design, training, and institutional environment. Farhan et al. (2018) use a systematic literature review to identify CSFs related to the implementation of customer relationship management systems, employing a three-step methodology that begins with identifying research questions to guide the entire systematic review. Once the set of Critical Success Factors (CSFs) is defined, it is necessary to prioritize them based on their impact on the project’s implementation. Several methods can be used to classify the importance of each CSF. The prioritization matrix involves placing each CSF in a matrix based on its level of importance and achievement, with high importance and performance factors considered the most critical. Pareto analysis classifies factors based on their overall impact or contribution to the project’s success, with the highest impact factors deemed most critical. The weighted scoring model assigns a numerical value or weight to each CSF based on its importance, with the highest-weighted factors considered the most critical. Surveys and expert evaluations gather information from experts or stakeholders to rank each CSF’s importance. The method chosen to classify the importance of CSFs depends on the specific project or organization and the available information. The field of CSF study is still consolidating and requires theoretical and methodological advances to reach a mature state, but it is a validated tool for academic investigation and practical application.

When addressing maturity models, the first point that arises is the Capability Maturity Model Integration (CMMI), a framework containing best practices for product development, which has rapidly spread to various other applications (Wendler, 2012). This concept began with Shewhart (1931), was developed by Crosby (1979) with the introduction of the quality management process maturity grid, and expanded in the early 21st century. In simplified terms, a maturity model is a structure used to measure the maturity level of an organization, process, or system through the analysis of multiple dimensions. Maturity levels typically represent different stages of development or improvement and can help identify areas needing enhancement. Common examples of maturity levels include ”initial,” ”managed,” ”defined,” ”quantitatively managed,” and ”optimizing.” Definitions of maturity models, such as those presented by Paulk et al. (1993) and Pullen (2007), provide a basic conceptual understanding but do not detail the constitutive elements of a model, varying in terms of application and purpose. The field of maturity model studies is still evolving, similar to CSFs. A recent example is the work of Medina et al. (2021), which seeks to create a representative model to assess the maturity of DT implementations in OEMs of the commercial aerospace industry. Using Design Science Research (Hevner et al., 2008), the study addresses three main components: the environment, the knowledge base, and the model design. The environment defines the problem space, such as primary health units; the knowledge base includes relevant literature and research; and the model design refers to the requirements and foundations derived from the environment and knowledge base.

### 2.3 *Digital twins*

The concept of a Digital Twin (DT) has existed for decades, first proposed in 2002 by Dr. Michael Grieves, who defined it as “a virtual representation of a physical object or system throughout its life cycle, including its design, manufacturing, operation, and disposal” (Grieves, 2003). A DT is a digital replica of a physical object or system that uses sensor data and other sources to create a real-time model, enabling the analysis and optimization of its performance. DTs are commonly used in manufacturing, transportation, and management to enhance efficiency, reduce costs, and improve customer satisfaction. They have five predominant applications: design and simulation, monitoring and forecasting, remote operations, training, and decision support.

The Digital Twin (DT) can be analyzed in three main components, which simplify the description by grouping the five dimensions proposed by Qi et al. (2021). The first component involves sensors and actuators, where the physical system is equipped with sensors to capture signals for the virtual system and actuators to execute actions based on analysis and predictions from the virtual system. The second component is data processing, requiring optimized techniques for encoding, decoding, high-dimensional data analysis, data concatenation algorithms, and mathematical model simulations for real system predictions. Finally, the third component is communication, where the DT must enable near-real-time communication between the physical environment, the virtual system, and other DTs within the ecosystem, playing a crucial role in the bidirectional dynamics of signal collection and action execution.

Given the characteristics of DT, the manufacturing industry is particularly fertile ground for their application and development. However, services and management areas have also begun to explore this technology. DT has shown significant advantages in support analyses in healthcare, maintenance, and planning, especially in monitoring anomalies, fatigue, crack propagation, geometric and plastic deformation of materials, and the reliability of physical system models (Zhang et al., 2021). Another broad application is the digital mirroring of physical entities to study long-term system behavior and predict performance under various conditions. Additionally, DTs are being increasingly applied in management and administration, leveraging the growing digitalization of the economy and organizational structures. Parmar et al. (2020) suggest that implementing DTs in organizational decision-making can increase efficiency, effectiveness, and profitability by optimizing managerial systems.

The first principle emphasizes starting with the existing organizational structure for implementing a DT. This involves a comprehensive assessment of the digital technologies already in use, focusing on assets, processes, and interactions within the organization. The second principle addresses the hierarchy of data silos within the organization, emphasizing the need to free data from these silos for full DT functionality while ensuring compliance with data protection laws. The third principle, ”moving the digitalization frontier,” involves seeking opportunities within the organization for further digitalization, leveraging information and communication technologies (ICTs) to modernize and expand communication tools across all organizational levels. The fourth principle encourages exploring new digital opportunities, as the digitalization process opens up avenues for innovation, asset repurposing, and organizational flexibility. Finally, the fifth principle, ”enhance models,” describes how the initial implementation of a DT leads to the model’s evolution through regular maintenance and improvements, driven by the recursive processes described in the third and fourth principles (Parmar et al., 2020).

Oliveira Ribeiro et al. (2022) conducted a bibliometric analysis correlating the research fields of Digital Twins (DT) and Health Management. The study examined peer-reviewed articles written in English with at least 10 citations between 2017 and 2022, resulting in a database of 33 manuscripts, including 12 articles, 13 conference papers, and 8 review articles. The data revealed a global interest in the intersection of these topics, with publications from 14 different countries, led by China, Germany, Italy, and the United States. The analysis of keyword cooccurrence highlighted several clusters related to the integration of DT and Health Management, emphasizing areas like cloud computing, personalized medicine, and machine learning. The study concluded that while China leads in this research area, the global collaboration is still limited, and current applications of DT in Health Management are mostly confined to automated diagnostics, treatment monitoring, and complex optimization resources. The study also identified opportunities for adapting industrial and service-related DT applications to health management processes with minor adjustments.

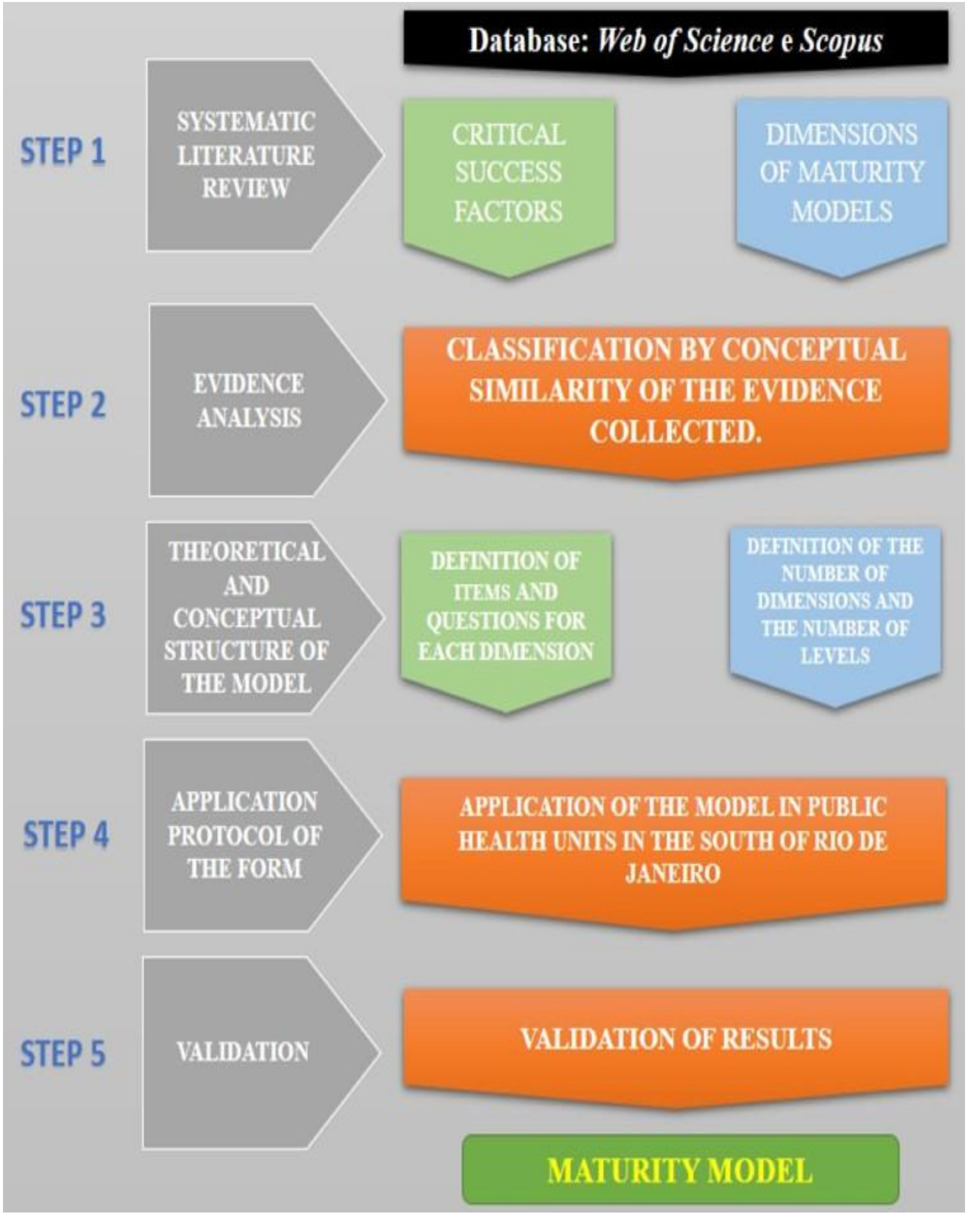
The Digital Twin paradigm is gaining prominence in healthcare (Hempel, 2017; Bruynseels et al., 2018), with applications like personalized medicine, where DTs are used as digital replicas of patients for more effective and predictive interventions. The success of DT implementation depends on various Critical Success Factors (Medina et al., 2021), such as clear objectives, data quality and availability, interoperability, scalability, security, and human integration in decision-making processes. Current literature highlights the need for a structured model to assess CSFs in the adoption of DTs, especially in sectors like supply chains. Kinman and Tutt (2023) categorizes CSFs into three groups: organizational components (innovation, communication), processes (governance, simulation), and technology (IoT, AI). These factors are crucial for successful implementation and digital transformation within organizations.

## 3. Methods and Data

The research process includes problem formulation, planning, data collection and interpretation, and communication of results, and should be conducted with scientific rigor to contribute to the development of basic and applied science (Bunge, 1980). To facilitate understanding and evaluation, research should be classified according to its nature, approach, and procedures (Santos et al., 2018; Koche, 2016). This paper is an applied research study that utilizes both a qualitative approach, employing the Action Research method, and a quantitative approach, using the exploratory method. The applied nature of this research lies in its aim to find solutions to improve public health services by investigating the feasibility of implementing a Digital Twin (DT) in a specific healthcare unit. The exploratory aspect is focused on investigating and understanding the application of a DT in public health services, a topic that is underexplored and lacks theoretical content in Brazil (Cruz & Tonin, 2022; Oliveira Ribeiro et al., 2022).

Regarding the approach, this research can be classified as both qualitative and quantitative, as it utilizes both methods for the analysis and interpretation of the collected data. The quantitative research aims to transform the information obtained into numerical data through a survey conducted at public health units in the municipalities of southern Rio de Janeiro. In contrast, the qualitative research involves interpretive analysis of the data obtained, even if they are not directly measurable from the results of the literature review. The approach can be concatenated into five phases, as shown in Figure 1. At the end of these phases, a maturity model for implementing a DT in a Brazilian public health unit is proposed, composed of dimensions and maturity levels.

**Figure 1** - Main Activities and Methodological Procedures for the Development of the Maturity Model.




Source: Research data (2025).

Oliveira Ribeiro et al. (2022) conducted a systematic literature review to analyze the relationship between the fields of DT and health management using the Web of Science database. They utilized the Bibliometrix package and the VOSviewer application to mine data and identify research clusters and future trends. The study found that DT applications in health management are primarily focused on diagnosing and monitoring chronic diseases. Keywords identifying articles that connect these two themes were presented in Table 1. Keywords summarize the main topic of an article and are used for indexing in databases and search systems. Selected by the author or editors, they should be relevant to the article's content and can serve as initial delimiters of a knowledge field (Garcia et al., 2019).

**Table 1** - The 33 keywords defining the relationship between the fields of Digital Twins (DT) and Health Management obtained by (Oliveira Ribeiro et al., 2022).

| Keywords | Occurrences | Total Connections |
|---|---|---|
| digital twin | 29 | 78 |
| simulation | 7 | 27 |
| design | 4 | 19 |
| industry 4.0 | 4 | 14 |
| internet of things | 4 | 19 |
| management | 4 | 17 |
| performance | 4 | 20 |
| bim | 3 | 9 |
| future | 3 | 12 |
| information modeling bim | 3 | 17 |
| internet | 3 | 16 |
| manufacturing system | 3 | 3 |
| model | 3 | 12 |
| network | 3 | 13 |
| big data | 2 | 10 |
| brain image | 2 | 7 |
| building information modeling | 2 | 13 |
| cloud computing | 2 | 5 |
| deep learning | 2 | 6 |
| digital thread | 2 | 6 |
| fault-diagnosis | 2 | 8 |
| genetic algorithm | 2 | 9 |
| image segmentation | 2 | 7 |
| machine learning | 2 | 6 |
| modelling | 2 | 3 |
| personalized medicine | 2 | 4 |
| precision medicine | 2 | 5 |
| real-time | 2 | 6 |
| scheduling | 2 | 8 |
| smart manufacturing | 2 | 6 |

Source: Research data (2025).

Booth et al. (2021) list sixteen possible types of literature reviews in their book Systematic Approaches to a Successful Literature Review. Among these, Pati and Lorusso (2018) highlight three key types: meta-analysis, systematic qualitative review or synthesis of qualitative evidence, and systematic review. These types share several common attributes, including the need for a systematic and comprehensive search, evaluation of study quality, proper interpretation of results, and transparency in methodology to ensure the study can be replicated.

Meta-analysis is a statistical technique used to estimate the effect size of a specific intervention based on quantitative data from similar studies. Systematic qualitative review, on the other hand, shares the same objective as meta-analysis but focuses primarily on qualitative studies. While it follows the same methodological principles as systematic review, its emphasis on qualitative studies may lead to different conclusions and applications compared to meta-analysis or systematic reviews that deal with quantitative studies. The systematic review, which adheres to standardized methodologies of research, filtering, reviewing, interpreting, and synthesizing evidence from both qualitative and quantitative studies, is considered an appropriate approach for identifying available evidence in a specific field of knowledge (Pati and Lorusso, 2018). In this study, the systematic review will be applied, following five steps: 1. Define the research question: ”What are the CSFs for the implementation of a DT?”; 2. Search for evidence in the Scopus and Web of Science databases, using the search logic presented TITLE-ABS-KEY ( ( ”Digital Twin” OR simulation OR design OR ”industry 4.0” OR ”internet of things” OR management OR performance OR bim OR future OR ”information modeling bim” OR internet OR ”manufacturing system” OR model OR network OR ”big data” OR ”brain image” OR ”building information” OR modeling OR ”cloud computing” OR ”deep learning” OR ”digital thread” OR fault-diagnosis OR ”genetic algorithm” OR ”image segmentation” OR ”machine learning” OR modelling OR ”personalized medicine” OR ”precision medicine” OR real-time OR scheduling OR ”smart manufacturing” ) AND ( ( ( ”critical success factors” ) OR ( ”Key Success Factors”) ) AND ( ( ”digital twin” ) OR ( ”digital twins” ) ) ) ), which involves the intersection of the terms CSFs, DT, and the keywords from Table 1; 3. Review and select the articles, discarding those not aligned with the research theme; 4. Analyze the methodological quality of the articles, aggregating the evidence obtained and classifying it into representative conceptual categories, as outlined in the appendices I and II; 5. Identify thematic adherence, where the results of the category analysis should provide an answer to the question defined in the first step.

The CSFs, obtained from step 4, are classified into categories based on conceptual similarity. According to Campos (2004), a classification of hierarchically ordered concepts, known as taxonomy, is used to represent a particular domain of knowledge. The classification is carried out through the technique of clustering by similarity, where terms are grouped into categories based on their conceptual resemblances. It is important to note that there are numerous methods for taxonomic classification, and all of them involve a degree of subjectivity (de Almeida Campos and Espanha Gomes CNPq-hagar, 2007; Williams and Ramaprasad, 1996; Catae, 2012).

A systematic review was conducted with the objective of identifying existing maturity models developed for the implementation of DT in organizations or projects, using the same methodological approach previously applied. The main focus of the investigation was to identify the dimensions employed in current maturity models aimed at DT implementation. For this purpose, specific search parameters were defined for two scientific databases. In the Web of Science database, the search expression (((”Maturity model”) AND (”digital twin” or ”digital twins”))) was applied to all fields. In the Scopus database, the search was conducted using the expression TITLE-ABS-KEY (((”Maturity model”) AND (”digital twin” or ”digital twins”))), restricted to titles, abstracts, and keywords.

The development of the maturity model began with the adaptation of the dimension classes identified in the systematic literature review to the context of public health units (Delgado and Oyedele, 2021; Stahmann et al., 2021). Next, the relevant CSFs were associated with each dimension through a cross-analysis of their respective classifications. Based on this correlation, a set of hierarchically structured questions was formulated, in which a negative response to one item implies a negative response to the following item. Finally, maturity levels were defined by assessing the current state of the organization in relation to each selected dimension through the application of a structured questionnaire. In the proposed model, the dimensions are treated as independent, with no prioritization among them.

Finally, evaluation criteria were defined for each maturity level based on the questionnaire responses, using a binary scoring scale (Yes = 1, No = 0) to measure the organization’s progress in each dimension. The results are presented in a RADAR chart, where each axis represents a dimension. In this initial version of the model, the numerical values of the levels do not have a specific absolute meaning and are instead represented on a scale normalized to 1 (Medina et al.,2021).

For a given dimension i (Di), for a given level j (N j) that has n questions (Pn), the level j thus has the degree (equation 1) of this level given by:

$$N_j = \frac{\sum_{n=1}^{m} P_n}{\sum_{n=1}^{m} \max(P_n)} \qquad (1)$$

In words, the degree of each level of a given dimension is normalized to 1, and for the advancement of Nj to Nj + 1 it is required that Nj has the maximum degree, i.e., degree 1. As mentioned earlier, the dimensions do not have a hierarchical relationship, and therefore, it is not necessary to compute an overall value for the model. After defining the questions, levels, dimensions, and the metric to be addressed, the next step is to create the digital form using the Google Forms platform (da Silva Mota, 2019) and send it to the Municipal Secretariats of the municipalities in the South Fluminense region.

## 4. Results

The systematic literature review on Critical Success Factors (CSFs) for the implementation of Digital Twins (DTs), conducted in the Web of Science and Scopus databases, initially identified eleven publications, of which six were considered relevant after applying inclusion and exclusion criteria. The extraction of CSFs from these publications revealed a variety of elements considered vital to the success of DT implementation projects.

These CSFs were grouped into six conceptual classes based on their similarities:

- CF1: Modeling and Simulation – Factors related to the use of advanced technologies and project management methodologies to ensure project success (Anjos et al., 2020; Anderl et al., 2021; Cirullies and Schwede, 2021).
- CF2: Security – Factors concerning data management and information security (Cirullies and Schwede, 2021; Dohale et al., 2022).
- CF3: Information Sharing – Factors linked to collaboration, communication, and knowledge exchange among stakeholders (Anderl et al., 2021; Cirullies and Schwede, 2021).
- CF4: Structure – Factors related to the physical and technological infrastructure required for DT implementation (Stoll et al., 2020; Opoku et al., 2021; Dohale et al., 2022).
- CF5: Management – Factors associated with resource management, strategic alignment, and innovation (Stoll et al., 2020; Anjos et al., 2020; Dohale et al., 2022).
- CF6: X – A residual class for factors that are difficult to measure, such as flexibility, preparedness, and persistence, which were not used in the subsequent stage (Dohale et al., 2022).

Despite the limited number of studies found, the conceptual categorization of the CSFs provided valuable insights for formulating the questions in the proposed maturity model. The identification of factors such as the importance of information modeling, data management, and technological infrastructure underscores the complexity of DT implementation and the need for a comprehensive assessment of organizational readiness.

The search for existing maturity models for DT implementation in the Web of Science and Scopus databases initially yielded thirty publications, with a final sample of fourteen after filtering. Analysis of these publications enabled the identification of dimensions considered relevant for assessing maturity in DT adoption.

The identified dimensions were grouped into six conceptual classes:

- CD1: Organizational Management – Encompassing aspects such as organizational impact, value creation, quality, collaboration, user focus, strategies, culture, ecosystem, and governance, with an emphasis on digital transformation (Chen et al., 2021; Cognet et al., 2019; Nick et al., 2022; Rocha-Ja´come et al., 2021; Stahmann et al., 2021).
- CD2: Information System – Including elements such as asset detection, advanced technology, cloud scheduling and monitoring, real-time tracking, data interoperability, and system integration (Chen et al., 2021; Cognet et al., 2019; Narula et al., 2020; Mostafa et al., 2021; Weber et al., 2017).
- CD3: Structure – Involving physical infrastructure, computing resources, human-machine interface, and context (Chen et al., 2021; Duan and Tian, 2020; Mostafa et al., 2021; Narula et al., 2020; Weber et al., 2017; Song and Li, 2022).

- CD4: Information Management – Including data accessibility, identification and integration of data sources, information models, data curation, inspection and testing digitization, software-based management, big data, and analytical capabilities (Chen et al., 2021; Mostafa et al., 2021; Uhlenkamp et al., 2022; Weber et al., 2017; Malakuti, 2021).
- CD5: Model – A class related to the creation, use, and behavioral analysis of the model, including fidelity, authenticity, and other modeled characteristics (Duan and Tian, 2020; Medina et al., 2021; Mostafa et al., 2021; Nick et al., 2022; Stahmann et al., 2021; Uhlenkamp et al., 2022; Li et al., 2021).
- CD6: Integration – Incorporating decision implementation, product lifecycle integration, human-machine interaction, stakeholder integration, and correlations between different models (Chen et al., 2021; Cognet et al., 2019; Mostafa et al., 2021; Nick et al., 2022; Stahmann et al., 2021; Uhlenkamp et al., 2022; Delgado and Oyedele, 2021).

The results of this review revealed a significant lack of publications specifically dedicated to the implementation of maturity models for Digital Twins. This gap suggests that the topic is still in an early stage of academic exploration, indicating an opportunity to develop more specific models adapted to different contexts, such as public health.

The maturity model developed for the implementation of DT in Brazilian public healthcare units is structured around four dimensions and four maturity levels. The model's dimensions comprise infrastructure, organization, processes, and information management. The diagnostic questions designed to assess the maturity state within each dimension were formulated based on the categories and constituent elements of CSFs. These questions were arranged in a hierarchical and sequential manner to define the progression stages within the model.

The theoretical framework underpinning the model assumes maturity as a serial progression through linear stages—an approach widely recognized in the literature. The model delineates four distinct maturity levels that reflect the healthcare unit's degree of development: Level 1 (Initial), Level 2 (Basic), Level 3 (Intermediate), and Level 4 (Advanced). As the organization progresses through the levels, an incremental evolution in the maturity of each dimension is observed.

This model enables organizations to assess their current positioning across the four dimensions and to identify areas requiring improvement in order to achieve higher levels of information technology maturity. The linear stage-based structure provides a systematic and progressive framework for the technological advancement of the organization.

To evaluate the maturity level for Digital Twin implementation in Brazilian public healthcare units, a structured assessment instrument was developed utilizing the Google Forms platform. This instrument is designed to be applied to public health units to gauge their current state of readiness across the defined dimensions of the maturity model. A prototype of the assessment form is presented in 2, which illustrates the structure and types of questions included.

The assessment form is organized around the four dimensions of the proposed maturity model: infrastructure (D1), organization (D2), processes (D3), and information management (D4). For each dimension, questions are formulated to assess the organization's progress through four distinct maturity levels: Level 1 (Initial), Level 2 (Basic), Level 3 (Intermediate), and Level 4 (Advanced). The questions within each level are designed to identify specific technological and organizational capabilities relevant to Digital Twin implementation. Each question within the assessment form employs a binary scoring scale, where an affirmative response (”yes”) is assigned a value of one (1), and a negative response (”no”) is assigned a value of zero (0). This binary approach facilitates a straightforward measurement of the organization's attainment of specific criteria at each maturity level within each dimension. The degree of attainment for each level (Nj) within a given dimension (Di) is normalized to one (1). Advancement from level Nj to the subsequent level Nj + 1 necessitates achieving the maximum degree (degree 1) at level Nj. This hierarchical progression underscores the sequential nature of maturity within each dimension. Notably, the dimensions themselves are considered independent and non-hierarchical, and therefore, an overall aggregate maturity score for the entire model is not computed in this initial version Table 2, next, presents a form with questions defined for each level of each dimension:

**Table 2** - Form with questions defined for each level of each dimension.

| LEVEL / DIMENSION | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| INFRASTRUCTURE (D1) | COMPUTERS?<br>SMARTPHONES OR TABLETS?<br>COMPUTER NETWORK? | STRUCTURED NETWORK?<br>INTERNET ACCESS? | INTRANET?<br>NETWORKED UNITS? | IOT DEVICE INTEGRATION? |
| ORGANIZATION (D2) | INVESTMENT IN DIGITALIZATION? | ORGANIZATIONAL CULTURE MANAGEMENT?<br>CONTINUING TRAINING PROGRAM? | IT DEPARTMENT?<br>DEDICATED IT TEAM? | DIGITAL HEALTH PROGRAM?<br>TELEMEDICINE? |
| PROCESSES (D3) | INTERNAL CONTROL? | QUALITY INDICATORS?<br>PROCESS MANAGEMENT? | STANDARDIZATION OF PROCESSES? | AUTOMATED PROCESSES? |
| INFORMATION MANAGEMENT (D4) | INFORMATION SYSTEM? | DATA UPDATED IN REAL TIME? | GESTÃO DA INFORMAÇÃO?<br>SEGURANÇA DA INFORMAÇÃO? | AUTOMATED DECISION SUPPORT SYSTEM? |

Source: Research data (2025).

The development of the specific questions for each level and dimension was informed by the FCS identified through the systematic literature review and the conceptual framework established for this research. The questions related to the initial levels (e.g., Level 2 of the infrastructure dimension) aim to evaluate the foundational technological development of the organization, such as the structuring of the computer network and internet access. Progressing to higher levels (e.g., Level 4 of the infrastructure dimension), the questions assess more advanced capabilities, such as the integration of IoT devices for real-time data collection. Similarly, questions within the organizational dimension explore aspects ranging from basic digitalization investments to the presence of dedicated IT teams and digital health programs. The information management dimension assesses the existence of information systems, real-time data updating, formal information management practices, information security measures, and the presence of automated decision support systems.

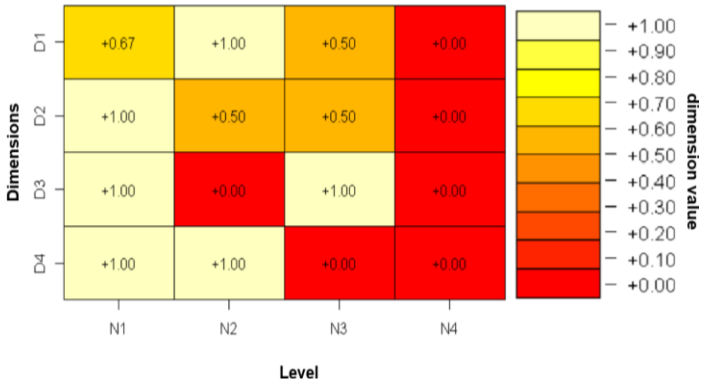
**4.1Validation of the Maturity Model**

The current research on the validation of maturity models reveals a limited number of studies where authors explicitly validate their proposed models. While some suggest the use of case studies or interviews for validation, a substantial portion of the literature lacks empirical validation. In this study, the approach adopted for validation involved the application of the developed maturity model to public health units and hospitals, followed by an analysis of the results and feedback from the involved management. This strategy aimed to assess the model's ability to measure the maturity levels across different organizational contexts.

The model was applied to basic health units in two citys of the South Fluminense region: a medium-sized municipality (city A) and a large-sized municipality (city B). Notably, the responses from the basic health units within each municipality were found to be homogeneous. The model was also applied to two hospitals: Hospital A, a well-established public institution with significant advancements in addressing a specific health condition, and Hospital B, a part of a widely recognized private healthcare network. The inclusion of Hospital A aimed to evaluate the upper limits of the model due to its advanced nature, while Hospital B was included to examine the model's applicability beyond public institutions.

The results for city A Figura 2 indicated a foundational level of technological infrastructure, with structured computer networks and internet access. In the organizational dimension, while there was investment in digitalization at Level 1, the absence of a digital-oriented organizational culture at Level 2 was noted as a potential barrier. Process management showed internal control and quality indicators at Levels 1 and 2, but lacked process standardization and automation. Information management revealed a basic information system at Level 1, real-time data updates at Level 2, but deficiencies in formal information management and security at Level 3, and the absence of an automated decision support system at Level 4

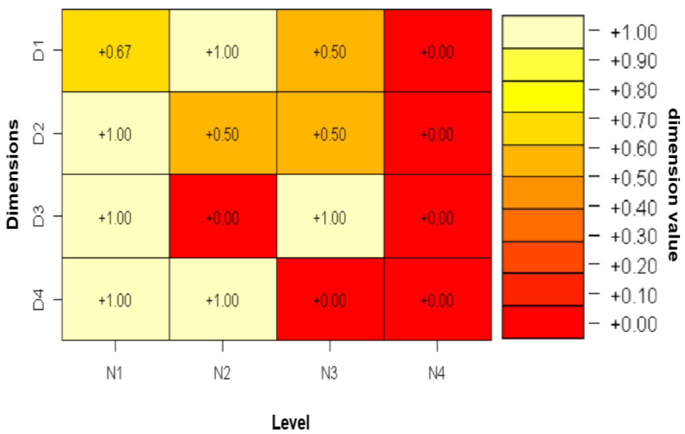
**Figure 2** - Presentation of the responses of the maturity model for the health units of city A. The color scale is normalized to 1 as described in equation 1. In the graph, the dimensions are identified as: infrastructure (D1), organization (D2), processes (D3), information management (D4).




Source: Research data (2025).

City B Figura 3 demonstrated maximum scores up to Level 3 across all dimensions in its basic health units. Similar to city A, the infrastructure, process, and information management dimensions followed a comparable pattern. However, a significant advancement to Level 4 was observed in the organizational dimension due to the presence of a digital health program. The absence of telemedicine was identified as an area for future consideration.

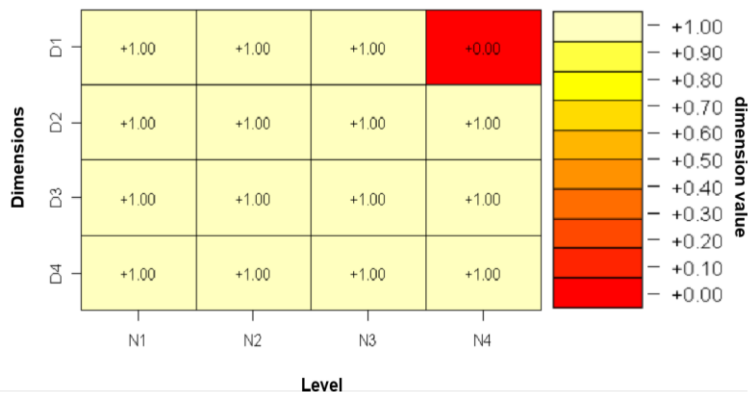
**Figure 3** - Presentation of the responses of the maturity model for the health units of city B. The color scale is normalized to 1 as described in equation 1. In the graph, the dimensions are identified as: infrastructure (D1), organization (D2), processes (D3), information management (D4).




Source: Research data (2025).

Hospital A Figura 4 demonstrated high maturity across most dimensions, reaching the maximum score up to Level 3. The only exception was Level 4 of the infrastructure dimension, where the integration of IoT devices was not yet achieved. This highlighted a potential area for further technological advancement despite the hospital's overall integrated and excellent infrastructure.

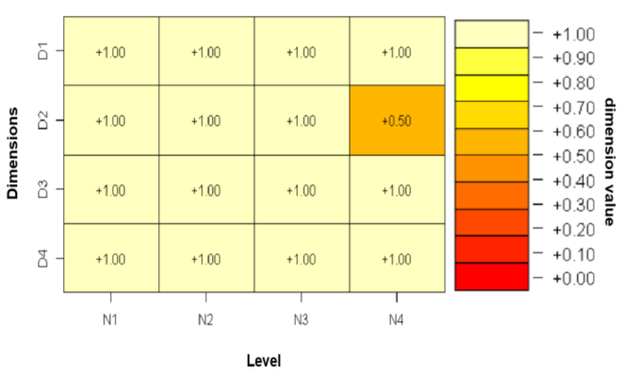
**Figure 4** - Presentation of the responses of the maturity model for hospital A. The color scale is normalized to 1 as described in equation 1. In the graph the dimensions are identified as: infrastructure (D1) organization (D2) processes (D3) information management (D4).




Source: Research data (2025).

Hospital B Figura 5 also met almost all criteria up to Level 3, similar to Hospital A. The exception was Level 4 of the organizational dimension, specifically the absence of telemedicine services. This indicated a gap in the adoption of remote healthcare solutions. It is possible to effectively distinguish the degree of maturity of the organizations and identify which dimensions require special attention for the implementation of the Digital Twin. The successful differentiation of maturity levels across the dimensions for the participating municipalities and hospitals provides evidence of the model's usability and utility. The model's ability to distinguish organizations with varying characteristics suggests its potential for broader application. Furthermore, the application to a private health unit offers a promising perspective for validating the model in diverse contexts. The feedback from the management regarding the model's application will be discussed further. The findings suggest that the developed maturity model demonstrates a substantial capacity to adequately differentiate the maturity levels across various basic health units and has promising potential for application in private healthcare units as well.

**Figure 5** - Presentation of the responses of the maturity model for hospital B. The color scale is normalized to 1 as described in equation 1. In the graph the dimensions are identified as: infrastructure (D1) organization (D2) processes (D3) information management (D4).




Source: Research data (2025).

## 5. Discussion and Conclusions

This study addressed the gap in research by developing a maturity model to evaluate the readiness of Brazilian public health units for the implementation of Digital Twins (DTs). The motivation stemmed from the recognized potential of DTs, as technologies of Industry 4.0, to enhance public health resource management through near real-time process insights. The absence of dedicated models for this specific context underscored the significance of this research.

The analysis of Critical Success Factors (CSFs) revealed key thematic categories essential for successful DT implementation in public health. These included: Modeling and Simulation (CF1): Emphasizing the adoption of advanced technologies and project management methodologies to ensure project success and informed decision-making. Security (CF2): Highlighting the critical role of data management and information security in maintaining data quality, privacy, and integrity. Logistics (CF3): Underscoring the importance of efficient supply chain management, where DTs can provide enhanced visibility and facilitate better decision-making. Structure (CF4): Addressing both the physical infrastructure of the health unit and the technological infrastructure required for DT implementation. Management (CF5): Incorporating organizational, strategic, and environmental management factors crucial for DT success, including resource management and strategic alignment.

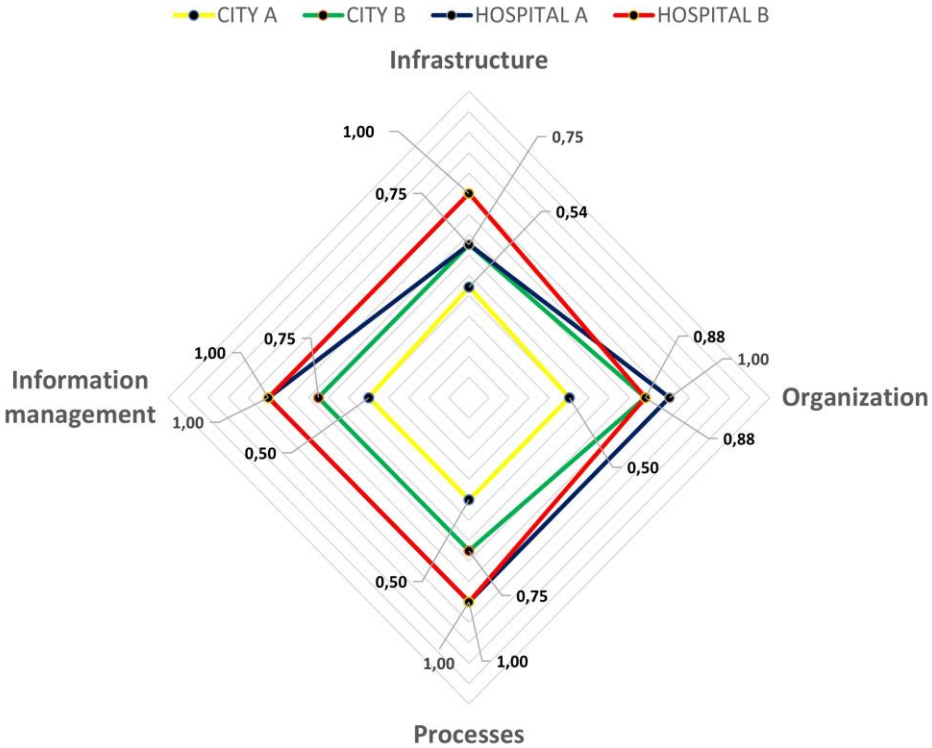
This systematic categorization of CSFs, despite the limited number of studies specifically focusing on DT implementation CSFs, provided a robust foundation for the development of the maturity model's dimensions and levels. The scarcity of prior research in this specific intersection of DTs and public health management may be attributed to the novelty of the concept in this area. The identified dimensions of maturity further reflected the multifaceted nature of preparing a public health unit for DT adoption. These dimensions, ranging from organizational management to information systems and integration, align with the complex and interconnected landscape of public healthcare and its digital transformation. The inclusion of dimensions such as "Information System," "Structure," and "Information Management" underscores the necessity of advanced technologies, a robust infrastructure, and a strategic approach to data handling. The "Organizational Management" dimension acknowledges the importance of value creation and quality of care, while "Integration" highlights the collaborative nature of public health and the need for effective stakeholder engagement.

The maturity model developed, comprising four dimensions (Infrastructure, Organization, Processes, and Information Management) and four hierarchical levels (Initial, Basic, Intermediate, and Advanced), shares similarities with existing maturity models in its staged approach to organizational development. The model's application in selected public health units (city A and B) and hospitals (Hospital A and B) provided preliminary evidence of its usability and ability to differentiate maturity levels across various organizational contexts. The differentiation achieved among the participating entities supports the model's potential for broader application in assessing readiness for DT implementation within the Brazilian public health system and offers a promising avenue for validation in private healthcare settings. However, the study also encountered some limitations. The hierarchical progression through the maturity levels was not strictly linear in all cases, potentially due to the formulation of specific questions or a possible lack of complete understanding of the questions by the involved management.

This research successfully developed a novel maturity model specifically designed to evaluate the readiness of Brazilian public health units for the implementation of the Digital Twin. This model contributes significantly by addressing the existing gap in both academic literature and practical tools for this emerging field. The identification and categorization of critical success factors and maturity dimensions provide a comprehensive understanding of the key elements necessary for successful DT adoption in this context. The preliminary validation through application in diverse healthcare settings demonstrates the potential of the model for strategic decision making and resource allocation toward effective DT implementation, ultimately aiming to enhance the efficiency and quality of public health services.

Figura. 6 illustrates a radar chart comparing the four maturity models developed in this dissertation. The model's ability to evaluate the units, characterizing them in a specific way, is evident. City A, whose basic units have more limited resources, recorded the lowest scores in all dimensions, falling behind all other units. In contrast, city B, which has a more robust care network, obtained a higher evaluation than city A. Both hospital A and hospital B, which have significantly more resources than the units in cities A and B, were evaluated as having better performances.

**Figure 6** - The figure presents a radar chart with 4 dimensions of model maturity for the studied samples. An interesting finding highlighted by the model is that, in relation to the organizations dimension, the health units of city B demonstrate greater proximity to hospitals A and B than the health units of city A. This observation can be attributed to the fact that city B implemented a telemedicine program throughout its network of basic health units.




Source: Research data (2025).

Future research directions include refining the assessment instrument to ensure clearer interpretation of questions and conducting more extensive validation across a larger and more diverse sample of public and private health units. Further investigation could also explore the interdependencies between the model's dimensions and the development of specific strategies for progressing through the maturity levels. Comparative studies across different countries could further enhance the robustness of the model and identify universal factors in the implementation of DT within healthcare systems.

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